ASTRI Mini-Array
Stellar Intensity Interferometry Instrument
Conceptual Design Document

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DOCUMENT HISTORY		
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2.1	14/03/2021	Second release (revised)
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1 Introduction

The ASTRI (Astrofisica con Specchi a Tecnologia Replicante Italiana) Mini-Array is an INAF project finalized to the construction 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 in the TeV spectral band. Besides carrying out a scientific program in the Very High Energy Gamma-ray band, the ASTRI Mini-Array will also perform stellar intensity interferometry observations of bright stars.

1.1 Purpose

This document details the design activities leading to the definition of a baseline for the ASTRI Stellar Intensity Interferometry Instrument (SI^3). It is directed to the ASTRI members involved in the construction and development of SI^3 and to the external panel appointed for performing the initial assessment of the design.

1.2 Scope

This document describes a fast single photon counting instrument for performing intensity interferometry observations of bright stars with the ASTRI Mini-Array. It focuses on the key design requirements of the instrument, how they derive from functional requirements, and on the current selected baseline.

1.3 Definitions and Conventions

1.3.1 Abbreviations and acronyms

The following abbreviations and acronyms are used in this document:

ADAS	Array Data Acquisition System
AIT	Assembly Integration and Testing
AIV	Assembly Integration and Verification
ASIC	Application Specific Integrated Circuits
ASTRI	Astrofisica con Specchi a Tecnologia Replicante Italiana
AR	Acceptance Review
ATRR	Acceptance Test Readiness Review BEE Back End Electronics
BEE	Back End Electronics
CCU	Control and Communication Unit
CDR	Critical Design Review

CFI	Customer Furnished Item
COTS	Commercial Off The Shelf
DCR	Dark Count Rate
DR	Design Requirement
EN	Electronic Noise
FoV	Field of View
FPM	Focal Plane Module
FPO	Focal Plane Optics
FPR	Functional or Performance Requirement
FEE	Front End Electronics
FMECA	Failure Mode Effects and Criticality Analysis
HW	Hardware
IAC	Instituto de Astrofísica de Canarias
IIM	Intensity Interferometry Moduleipc
INAF	Istituto Nazionale di Astrofisica
IPC	Industrial Computer
IR	Interface Requirement
ITW	Integration Time Window
KOM	Kick Off Meeting
LLI	Long Lead Item
MIUR	Ministero dell'Istruzione, dell'Università e della Ricerca
MOT	Maximum Operating Temperature
MSA	Mechanical Structure Assembly
MUSIC	Multichannel SiPM readout ASIC
PA	Product Assurance
PBS	Product Breakdown Structure
PCB	Printed Circuit Board
PDM	Photon Detection Module
PDR	Preliminary Design Review
PR	Production Review
OPC-UA	Open Platform Communications - Unified Architecture
PDE	Photon Detection Efficiency
PRE-FEE	Preamplification Front End Electronics
PSF	Point Spread Function
QA	Quality Assurance
QR	Qualification Review
QTRR	Qualification Test Readiness Review
RAM	Reliability, Availability and Maintainability

RR	Requirements Review
SCADA	Supervisory Control And Data Acquisition system
SE	System Engineering
SII	Stellar Intensity Interferometry
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
VVR	Verification and Validation Requirement
WR	White Rabbit

1.3.2 Definitions

Degree of coherence. Measurement of the spatial or temporal correlation between the photons fluxes of a star received at two telescopes.

Focal Plane Optics. Sub-assembly of SI^3 containing all the optical elements of the instrument, including a filter wheel.

Front End Electronics. Sub-assembly of SI3 made of the 2x2 detector array, the readout board (preamplification Front End Electronics, positioned at the focal plane), and the module that performs signal conditioning.

Focal Plane Module. Sub-assembly made of the Focal Plane Optics and part of the Front End Electronics.

Back End Electronics. Sub-assembly of SI3 that acquires the signals from the Front End Electronics and streams them to the Supervisory Control And Data Acquisition system.

2 Related Documents

2.1 Applicable Documents

[AD1] ASTRI Quality Plan: ASTRI-INAF-PLA-3000-001
[AD2] ASTRI Common Technical Standard: ASTRI-INAF-SPE-2000-003
[AD3] ASTRI Mini Array Environmental Conditions: ASTRI-INAF-SPE-2000-002
[AD4] ASTRI Mini Array Product Tree: ASTRI-INAF-DES-2000-001
[AD5] ASTRI Mini Array Optical design description: ASTRI-INAF-DES-7200-001
[AD6] ASTRI Mini Array Telescope Mechanical Structure Design Requirements Specification: ASTRI-INAF-SPE-7100-001

2.2 Reference Documents

[RD1] ASTRI Mini-Array Operation Concept: ASTRI-INAF-SPE-1000-001
[RD2] ASTRI Mini-Array Core Science at the Observatorio del Teide, Vercellone, S. et al. (2021), Journal of High Energy Astrophysics, in preparation
[RD3] ASTRI Mini-Array Stellar Intensity Interferometry Instrument Science Requirements: ASTRI-INAF-SCI-7400-001
[RD4] ASTRI Mini-Array Stellar Intensity Interferometry Instrument Requirements Specifications: ASTRI-INAF-SPE-7400-002
[RD5] Bonanno, G. & Romeo, G., “Elettronica di Front-End per modulo di Interferometria di Intensità”: ASTRI-INAF-REP-7400-001
[RD6] ASTRI Mini-Array Top Level Software Architecture: ASTRI-INAF-DES-2100-001

3 Instrument Overview and Functional Workflow

The ASTRI (Astrophysics with Italian Replicating Technology Mirrors) project was approved in 2010 to support the development of technologies within the Cherenkov Telescope Array project. In this framework INAF is building an independent Mini-array of 9 Cherenkov 4m-class telescopes in Schwarzschild-Couder optical configuration in Tenerife (Spain) [RD1]. Because of the adequate collecting area and the long (100-700 m) baseline provided by the 9 telescopes, the ASTRI Mini-array represents also a suitable infrastructure for performing stellar intensity interferometry (SII) observations [RD2]. The theoretical resolving capability of the Mini-array as an interferometer is clearly shown in Figure 1, where the discrete degree of coherence between two telescopes is shown as a function of their separation for sources of different angular sizes [RD3]. The 9 telescopes offer up to 36 different baselines for performing simultaneous measurements.

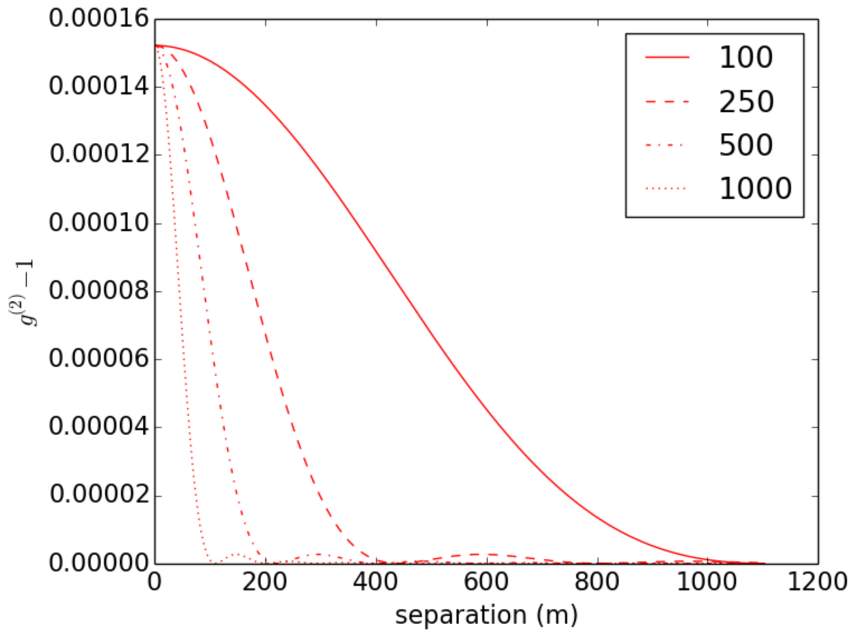


Figure 1 - Discrete degree of coherence as a function of telescope separation for stars (approximated as discs with uniform brightness) with different angular sizes (in microarsec; sampling time 1 ns). The separation of the 9 telescopes of the ASTRI Mini-array is in the range 100-700 m.

Such an infrastructure, properly equipped with dedicated instrumentation, is ideal to perform imaging through optical intensity interferometry and can potentially reach an extraordinary resolving capability (below 100 microarsec) in the optical band. The ASTRI Mini-Array can then provide the first images of bright Galactic stars with sub-mas angular resolution. This capability will open up unprecedented frontiers in some of the major topics in stellar astrophysics [RD3].

In order to implement SII capabilities on Cherenkov telescopes, dedicated instrumentation is needed, capable of correlating their signals over short time bins (~1 ns) or high sampling frequencies (~1 GHz), exploiting the large photon fluxes while maintaining affordable rates (without reducing the coherence), and handling the computational effort required for managing the photon detection/acquisition and the calculation of the coherence.

The ASTRI Stellar Intensity Interferometry Instrument (SI^3) is conceived to achieve this goal. It is a fast single photon counting instrument for performing intensity interferometry observations of bright stars with the ASTRI Mini-Array. SI^3 is designed to perform accurate measurements of single photon arrival times (1 ns) in a narrow optical window (3-8 nm) centered at a wavelength in the range 420-500 nm. Measurements with the SI^3 instruments mounted on the telescopes of the array will be used to determine the second order degree of spatial and temporal coherence of a star. A simultaneous measurement of the degree of coherence at zero baseline will also be done by placing a 2x2 array of detectors on the focal plane and correlating the signal among them. All measurements of the coherence will be performed counting photon coincidences in post-processing by means of a single photon software correlator. Processing data off-line has the advantage that the data reduction chain can be repeated more times, enabling the possibility to check for systematics, tune the parameters of the analysis, optimize the procedure, and increase the accuracy of the results. In principle, it could also enable the computation of correlations among three or more telescopes [RD3].

Simultaneous measurements with the 36 available baselines will allow to carry out image reconstruction through classical interferometric techniques.

The expected photon rate of the ASTRI telescopes in the wavelength range of a narrow band (3 nm + polarizer) filter centered at 440 nm is reported as a function of star V magnitude in Figure 2. The telescope optical transfer function (mirror reflectivity+transmission of the optics and filter) is 0.17 and the detector efficiency is 0.5. The count rate is around ~100 Mcounts/s and exceeds this value only for an A-though-O type star with magnitude V < 0.5. Changing the telescope optical transfer function between 0.14 and 0.2 and the detector efficiency between 0.45 and 0.55 causes a variation of the maximum rate between ~75 and ~130 Mcounts/s for the limiting case of a V=0.5 mag O-type star.

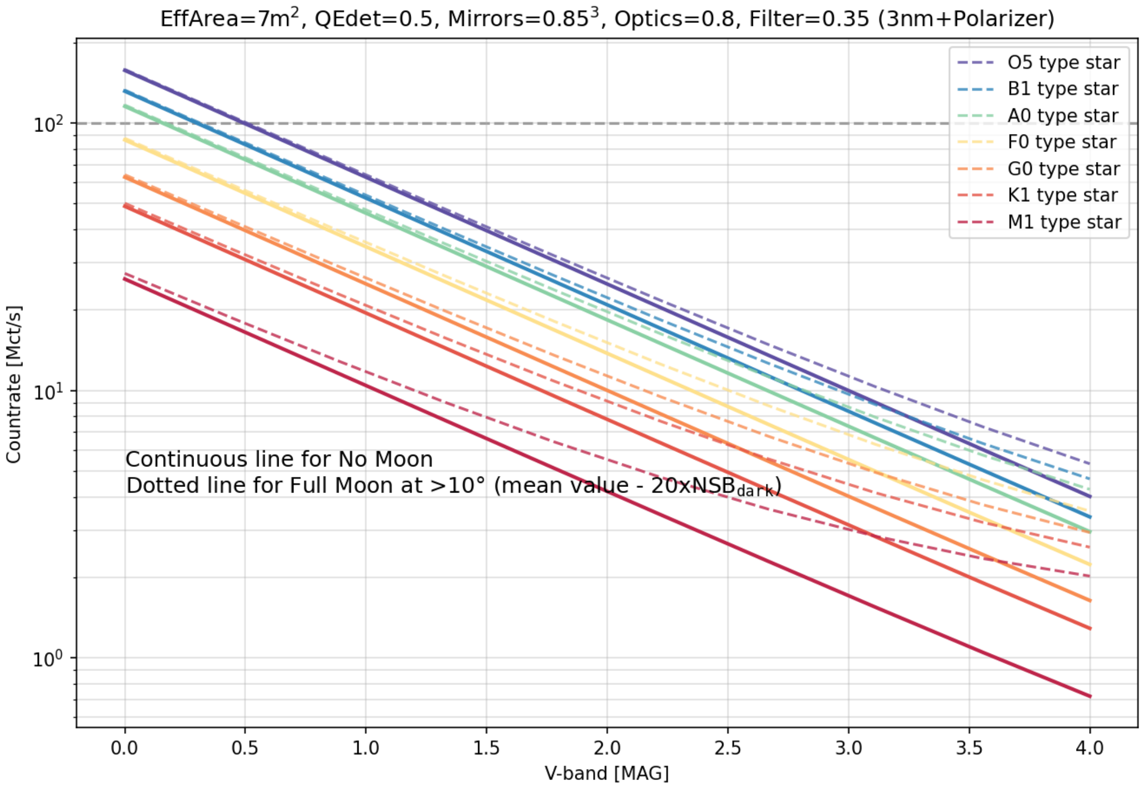


Figure 2 - Expected ASTRI telescopes photon rate in a narrow band (3 nm + polarizer) filter centered at 440 nm as a function of V band magnitude for stars of different spectral types, including sky and Moon background.

The quality of a SII measurement is dictated by the signal-to-noise (S/N) ratio of the degree of coherence, the main SII observable, that depends linearly on the photon rate. Figure 3 shows the S/N for a measurement at zero delay with two ASTRI telescopes as a function of stellar magnitude. Stars with magnitude V<3 are observable with the ASTRI Mini-array telescopes with a S/N>5, for an exposure time of <8 hours.

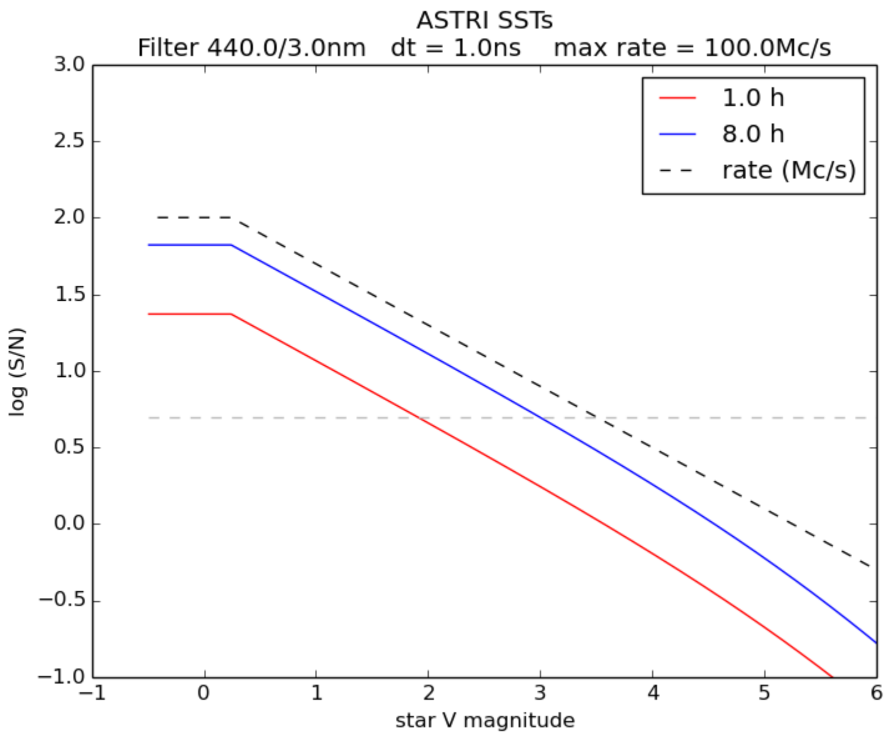


Figure 3 - S/N ratio for a SII measurement at zero delay with two ASTRI Mini-Array telescopes as a function of stellar magnitude. The source photon flux is limited in order to give a maximum rate of 100 Mcounts/s. The simulation is done using a narrow-band filter centered at 440 nm and with a FWHM of 3 nm (+ a polarizer). The bin time is 1 ns and the observing time is 1 hr (red line) and 8 hrs (blue line). The gray dashed line corresponds to S/N=5. The instrumental noise is taken into account.

3.1 Functional Workflow of ASTRI SI^3

The ASTRI SI3 will perform SII observations of bright (V<3) stars in the nights around Full Moon. In order to achieve the best performance, it will be positioned on the telescope optical axis in front of the Cherenkov camera through a dedicated arm. A schematic view of the instrument is shown later (Section 5).

The functional workflow of the instrument is shown in Figure 4 [RD4].

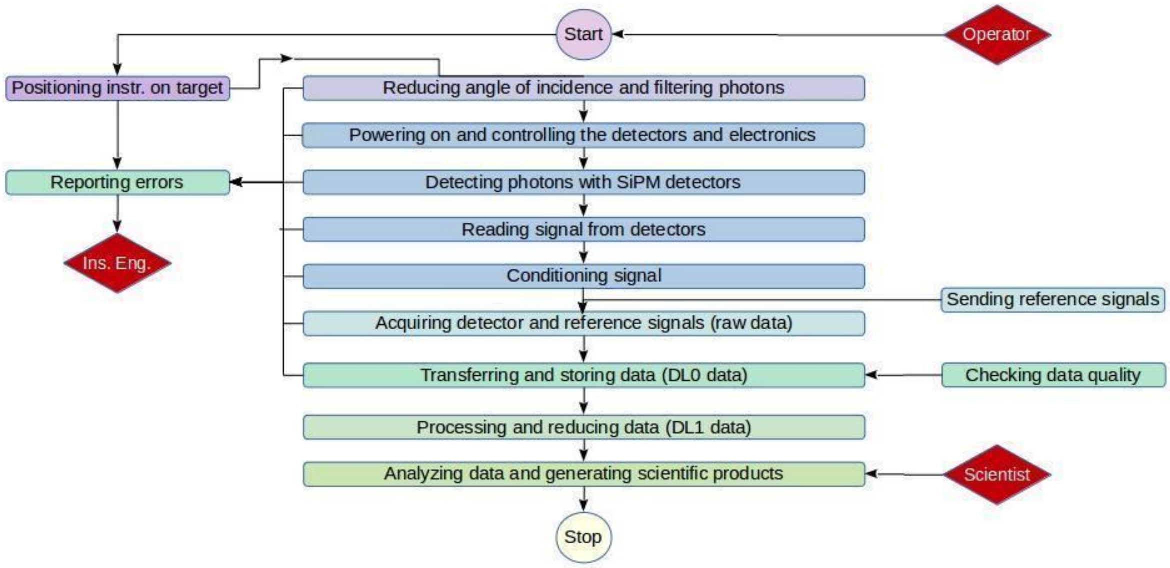


Figure 4: ASTRI SI^3 functional workflow [RD4].

To carry out a SII observation, SI^3 will perform the following operations:

- Positioning instrument on axis
- Reducing angle of incidence and filtering photons
- Powering on and controlling the detectors and electronics
- Detecting photons
- Reading signal from detectors
- Conditioning signal
- Acquiring detectors and time reference signals
- Transferring and storing science and housekeeping data to SCADA and off-site
- Processing and analyzing data and generating scientific products

A detailed description of each function of the system listed above is reported in the SI^3 system requirements document ASTRI-INAF-SPE-7400-002 [RD4].

Each function is associated to a specific instrument sub-system, as follows (see the block diagram in Figure 5):

- Positioning instrument on axis → Positioning arm
- Reducing angle of incidence and filtering photons → Focal plane Optics (FPO)
- Powering on and controlling the detectors and FEE → Voltage Distribution Board (VDB) and Control and Communication Unit (CCU)
- Detecting photons → Focal plane Detectors
- Reading signal from detectors → Preamplification Front End Electronics (PRE-FEE)

- Conditioning signal → Front End Electronics (FEE)
- Acquiring detector and time reference signals → Back End Electronics (BEE)
- Transferring and storing science and housekeeping data to SCADA and off-site → Local Acquisition and Control System
- Processing and analyzing data and generating scientific products → Science data processing system

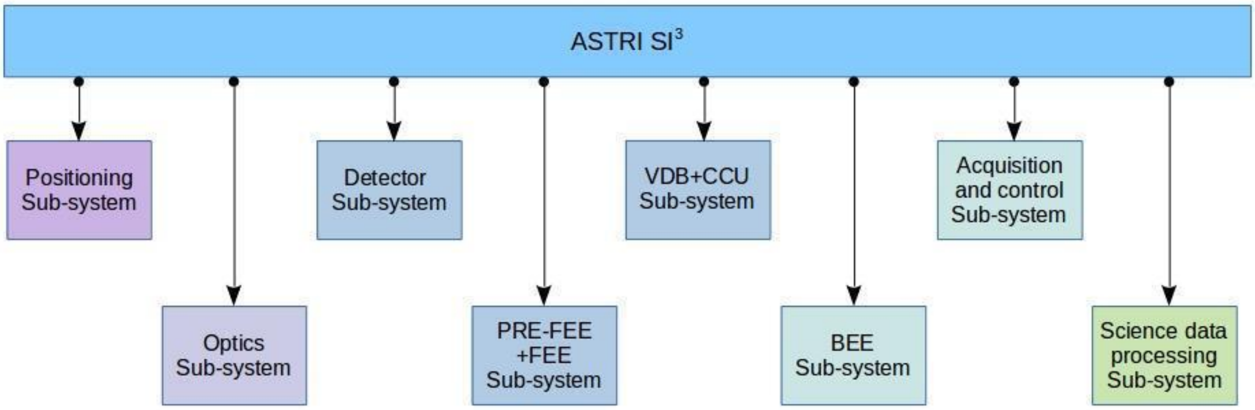


Figure 5 - ASTRI SI^3 block diagram

The block diagram of Figure 5 is exploded in the following Figure to show the entire product breakdown structure (PBS) of the instrument.

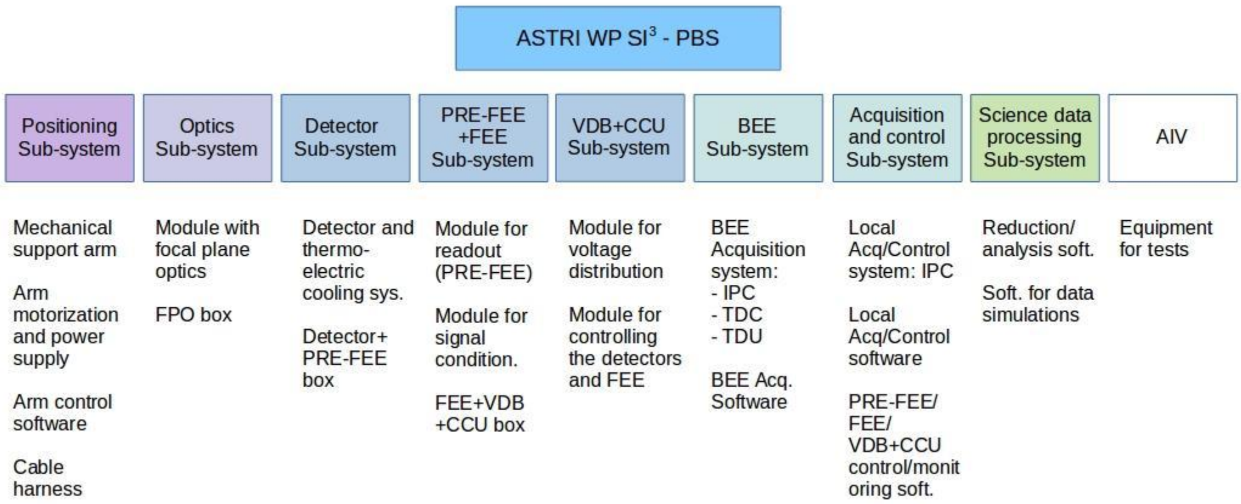


Figure 6 - ASTRI SI^3 product breakdown structure

Apart from the Positioning sub-system, a prototype version of all the other components of the instrument will be produced and tested by INAF personnel at the Catania and Asiago laboratories and at the ASTRI-Horn telescope in Serra La Nave (Catania, Italy). A prototype version of the positioning sub-system and the production of the final version of the 9 instruments will be outsourced.

The boundaries of the hardware/software systems of SI^3, and the flow of information between SI^3 and the external environment of the ASTRI Mini-array are shown in Figure 7, while the logical view and internal/external connections of the subsystems of SI^3 are shown in Figure 8.

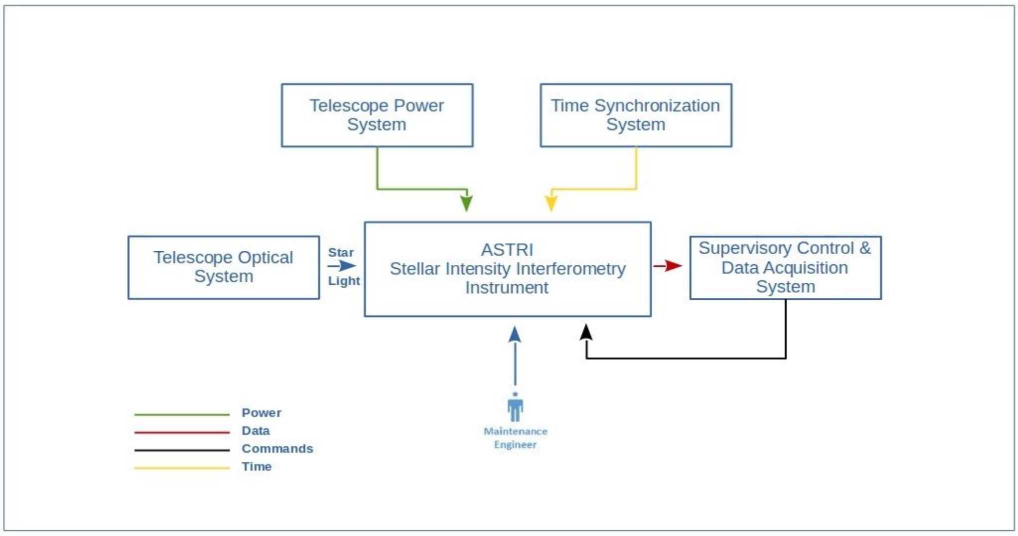


Figure 7 - ASTRI SI^3 context diagram.

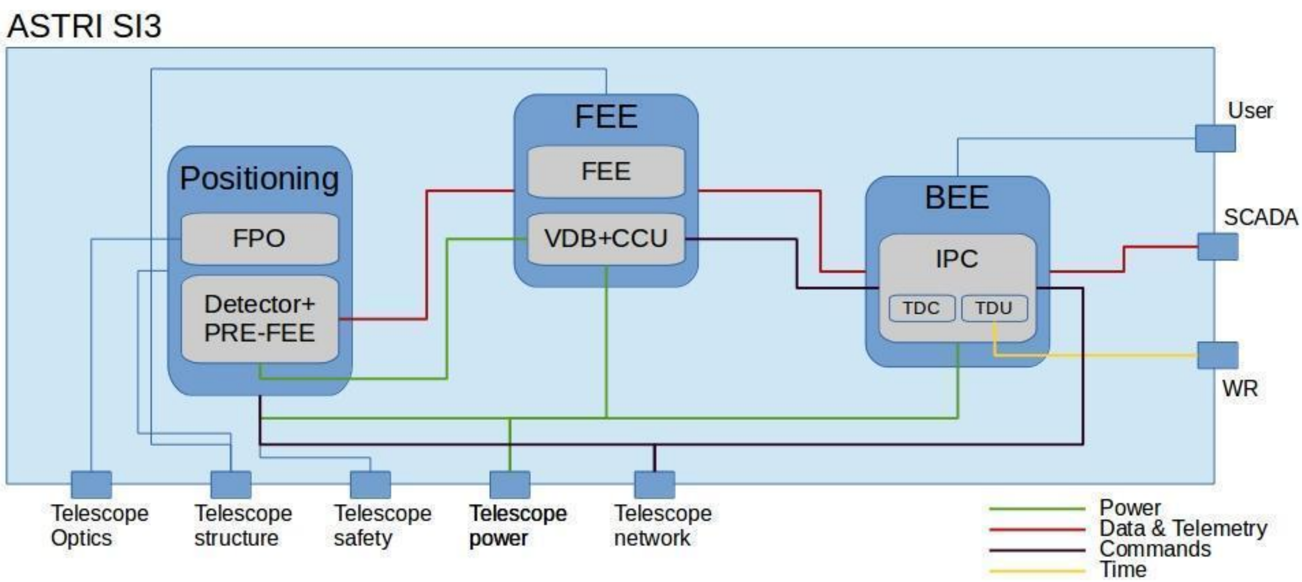


Figure 8 - ASTRI SI^3 logical view and internal/external connections.

4 Requirements

Starting from the functional workflow and system block diagram and PBS introduced in the previous Section, here we describe the requirements flow down of SI^3, listing the main functional requirements and the top level design requirements of each block that appears in the system decomposition (Figure 5). These requirements are listed (with their conventional ASTRI code) also in the companion SI^3 Requirements Specifications document ASTRI-INAF-SPE-7400-002 [RD1]. Some of these requirements depend on the adopted baseline design of SI^3 reported in Section 5. We list in this Section also the main requirements for the system interfaces. For the external connections and interfaces of SI^3 we refer to Figure 8.
In the following, **FPR** stands for Functional or Performance Requirement, **DR** for Design Requirement, and **IR** for Interface Requirement.

- Positioning Arm

  <u>Funtion: Positioning instrument on axis</u>

  DR 3000 - Positioning

  The SI^3 shall have a positioning arm that deploys (removes) the FPM on (from) the focal plane between the Cherenkov Camera and the secondary mirror of the ASTRI telescope.

  FPR 2300 - Positioning accuracy

  The position of all components of the FPM of SI^3 shall be known with an accuracy smaller than the tolerances listed in Table 5.

  FPR 2310 - Repositioning accuracy

  The FPM of SI^3 shall reposition in the nominal observing position with an accuracy of +/- 1 mm and +/- 0.07 degrees in tilt.

  IR 5002 - Arm safety

  The positioning arm shall communicate with the telescope safety system.

  IR 5005 - Arm network interface

  The positioning arm shall communicate with the telescope network.

  IR 5010 - Arm mechanical interface

  The telescope shall have an anchoring system for holding the positioning arm.

  IR 5020 - Arm electrical interface

  The positioning arm requires a 24 V power supply.

- Focal Plane Optics

  Function: Reducing angle of incidence and filtering photons (relay optics system)

  DR 3015 - Minimum Field of view

  The SI^3 shall deliver a minimum sensed Field of View (FoV) 1.2 times larger than the optical PSF (90% containment radius) to cope with the telescope tracking errors.

  DR 3020 - Maximum Field of view

  The SI^3 shall deliver a maximum sensed FoV between 1.4 times larger (in area) than the instrument PSF (90% containment radius) to minimize sky background contamination and maximize the signal-to-noise ratio.

  DR 3030 - Focal plane optics

  The optics sub-assembly shall have a portion of the optical path partially collimated, where to insert a narrow band (3-8 nm) filter.

  DR 3035 - Filter collection

  The optics sub-assembly shall have a collection of filters to perform multi-narrow-band observations of the continuum and/or of specific spectral lines.

  DR 3040 - Angle of incidence

  A fraction larger than 70% of the optical rays shall have an angle of incidence on the narrow band filter smaller than 15 degrees.

  IR 5000 - FPO optical interface

  The FPO shall receive light from the telescope optical system.

- Focal Plane Detectors

  Function: Detecting photons

  DR 3010 - Photosensitive focal plane

  The SI^3 must be fully instrumented with 4 photosensitive (photon counter) pixels of 3x3 mm^2, arranged in a 2x2 array layout (contiguous pixels) positioned on the instrument focal plane.

  DR 3012 - Detector operating temperature

  The detector shall be thermalized and maintained at a temperature of -20 +/- 1 °C.

  FPR 2010 - Average detection efficiency

The average efficiency of the SI^3, weighted with a reference spectrum of an O-through-G star in a narrow optical band (3-8 nm) and centered around a wavelength in the range 420-500 nm, shall be larger than 8.5%. This value includes the detector Photon Detection Efficiency (PDE) and dead space, the efficiency of the telescope and focal plane optics, and the transmission efficiency of the narrow band filter.

FPR 2020 - Dark count rate

The detectors shall have a dark count rate per pixel not exceeding 500 kcounts/s at 25°C or no more than 80 kcounts/s at -20°C (assuming an over voltage of 3V).

- PRE-FEE + FEE

  <u>Function: Reading signal from detectors and conditioning signal</u>

  FPR 2100 - Event rate

  The SI^3 shall collect and deliver events arriving at an average rate up to 100 Mevents/s (total on the 4 pixels) with a random distribution in time.

  FPR 2120 - Double hit resolution per pixel

  Two events occurring in the same pixel of the detector shall be resolved if separated by more than 6 ns.

  FPR 2140 - Double hit resolution per detector

  Two events occurring in different pixels of the detector shall be resolved if separated by more than 1 ns.

  FPR 2160 - Linearity

  Departure from linearity of the detectors and FEE shall be less than 15% for photon rates up to 25 MHz per pixel (100 MHz on the 4 pixels).

  IR 5015 - FEE mechanical interface

  The telescope shall have an anchoring system for holding the FEE box.

- VDB + CCU

  <u>Function: Powering on and controlling the detectors and FEE</u>

  DR 3080 - Input voltage

  The input voltage of the VDB+CCU shall be 24 V.

  DR 3090 - Housekeeping data acquisition

The CCU shall acquire the housekeeping data (voltage, current levels, temperatures) of the VDB, and shall control the detectors by acquiring the detector operating temperature and by setting the voltage to compensate for temperature variations.

DR 3095 - VDB voltage distribution

The VDB shall provide the power supply to the detectors, the PRE-FEE and the FEE, distributing all the needed voltage rails.

IR 5025 - VDB electrical interface

The VDB + CCU requires a 24 V power supply.

IR 5055 - CCU Internal Command interface

The CCU shall communicate via an ethernet link.

- BEE

  Function: Acquiring detector and time reference signals

  DR 3100 - Time synchronization system

  The SI^3 shall have a time synchronization system based on the White Rabbit technology.

  FPR 2070 - Detecting and tagging events

  The BEE shall be able to detect each photon-event from the FEE and associate to it a timestamp with a relative (among telescopes) time accuracy of less than 0.5 ns over the whole duration of an observing run.

  FPR 2220 - Data rate

  The SI^3 shall collect and deliver events to the SCADA at a maximum data rate of 500 MB/s.

  IR 5027 - BEE electrical interface

  The BEE requires a 24 V power supply.

  IR 5030 - Time Synchronization System interface

  The BEE shall have a timing link to a White Rabbit switch via a Single Fiber Bi-directional SFP transceiver.

- Local Acquisition and Control System

  Function: Transferring and storing science and housekeeping data to SCADA and off-site

  DR 3110 - Scientific data

The SI^3 shall deliver the scientific data to ADAS via File Transfer Protocol (in telemetry format).

DR 3120 - Controlling and monitoring the instrument

The SI^3 shall have a Local Control and Monitoring software running on the CCU and an Industrial Computer (IPC). The SI^3 Local Control and Monitoring software shall use an OPC-UA protocol to communicate with the Telescope Control System and the Monitoring system. The software shall deliver to the Telescope Control System and the Monitoring system all monitoring data and error conditions, and shall receive from them the instrument status.

FPR 2400 - Remote control

The SI^3 shall be controllable in remote mode via an OPC-UA server interface.

FPR 2410 - Local control

The SI^3 shall implement a local control mode for maintenance and diagnostic purposes, during which remote operation of safety-relevant sub-systems is blocked. SCADA shall be informed when SI^3 enters Local Mode.

FPR 2420 - State Machine

The SI^3 system shall implement a state machine. The state machine will be accessible via the OPC-UA server.

IR 5040 - Data interface

For the scientific and housekeeping data the SI^3 shall have a dedicated link to the Camera Server of the ADAS system via a Fiber Bi-directional SFP+ transceiver.

IR 5050 - Command interface

For the instrument control the SI^3 shall have a link via an ethernet cable.

- Science data processing system

  Function: Processing and analyzing data and generating scientific products

FPR 2600 - Data processing

The SI^3 data processing system performs all the operations for reducing and analyzing the raw data, producing the data products, and simulating the performance of the instrument. It shall be capable of processing a maximum volume of 110 TB of data per month in single packets of 150 GB.

FPR 2620 - Final science-processed data output

The size of the final processed data for scientific analysis shall not exceed 18 TB/month.

5 Baseline design

The baseline design of SI^3 was selected after careful consideration of different options. The criteria adopted to guide the final choice are:

- minimizing the impact on the ASTRI telescopes, limiting the instrument size, weight, and number of interfaces;
- adopting all the network standards and the timing and communication protocols used by the ASTRI Mini-Array;
- realizing a compact and independent instrument, with no impact on the development, operations and maintenance of the Cherenkov camera;
- requiring no on-site intervention (apart from maintenance operations);
- minimizing the development of new components and, if capable of the required performance, use what is available on the market;
- focusing on truly application-specific aspects of the instrumentation, that have a crucial impact on the performance;
- adopting a fully photon counting, post-processing approach for the calculation of the correlation.

The design comprises three separate modules:

- the first containing the focal plane optics, the detectors and the read-out electronics, all mounted on a moveable arm that places them and removes them from axis;
- the second containing the front end electronics that performs signal conditioning;
- the third containing the back end electronics that tags the detected photons with the required timing accuracy. A schematic view of SI^3 is shown in Figure 9.

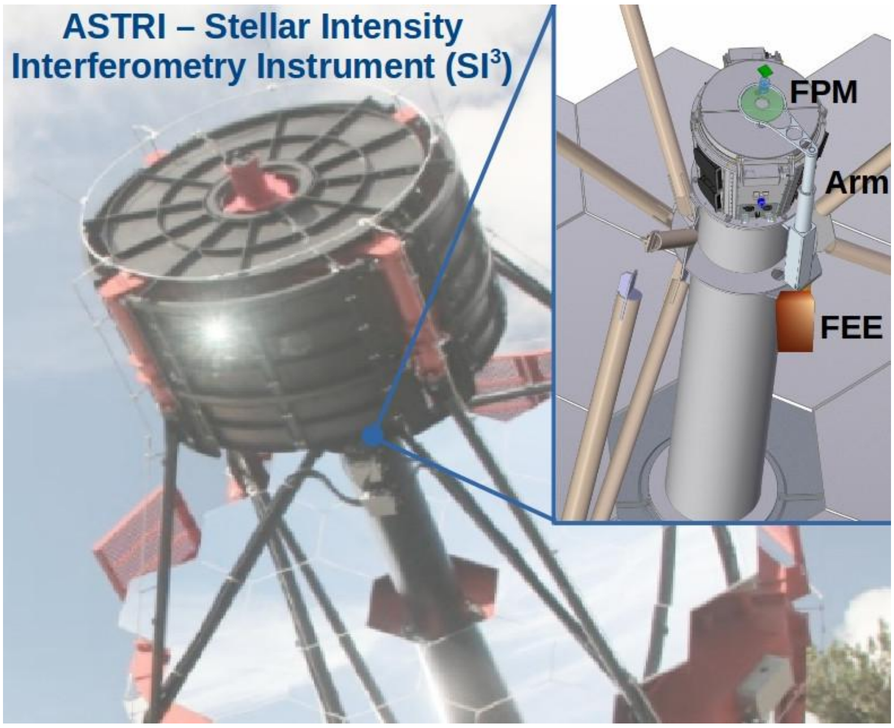


Figure 9 - ASTRI SI^3 schematic view.

In the following we provide a short description of the structure and properties of each component of the system appearing in the block diagram in Figure 5.

5.1 Positioning arm

The positioning-arm sub-system is composed of the following main subassemblies:

1. Mechanical support arm
2. Motorization
3. Control System
4. Cable harness

When in the observing mode position, the positioning arm deploys some subassemblies of the ASTRI SI^3 instrument on the focal plane between the Cherenkov Camera and the secondary mirror M2 of the ASTRI telescope. These subassemblies are the Focal Plane Optics (FPO) and the detector+PRE-Front End Electronics (PRE-FEE), which we collectively refer to as the Focal Plane Module (FPM). Both the FPO and detector+PRE-FEE are enclosed in dedicated boxes and mounted on the positioning arm.

The FPO subassembly contains all the FPO elements of the ASTRI SI^3 instrument shown in Figure 10. They are described in detail in Section 5.2 and consist of a spherical mirror (M3), three lenses (L1-L3) and an interferometric filter (IF). The weight of M3 + L1/L3 + IF is 0.56 kg (plus 20% contingency). The FPO contains also a filter wheel, for inserting filters centred at different wavelengths.

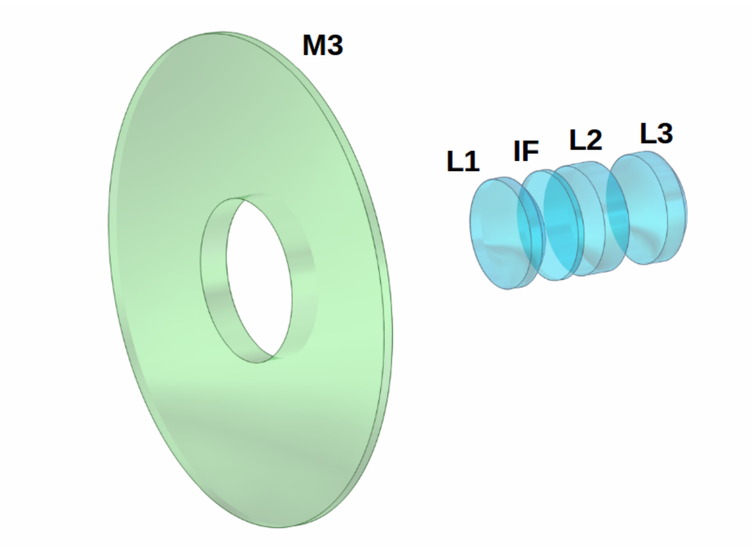


Figure 10 - ASTRI SI^3 FPO elements enclosed in the FPO box.

The detector and PRE-FEE subassemblies incorporate the detector and the PRE-FEE board, the accessories needed for their correct functioning, as well as the harness for the power supply and the data link. They are described in detail in Sections 5.3 and 5.4. This equipment shall be placed at the focus of the FPO (after lens L3), as shown in Figure 11. The detector shall receive light only through a window equipped with a light proof shutter, in order to permit the calibration of the detector itself. The detector shall be pre-aligned with the FPO in the laboratory.

To reduce the dark count rate, the detector needs to be thermalized in a narrow range of temperatures (see Section 5.3). For this reason it is enclosed in a metal case cooled by a small Peltier cell. The electric enclosure of the detector and PRE-FEE shall be designed with features able to dissipate the heat transferred by the Peltier module in air, and shall be water-proof.

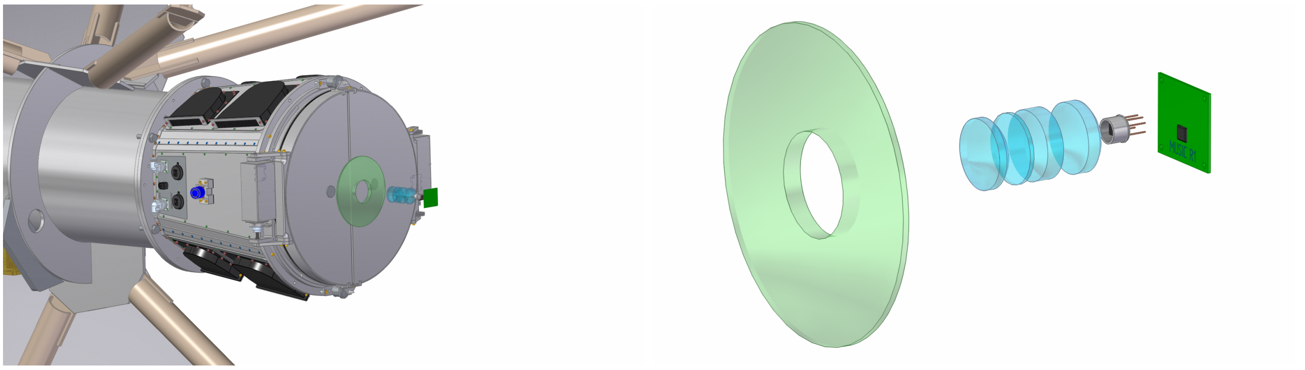


Figure 11 - Left panel: ASTRI SI^3 Focal Plane Module positioned between the Cherenkov camera and the secondary mirror M2 (observing mode position). Right panel: zoom-in of the ASTRI SI^3 FPM elements.

- **Mechanical support arm**

The mechanical support arm has the main scope of holding the FPM (FPO + PRE-FEE box subassemblies) on axis (Figure 11), driving also the harness to the PRE-FEE box. Its design shall be optimized in order to produce no shadow on M3 (apart from the supports holding the mirror). The rigid arm shall be protected against corrosion by means of a suitable treatment (painting, anodizing, zinc-coating).

- **Motorization**

The observations with the SI^3 instrument will be performed only when the Cherenkov observations are not. A simultaneous use of the SI^3 and the Cherenkov camera is not envisaged. Therefore, the FPM has to be mounted on a moveable and motorized arm, able to:

- ❏ In environmental conditions “observation” bring and maintain the FPM in the observing position in no more than 60 s and with the tolerances described in the following Section;

- In environmental conditions "transition" move the FPM from the observing position to the parking position in no more than 60 s;
- In environmental conditions "survival" keep the FPM in safety.

The movable arm and its mounting accessories, shall be compliant with all the static and dynamic safety requirements applicable for the telescope itself. The metal components of the moveable arm shall be protected against corrosion with coating, anodizing or zinc coating; metal components on the path of earthing, shall be protected with electrically conductive coatings. The input voltage of the motorized arm shall be 24V.

Parking position of the mechanical support arm and motorization

While the observing position is fixed and shown in Figure 11, the parking position of the FPM depends on the design choices. The main requirements for the parking position are the following:

- when in parking position the FPM shall not obstruct or limit in any way the telescope's movements along the azimuth or elevation axes;
- when in parking position the FPM shall produce no shadow on both the primary and the secondary mirrors of the telescope;
- when in parking position the FPM shall not obstacle the moving parts of the Cherenkov camera (lids, doors etc..);
- when in parking position the FPM shall be easily reachable for maintenance;
- when in parking position the FPM shall not interfere with the maintenance operations of the Cherenkov Camera.

The following Figures 12, 13 and 14 show 3 different concept designs of the moveable arm. We consider solution 3 (Figure 14), with the pushing-rotating system, as the best compromise between feasibility and fulfilment of the main mechanical and optical requirements outlined in this and the following Section.

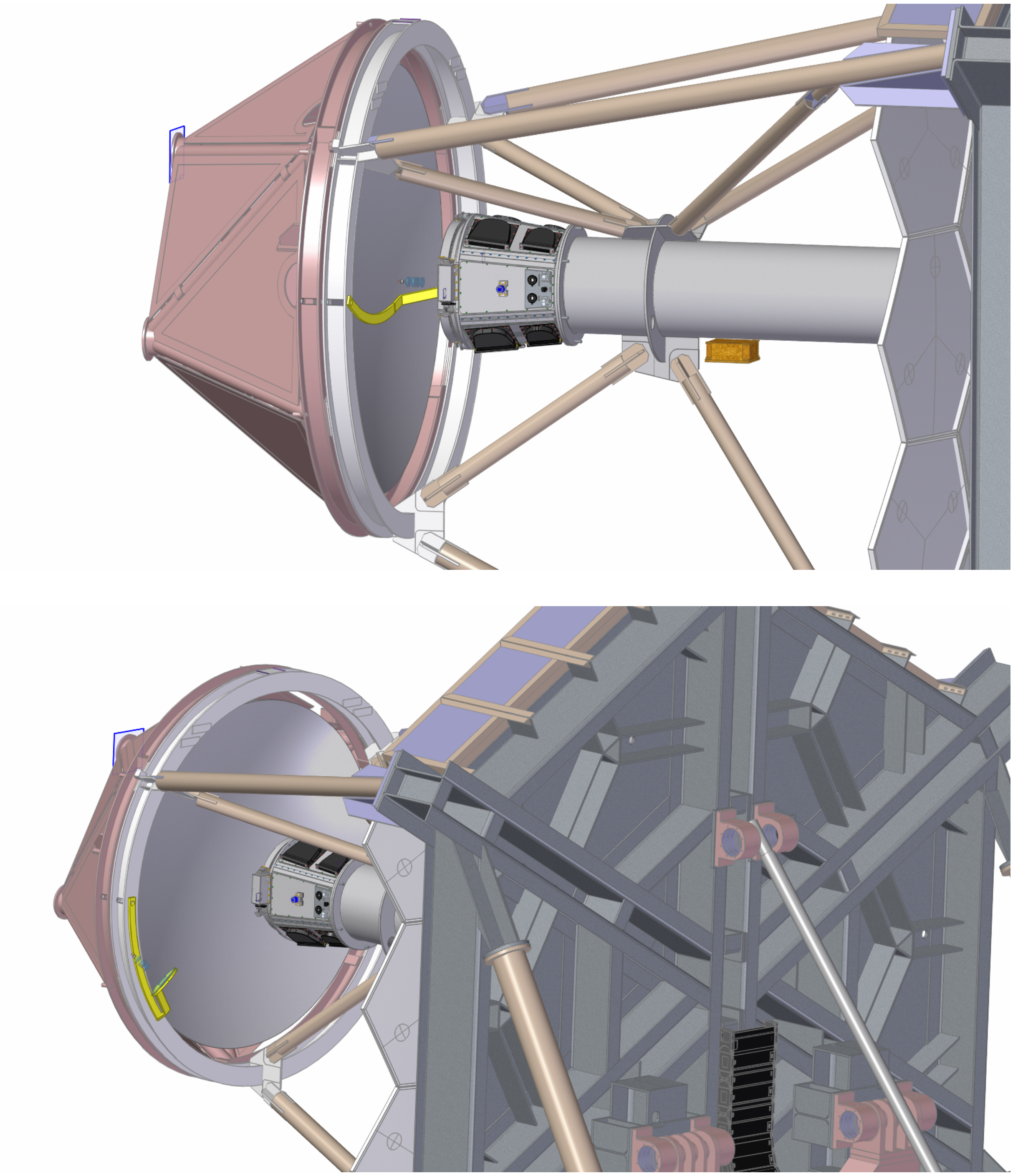
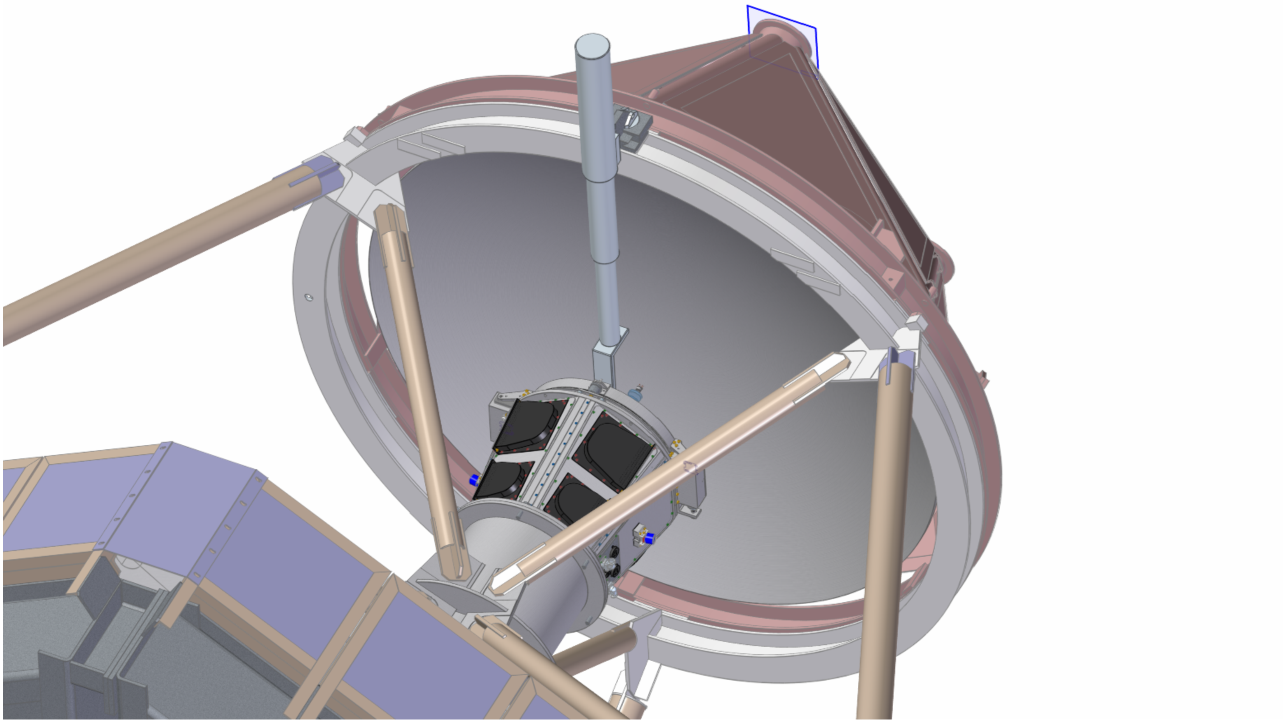


Figure 12 - **Solution 1** for the moveable arm of ASTRI SI3 (shown in yellow). Top panel: observing position. Bottom panel: parking position. The FEE box (orange) is on the telescope MAST.



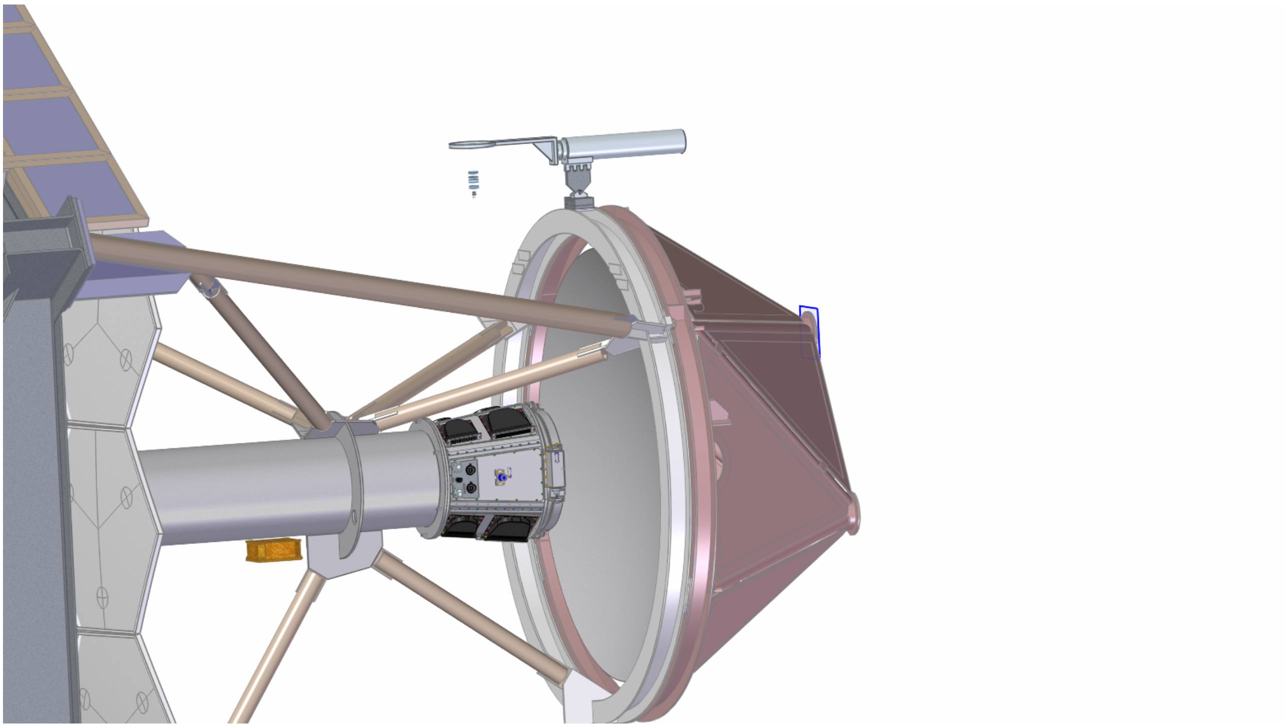


Figure 13 - **Solution 2** for the moveable arm of ASTRI SI^3 (shown in gray). Top panel: observing position. Bottom panel: parking position. The FEE box (orange) is on the telescope MAST.

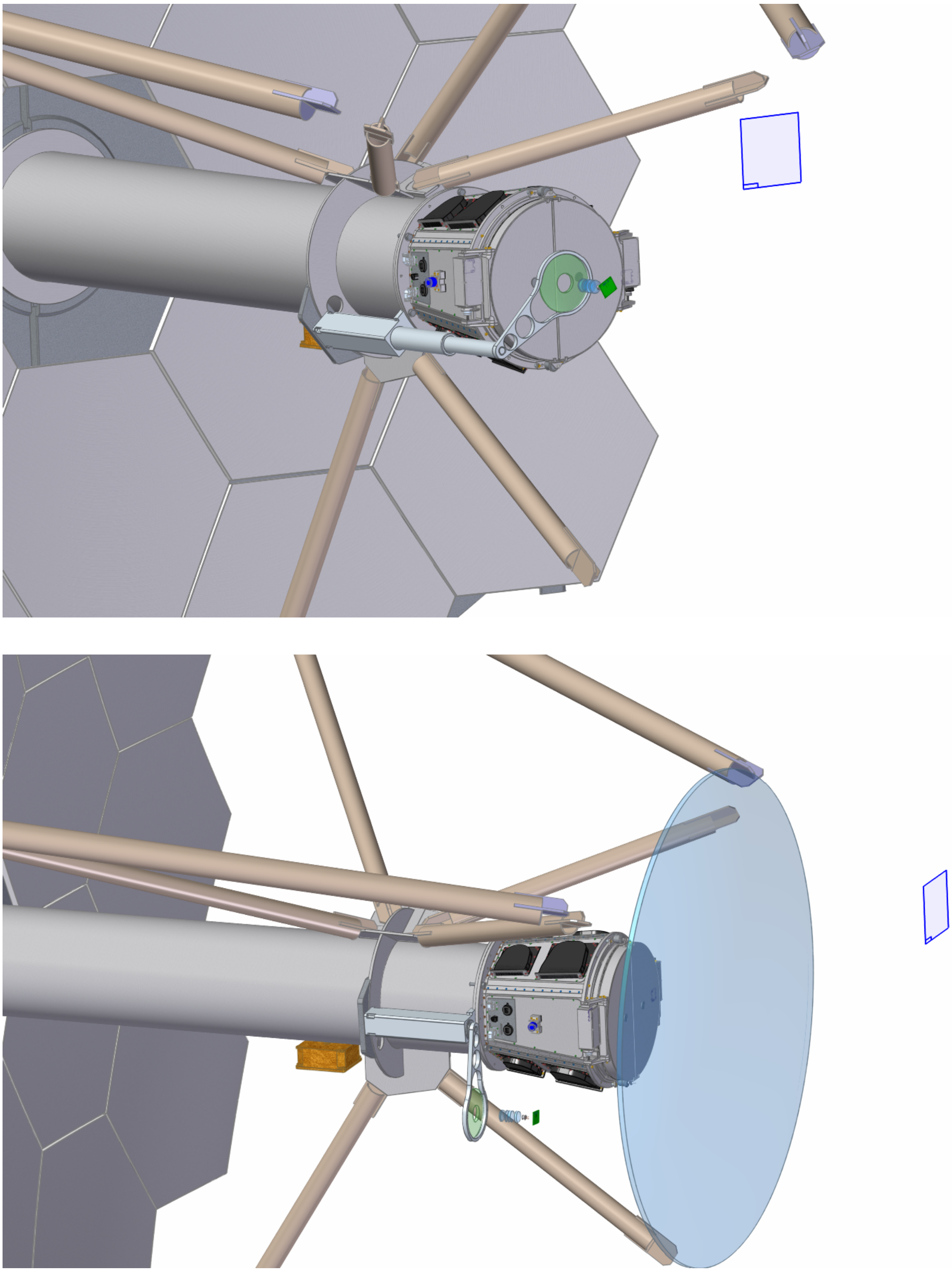


Figure 14 - **Solution 3** for the moveable arm of ASTRI SI3 (shown in gray). Top panel: observing position. Bottom panel: parking position. The FEE box (orange) is on the telescope MAST.

The specifications of the electrical actuators for the arm motorization for the three proposed solutions are given in Table 1.

The actuators shall be usable with the nominal power supply provided by the telescope and shall incorporate motor, encoder, local control devices, and terminals for remote control and programming connections, all housed in a self-contained sealed enclosure.

To maintain the integrity of the enclosure, all settings operations on torque levels, position limits, configuration of signaling contacts, etc. shall be performed only using a communication interface compatible with that of the telescope.

Size	The physical dimensions of the actuators shall be such that not to shadow the optical beam.
Environmental	The actuators shall be suitable for indoor and outdoor use, with a high standard corrosivity category.
Enclosure	The actuators shall be sealed with O-rings, watertight. The motor and all other internal electrical elements of the actuator shall be protected from the passage of humidity and dust. Input/output connections shall be made with special connectors.
Motor gearing	Motor and gearbox shall be enclosed in a sealed box and shall be able to operate in any position angle. The box shall have an electrical ground point. There shall be no operating LED visible from the outside during an observing session.

Table 1 - Specifics of the electrical actuators for the arm motorization.

- **Control system**

The positioning arm of SI^3 is controlled by the Arm Control System. Its software (Arm Control Soft., a module of the Local Control Software of the instrument delivered through an OPC-UA server) runs on the industrial PC described in Section 5.8. The SI^3 shall be interlocked with the Cherenkov Camera, in order to prevent the potentially dangerous simultaneous operation of the two instruments.

- **Cable harness**

  The cables for signal connection between the PRE-FEE and FEE, the power cables, those for the cooling of the detector, as well as those for the control of the filter wheel shall allow for bending, without exceeding the cable specifications. The cables will be bound with a suitable cable harness.

5.2 Focal Plane Optics

The optical design of the SI^3 module is based on a prefocal system deployed in front of the telescope Cherenkov focal plane as shown in Figure 15. The system is completely detached and independent of the ASTRI Cherenkov camera and it is deployed (and withdrawn) through a dedicated mechanical arm during the intensity interferometry observations. The SI^3 optical module is a catadioptric system composed of:

- One spherical, convex mirror, M3, 180 mm diameter
- Three spherical lenses, L1, L2, L3, 40 mm diameter
- One or more interference filters, IF, 40 mm diameter (filter)

A 2x2 SiPM (3 mm each) focal plane array is placed at the SI^3 focus. All optical elements are contained inside a dedicated box (FPO box).

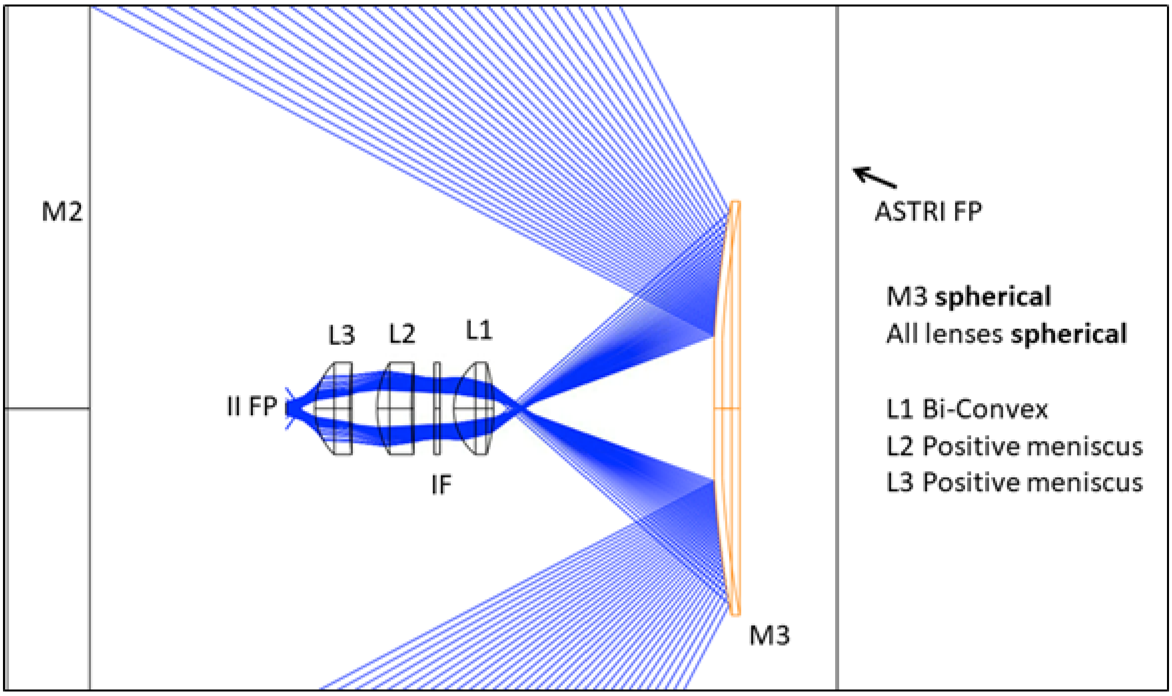


Figure 15 - Close-up view of the SI^3 catadioptric module deployed above the telescope Cherenkov focal plane (ASTRI FP). The beam is reflected off M3 and collimated and refocused by an objective lens group onto the intensity interferometry focal plane (II FP).

A summary of the main geometrical characteristics and inter-distance between the elements of the ASTRI telescope is given in Table 2.

Table 2 - Main geometrical parameters of the SI3 optical module

Geometrical parameter	**Size**	**Comment**
Separation M3 - ASTRI FP	42.5 mm	
Clearance from camera LID	20 mm	
Length of the system (separation M3 - II FP)	176 mm	

The M3 can have a central hole with a diameter of 60 mm (Figure 6 top) that can be used to mechanically hold the mirror. A zoomed view of the lenses group is shown in Figure 16 (bottom).

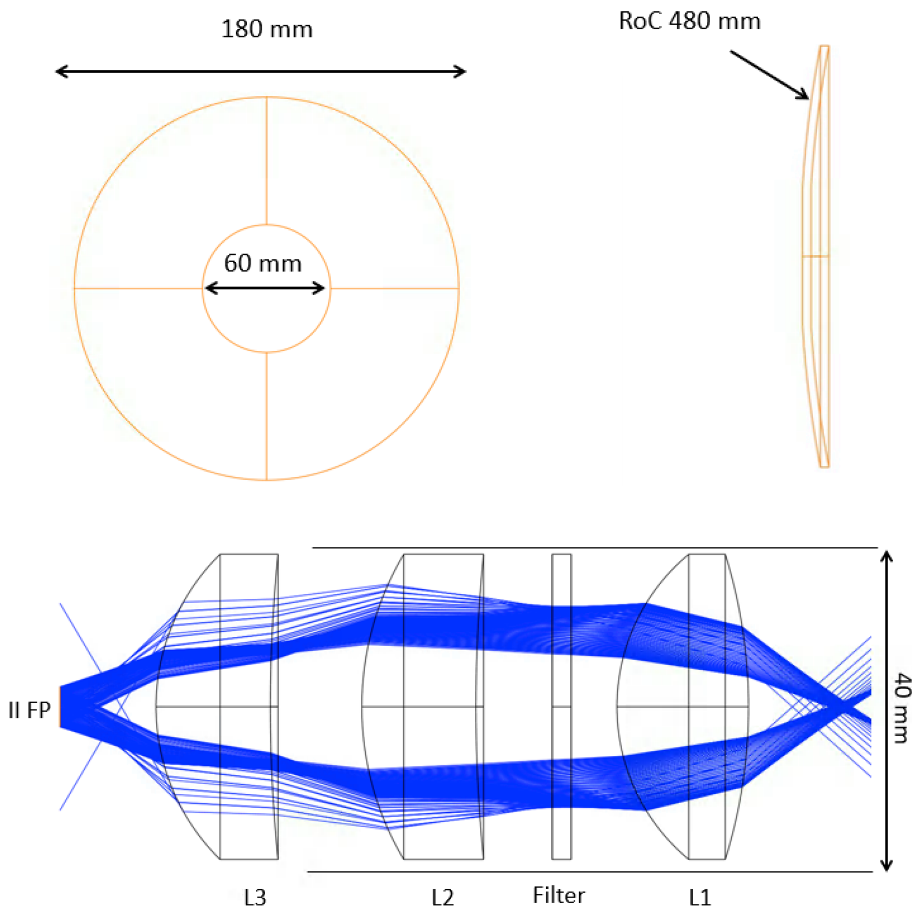


Figure 16 - Top: the reflecting element M3 has a central 60 mm diameter that does not work optically and it can be used to hold the mirror. Bottom: the transmitting elements are three lenses and one filter.

A narrow-band filter collection to perform multi-narrow-band observations of the continuum and/or of specific spectral lines will be held by a filter wheel. The SI^3 detector is placed at the II FP (Figure 15). An overall view of the SI^3 in the ASTRI 2M telescope is given in Figure 17.

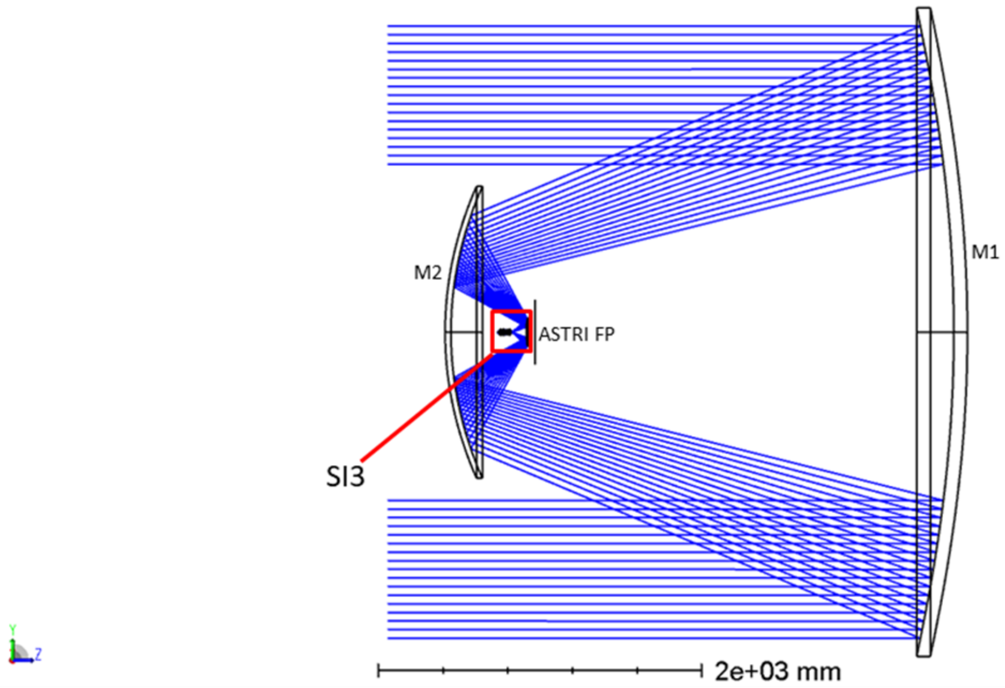


Figure 17 - Overall view of the ASTRI SI^3 module and ASTRI telescope in its prefocal position with respect to the ASTRI focal plane.

A summary of the optics main specification is given in Table 3 and the information about the SI^3 optical interface to the detector are collected in Table 4.

Table 3 - Main geometrical and optical characteristics of the SI^3 elements.

Element	**Diameter**	**Sag**	**Glass**	**Comment**
M3	180 mm	Spherical CX	TBD	Annular
L1	40 mm	Spherical CC,CC	N-LASF31A	
Filter	40 mm	Flat	SILICA	2 mm thickness
L2	40 mm	Spherical CX, CC	N-LASF31A	
L3	40 mm	Spherical CX, CC	N-LASF31A	

Table 4 - Optical interface characteristics of the SI3 system.

Effective focal length	-2680.398	mm
Plate scale	76.95	arcsec/mm
F/#	0.653	-
Back focal distance	9.97	mm

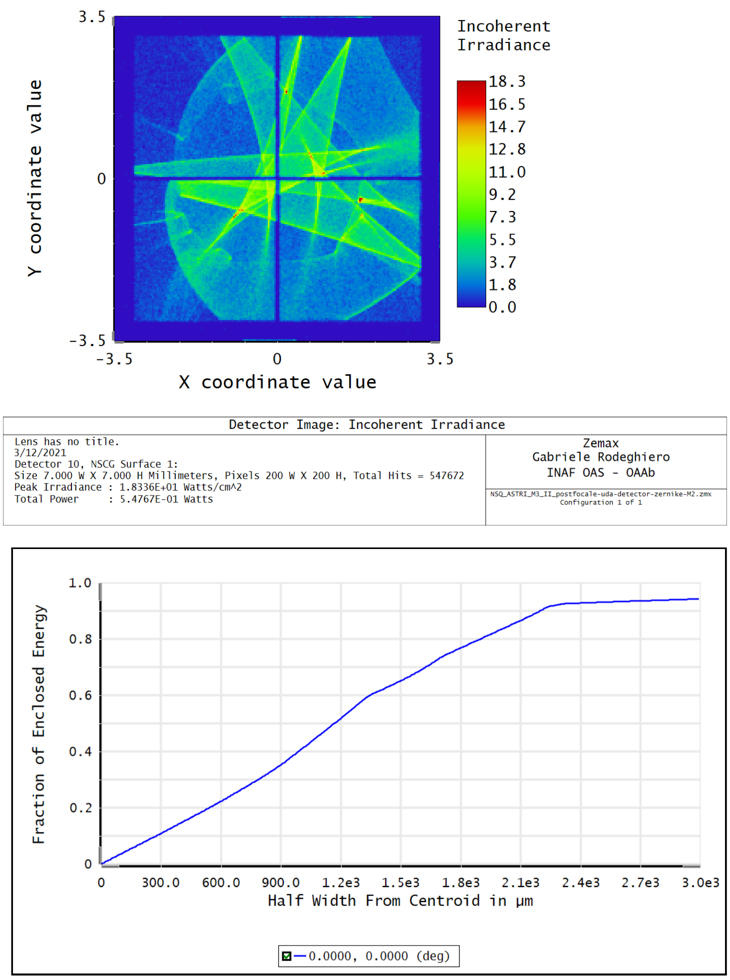


Figure 18 - Top: ray tracing of the SI^3 PSFprojected on top of the 2x2 SiPM focal plane array (including aberrations from the secondary mirror of the ASTRI telescope).
Bottom: esquared energy on a virtual pixel of 6 x 6 mm, the real focal plane is segmented in 2x2 3 mm SiPM detectors.

5.2.1 Optics Positioning and Stability Tolerances

The SI3 optical module requires a minimum set of positioning deployment & stability tolerances. The deployment tolerances apply to the deployment arm that brings the system from the parking off-axis position to the on-axis observing position. The stability tolerances apply to the whole opto-mechanical assembly, deployment arm and Astri telescope, once the SI^3 module is placed in the operation position. The reference frame into which the tolerances are given is shown in Figure 19.

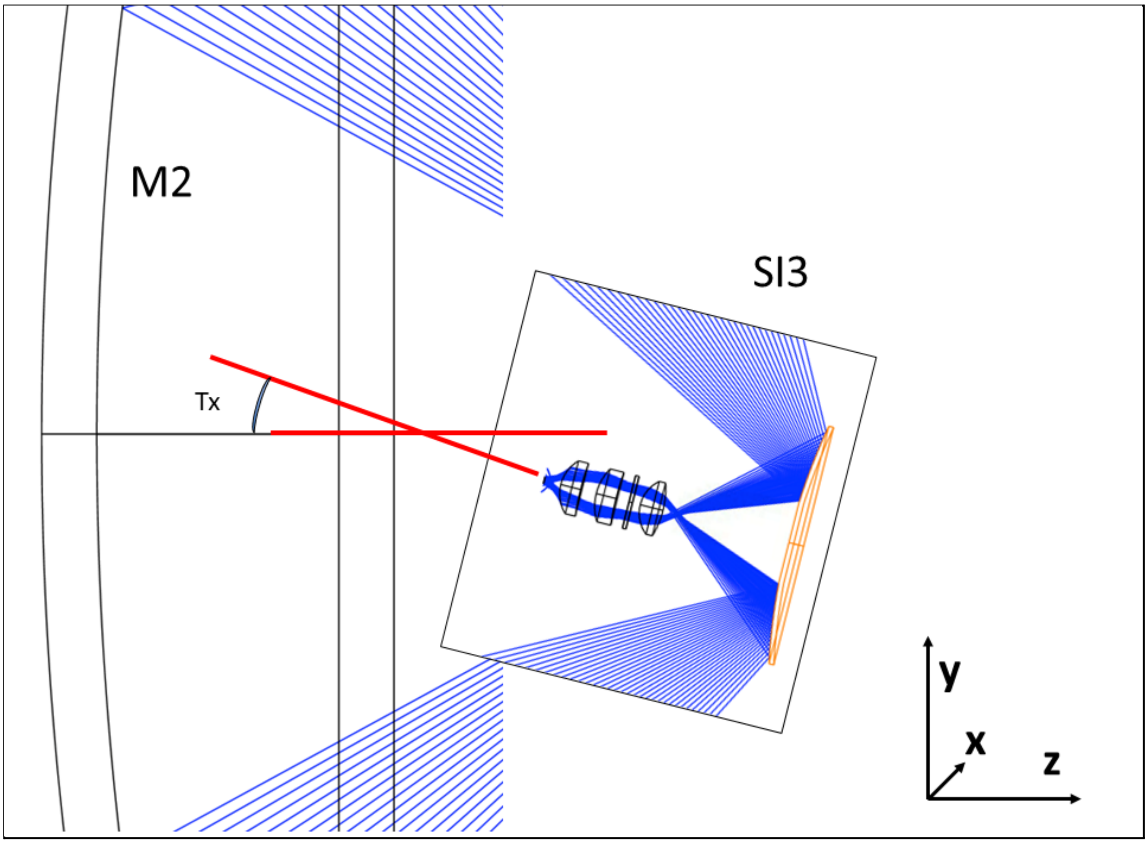


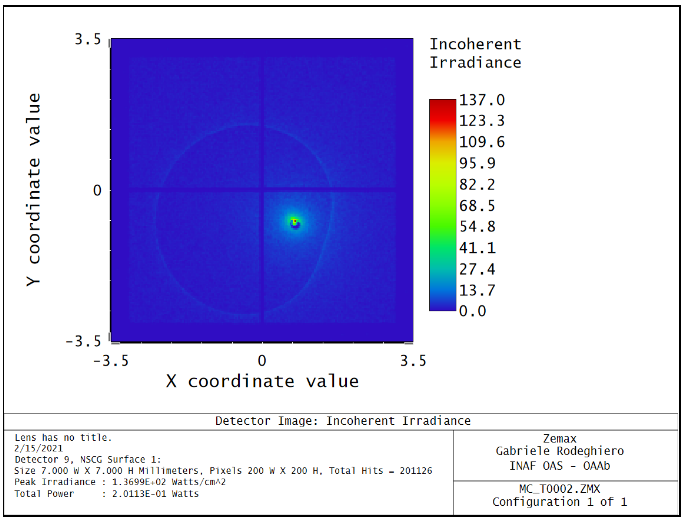
Figure 19 - Reference frame used for the calculation of the deployment and stability tolerances.

The worst offender of the opto-mechanical tolerances are the relative tilts (Tx,Ty) of the SI3 optical module, as rigid body, with respect to the optical axis of the telescope that we intend as traced by the opto-mechanical axis of the telescope M2. In Table 4 we report the summary of the tolerances for each optical element of the SI^3 system. The design of the deployment arm for the SI^3 shall consider the rigid body entry in Table 4. The system is insensitive to ΔTz tolerances. The worst offender parameters are the relative tilt between the optical axis of M2 and the optical axis of the SI^3 module.

Table 5 - Optical tolerances for the SI^3 module and its internal elements. In bold we highlight the required deployment and stability tolerances for the SI^3 (rigid body) optical module from the deployment arm. The system is insensitive to ∆Tz tolerances.The worst offender parameters are the relative tilt between the optical axis of M2 and the optical axis of the SI^3 module (red).

Element	**Deployment & stability tolerances**				
-	**∆x mm**	**∆y mm**	**∆z mm**	**∆Tx deg**	**∆Ty deg**
SI^3 module rigid body	**+/- 1**	**+/- 1**	**+/- 1**	**+/- 0.07**	**+/- 0.07**
M3	+/- 1	+/- 1	+/- 1	+/- 0.07	+/- 0.07
L1	+/- 0.2	+/- 0.2	+/- 0.2	+/- 0.05	+/- 0.05
Filter	+/- 0.2	+/- 0.2	+/- 0.2	+/- 0.05	+/- 0.05
L2	+/- 0.2	+/- 0.2	+/- 0.2	+/- 0.05	+/- 0.05
L3	+/- 0.2	+/- 0.2	+/- 0.2	+/- 0.05	+/- 0.05

The effect of a relative tilt between ASTRI-M2 and the SI2 module is highlighted in Figure 20 (right side) where the PSF of SI^3 is shifted towards the edge of the 2x2 SiPM focal plane array.



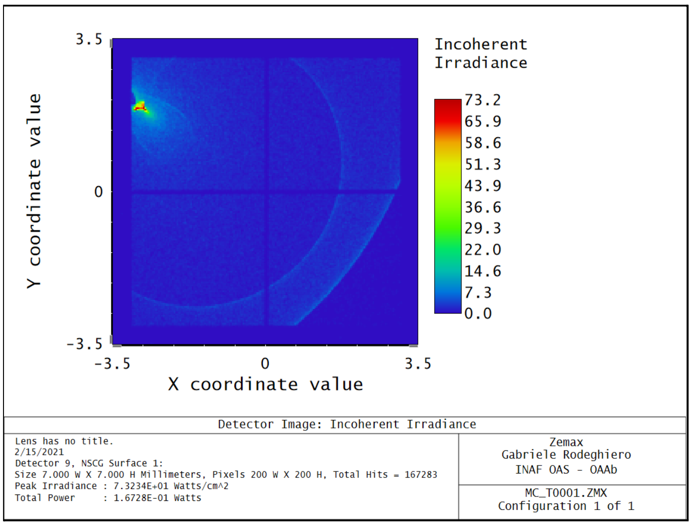
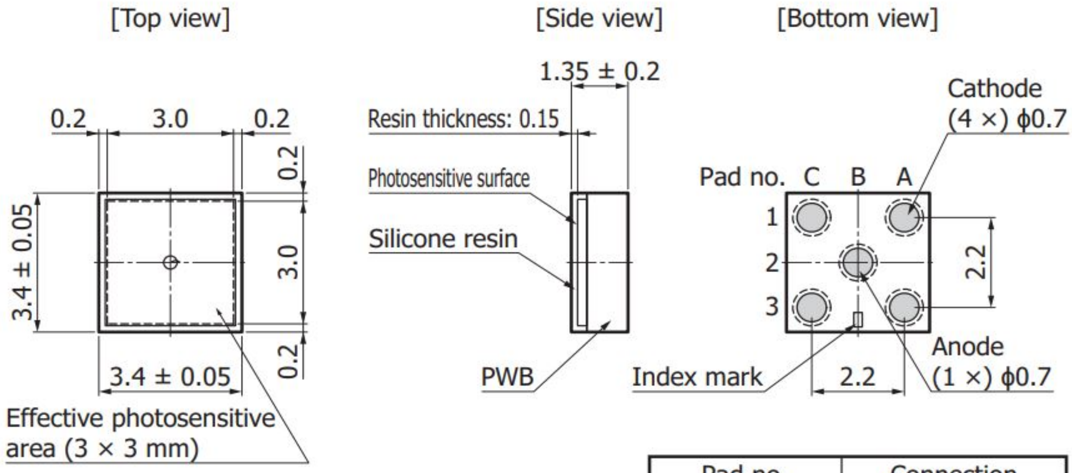


Figure 20 - Two Montecarlo realizations of the SI^3 system once the tolerances of Table 5 are applied to the system. When a large relative tilt between ASTRI-M2 and the SI^3 module takes place the PSF can marginally fall out the focal plane array (right).

5.3 Focal plane Detectors

The detector selected for the SI3 instrument is an array of 2x2 SiPM-type silicon photomultipliers from Hamamatsu Photonics (model S14520SPL, Peltier cooled). Each single SiPM has a size of 3x3 mm2 with a 50 µm microcell and with the dimensions shown in Figure 21.



Pad no.	Connection
A1, A3, C1, C3	Cathode common
B2	Anode

Figure 21 - A single pixel of the detector array of SI^3, made of SiPM-type silicon photomultipliers from Hamamatsu Photonics (model S14520SPL)

The focal plane detector array is composed of 2x2 pixels and will therefore have the dimensions of 6.8 x 6.8 mm2 (Figure 22).

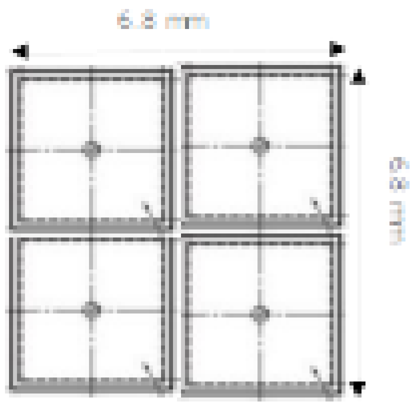


Figure 22 - The 2x2 detector array of SI3.

In order to have a very low DCR the SiPM detectors will be cooled through a Peltier Thermo Electric Cooler (TEC), that will allow the detector to operate at about -20°C. The package that will house the entire detection module (detector array + TEC) has the dimensions shown in Figure 23.

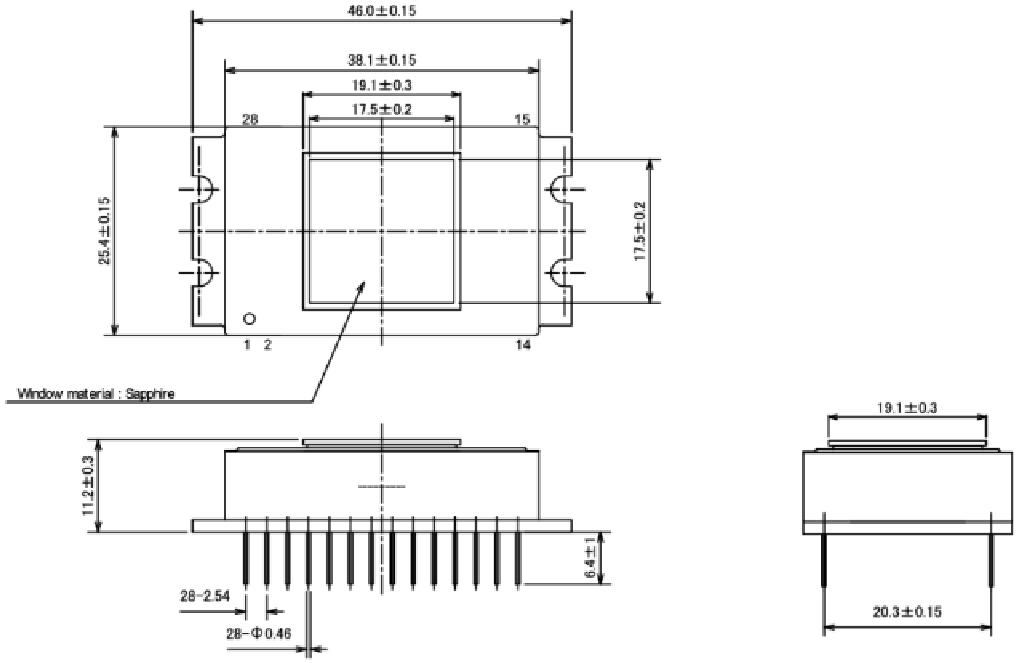


Figure 23 - Package housing the entire detection module (detector array + TEC). Note the dimensions of the detector array positioned in the central part of the package.

The detector and PRE-FEE (Sect. 5.4) are enclosed in a dedicated box and mounted on the positioning arm (detector+PRE-FEE box). The detector shall be pre-aligned with the FPO in the laboratory.

5.4 Front End Electronics (including PRE-FEE)

A key parameter of a front-end electronics is the time resolution between pulses that it can achieve. For this reason, in designing the FEE electronics of SI^3, particular attention was paid in selecting components characterized by high bandwidths so as not to limit the excellent time response offered by SiPM detectors. To optimize the time response and prevent a possible degradation of the timing performance, we selected an ASIC chip, called eMUSIC, that can offer 8 broadband input channels (150 MHz/channel). In each channel it is possible to introduce a derivative circuit via a programmable Pole Zero Cancellation (PZC), that allows us to minimize the dead time between two consecutive pulses.

In order to generate the digital signals needed by the Back End Electronics, we use external amplifiers and comparators. To this end, the output of the eMusic board is amplified by four broadband (6 GHz) Mini Circuit amplifiers and sent in input to two MAX 9601 high speed comparators (with ~300 ps response time). By selecting the appropriate threshold, the comparators generate PECL digital pulses which in turn are converted into TTL signals by four level translators (SN65ELT21).

A block diagram of the entire FEE, including the focal plane FEE (PRE-FEE) made essentially of the eMUSIC board, is shown in Figure 24.

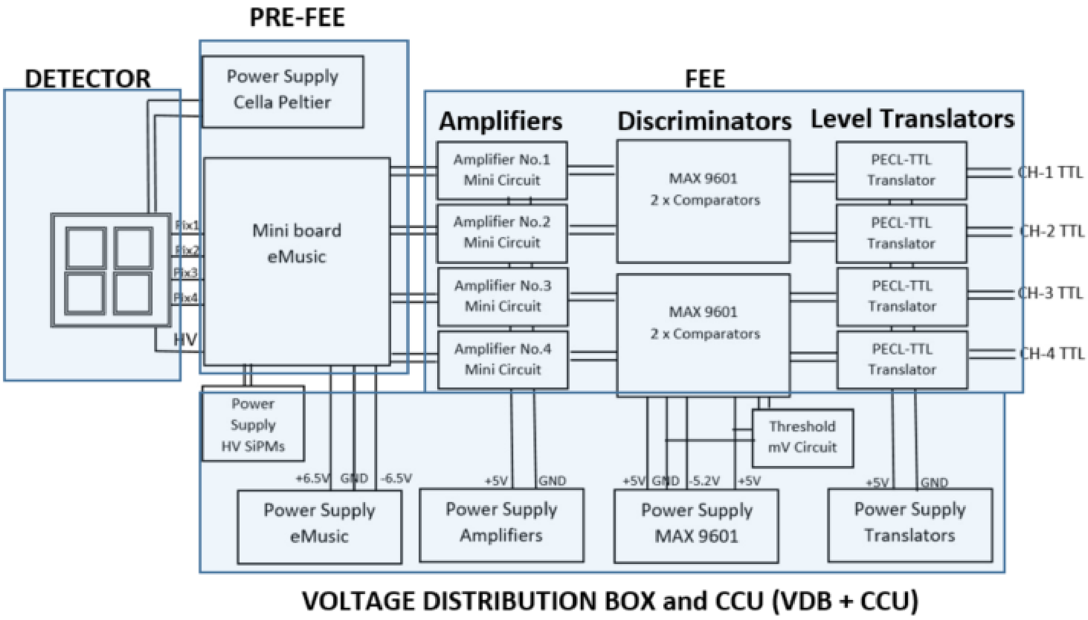


Figure 24 - Block diagram of the FEE (including the detector and PRE-FEE) and the VDB of SI[3].

In the following we list each component of the FEE and its main properties. For a more detailed description of these components we refer to [RD5].

- **ASIC MUSIC board (PRE - FEE)**

  The component used to condition the SiPM output signals is a dedicated board (eMusic Mini Board) equipped with the MUSIC R1 chip (Figure 25). The chip contains an adjustable pole-zero cancellation (PZ shaper) to account for different time constants (recovery time up to 100 ns).The shaper reduces the duration of the pulse generated by the detector, as shown in Figure 26. To connect our detector SiPM array to the board a dedicated adapter will be designed and realized.

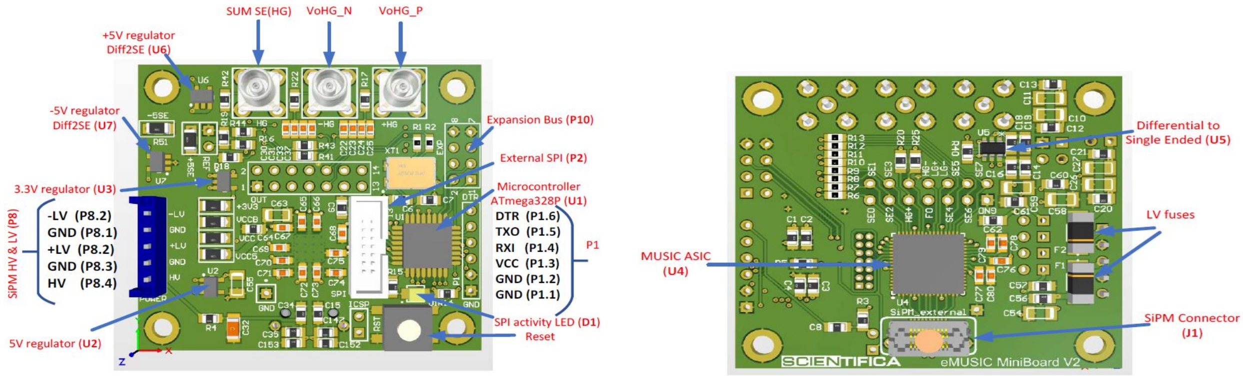


Figure 25 - eMusic Mini Board (PRE-FEE). Top view (left) and bottom view (right)

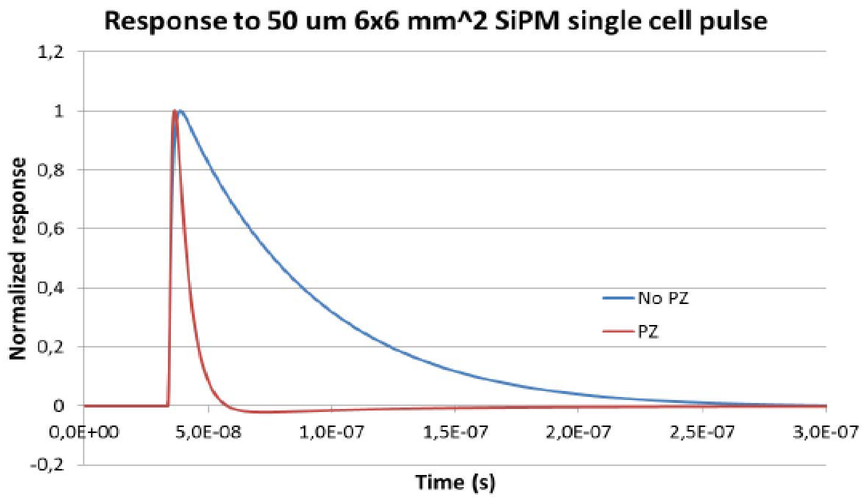


Figure 26 - Duration of a pulse without (blue) and with (red) the PZ shaper of the eMUSIC Mini Board

- **Wideband Low Noise Amplifiers (FEE)**

  The analog output signal from the MUSIC is amplified through the use of the wide band low noise amplifier (0.05÷8 GHz) ZX60-83LN-S + manufactured by Mini-Circuits (Figure 27). This amplifier uses HBT technology to deliver ultra-flat gain over a wide frequency range. It is needed to increase the amplitude of the signal sent to the leading edge discriminator, that works with amplitudes higher than 100 mV pp (see below). Since the detector array and the PRE-FEE are placed at the telescope focal plane, close to the Cherenkov camera, it is important to minimize the overall size of this component. For this purpose, we positioned the amplifiers at another position, more than 1.5 meters away from the eMusic board, and connected them to the eMUSIC through coaxial cables.

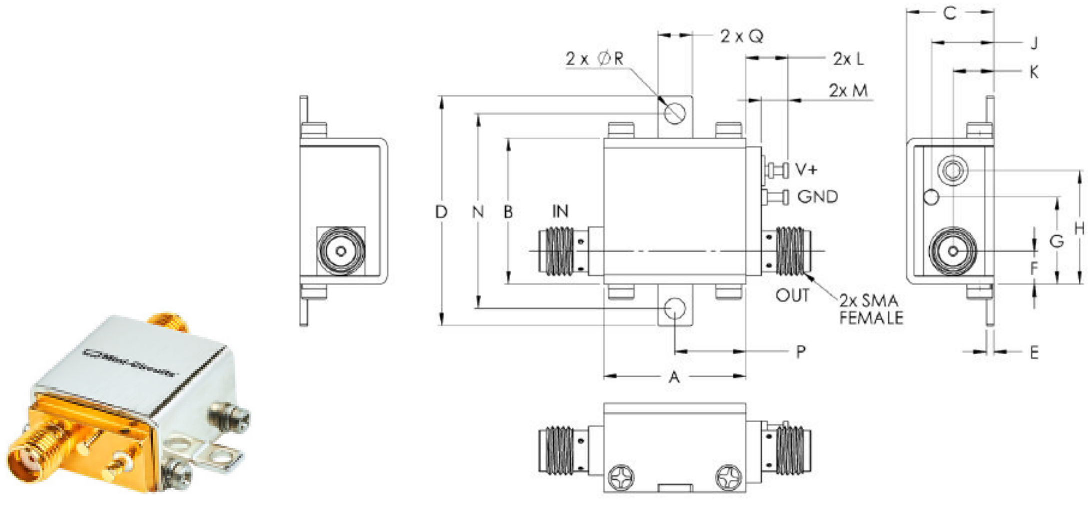


Figure 27 - Wide band low noise amplifier (0.05÷8 GHz) ZX60-83LN-S + manufactured by Mini-Circuits

- **Leading Edge Discriminators MAX 9601 (FEE)**

  As discriminators we used two dedicated boards that mount the MAX 9601 dual channel comparators with PECL output (Figure 28). The two comparators feature extremely low propagation delay (500ps) and minimize channel-to-channel skew (10ps). These features make them ideal for applications where high-fidelity tracking of narrow pulses and low timing dispersion is critical. The minimum level of the input signal is 100 mV pp.

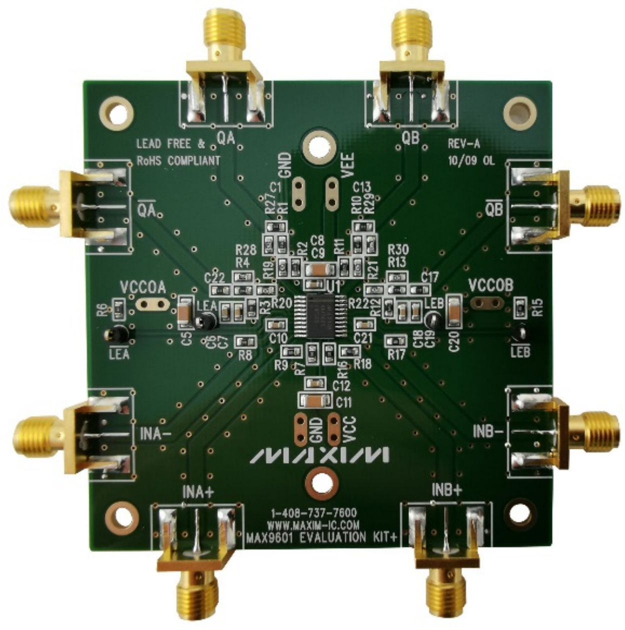


Figure 28 - Evaluation board mounting the MAX 9601 dual channel comparators

- **PECL – TTL Level Translator (FEE)**

  To make the output of the discriminator compatible with TTL levels, we used a SN65ELT21 chip, which is essentially a level shifter adapting the signal from PECL to TTL.

- **Threshold Generator (FEE)**

  To generate the thresholds for the comparators, a dedicated board was designed. It generates four independent thresholds starting from a voltage of -1.25V. The modulation of the thresholds levels is performed by four trimmers (one for each channel). In this way it is possible to adjust (fine tuning) the threshold in such a way to set the same threshold condition for each channel. Measuring the amplitude of the analog signal output from the amplifiers with an oscilloscope, it is possible to set the threshold following a calibration scale based on the amplitudes (1 p.e., 2 p.e. ... n p.e.).

5.5 Voltage Distribution Box and Control and Communication Unit

The VDB system comprises also the Control and Communication Unit (CCU) that provides the control of the detector and FEE. We designed the entire VDB plus CCU system distributed in five boards connected among them as shown in the scheme reported in Figure 29. Three DC-DC converters are used to power up the boards starting from the voltage (24V) of the main power supply.

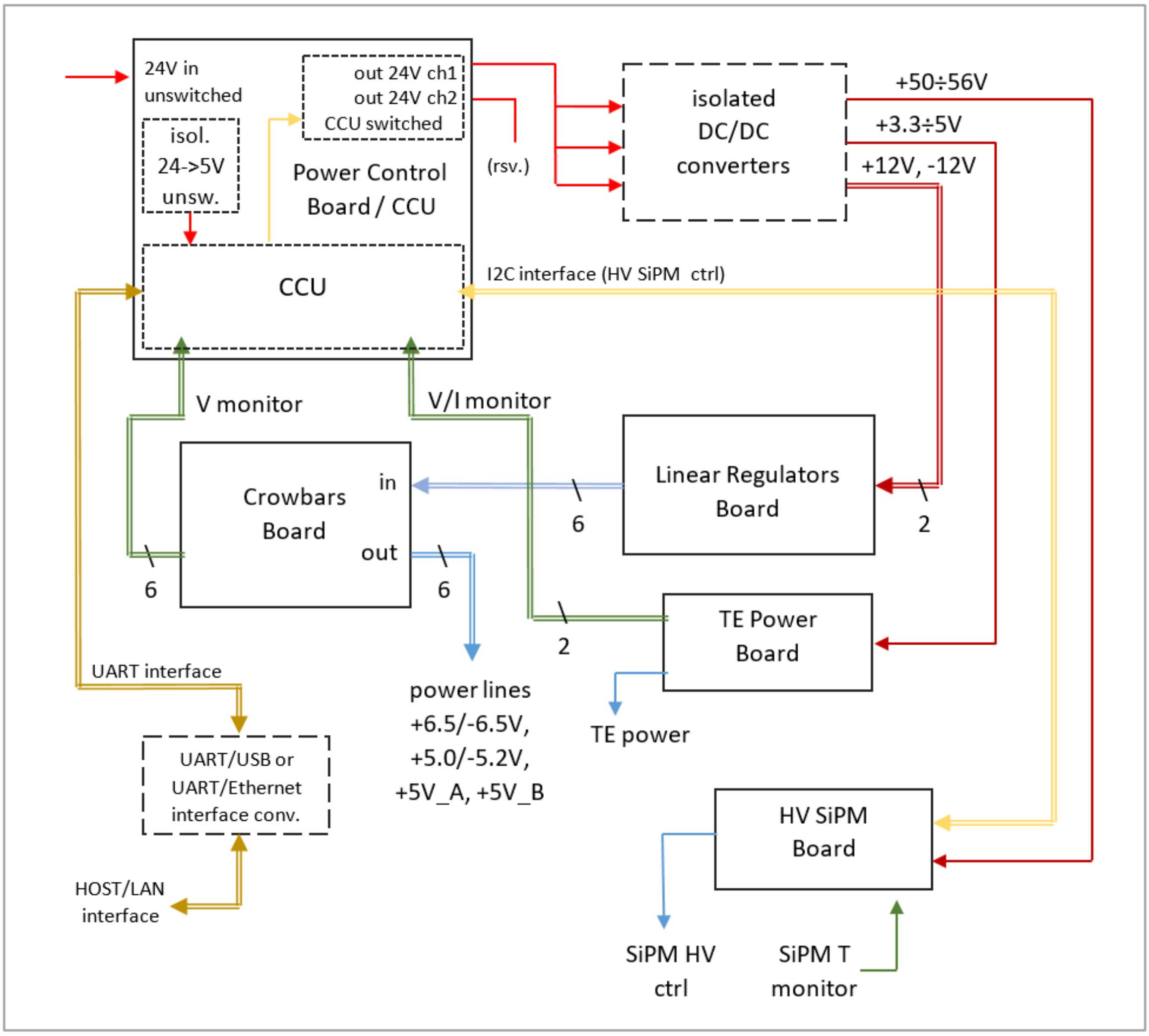


Figure 29 - Scheme of the VDB and CCU of the detector and FEE of SI^3, with all internal/external connections. The red arrow on the top left represents the input telescope power, while the light blue the arrows are the power output lines for the FEE (internal SI^3 power interfaces). All of them are marked in green in Figure 8. The dark yellow line represents the command (HOST/LAN) internal interface with the IPC (in black in Figure 8).

The five boards are capable to carry out:

- galvanic isolation with respect to the 24V power supply line;
- protection of the 24V line;
- distribution of the voltages needed for the operation of the downstream electronic system;
- protection of the downstream electronics from faults on the voltage regulation system (over voltages);
- remote on/off control of the power supply;
- remote monitoring of all the voltages, TEC power supply and temperatures.

We list below the main properties of each board. For a more detailed description we refer to [RD3].

- **Power Control board**

The main Power Control board is permanently powered by the 24 V line through a DC/DC converter with galvanic isolation. The first output allows power up three DC/DC converters, two 12V and one 3.3 V, used to power the subsequent VDB stages. The second output is provided as a backup for future needs. A microprocessor is mounted on this board for remote control and monitoring via a special communication protocol on a serial interface, via serial/USB (for diagnostics and bench tests) or serial/Ethernet converter (for communicating via the Ethernet line). The temperature inside the FEE box of SI^3 is measured by a sensor installed on the board itself.

- **Linear Regulators board**

This board is made of 6 linear regulators and provides the 5 different power supply voltages needed for the system: +6.5/-6.5V, +5.0/-5.2V and 5V (the latter divided into two separate channels). The linear regulators are needed to also reduce the output noise from the switching regulators.

- **Crowbars board**

The 6 power channels generated by the linear regulators are monitored by a Crowbars board which acts as a protection from any overvoltage. This board (mounted in piggyback on the Power Control board) sends the 6 voltages to the ADC circuitry managed by the controller for monitoring the status of the power supply system.

- **Thermo-Electric Cooler TE Power board**

The third DC/DC converter is designed to obtain galvanic isolation from the 24V line and realize the output voltage needed for the linear I/V regulation of the Peltier cell. This is achieved through the TE Power board. This board has two analog outputs which must be connected to the corresponding inputs of the Power Control board for monitoring the current and voltage of the TE power supply.

- **High Voltage SiPM board**

The acquisition and control of High Voltage (HV) and temperature of the detectors is obtained by means of the HV SiPM board. By a simple app running on a PC through a serial communication it is possible to set the V_{BR} of the SiPM and the V_{OV} to obtain the operating voltage V_{OP}.

An independent box shall contain the electronics for the signal conditioning, the voltage distribution and the control and communication unit (FEE+VDB+CCU box). It shall be separated by the moveable arm, but at a distance not larger than 3 meters. From the thermal point of view, this box shall permit the dissipation of the heat produced by the electronic boards, keeping their operating temperature below the MOT, but there will be no need for a strict thermalization.

5.6 Back End Electronics

The BEE of the ASTRI SI^3 is expected to work in the range of photon fluxes discussed in Section 3. It will then acquire signals from the FEE at a rate up to 100 Mcounts/s and will stream them to the Array Data Acquisition System (ADAS) of the telescope.

The BEE is made of a Time-to-Digital-Converter (TDC) board and a Time Distribution Unit (TDU), both mounted on an Industrial PC (IPC). A schematic view of the BEE of the ASTRI SI^3 is shown in Figure 30. The input voltage of the BEE is 24 V.

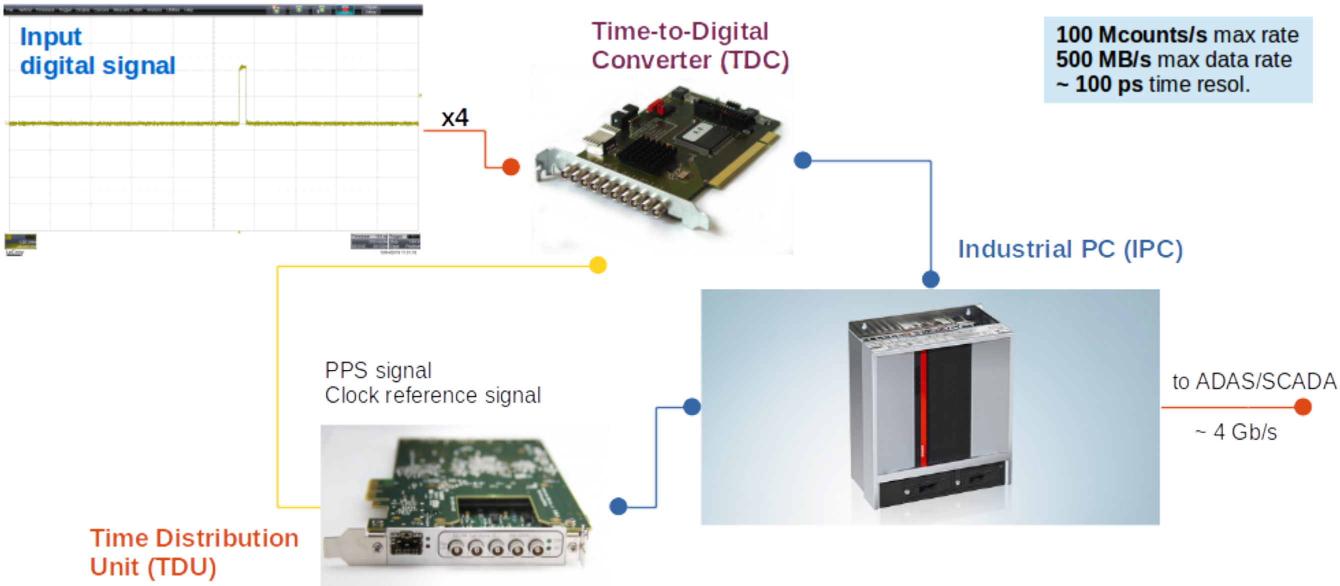


Figure 30 - Schematic representation of the components and internal connections of the BEE of ASTRI SI3.

- **Time-to-Digital-Converter (TDC) board**

  The TDC acquires the actual signal from the four channels of the FEE, with a resolution better than 100 ps, and streams them continuously to a solid state disc onboard the IPC. The TDC shall provide a compressed data output stream, with a maximum of 5 Bytes per event. A custom-version of a TDC produced by Cronologic (TDC10-11G), which is an evolution of the xHPTDC8-PCIe (technical data in Table 6), is capable of these performances for event rates up to 100 Mevents/s (data rates up to 500 MB/s).

TDC channels @ bin size	8 @13 ps
Additional inputs	slow ADC
Connectors	10x LEMO 00
Bin size	12 ps
Double pulse resolution	4 ns
Multihit	unlimited
Dead time between groups	none
Readout rate	48 MHits/s
Range	unlimited
Common start/stop	yes / yes
Number of boards that can be synced	8
Readout interface	PCIe x1
Time base	50 ppb on board

Table 6 - Technical data of the TDC xHPTDC8-PCIe made by Cronologic.

- **Time Distribution Unit (TDU)**

  The TDU delivers a reference signal and a PPS signal to two different channels of the TDC, that are then saved along with the data stream to disc. The reference and PPS signals are used to reconstruct the absolute (UTC) time in post-processing. The TDU has a time synchronization system based on the White Rabbit technology. A suitable TDU of this type is the FMC-DIO+SPEC board made by SEVEN Solutions.

- **Industrial PC (IPC)**

  The IPC acquires the scientific data from the TDC, saves them temporarily on an internal solid state disc, and transfers them in real time to the ADAS at an approximate maximum rate of 4 Gbit/s. The IPC shall be capable of managing this data rate (with at least one PCIe Gen3 x8 slot for the TDC and a SFP+ port for the ADAS link). A commercial product with these characteristics, made by BECKHOFF (C6670-0010), is available on the market (see Figure 31 and Table 7).

Figure 31 - IPC BECKHOFF C6670-0010. External (top panel) and internal (bottom panel) view.

Technical data	C6670-0010	Options
Device type	6 slot SSI EEB industrial server for control cabinet installation	
Slots for hard disk/flash	2 removable frames for hard disks	removable frames for SSDs
Protection class	IP 20	
Operating temperature	0…50 °C	
Weight of basic configuration	16 kg (35.2 lbs)	
Dimensions (W x H x D)	410 x 480 x 201 mm (16.1" x 18.9" x 7.9")	
Processor	2 x Intel® Xeon® Silver 4109T, 2.0 GHz, 8 cores per processor (TC3: 82)	up to 2 x Intel® Xeon® Gold 6138T 2.0 GHz, 20 cores each processor (TC3: 82)
Motherboard	server motherboard for Intel® Xeon® scalable processors	
PCIe/PCI slots	3 x PCIe-x8, 3 x PCIe-x16 for full-length plug-in cards	
Memory	64 GB DDR4 RAM ECC	up to 1024 GB DDR4 RAM ECC
Graphic adapter	graphic card, 1 DVI-I and 1 DVI-D connector, occupies a PCIe x16 slot	
Ethernet	2 x 10GBASE-T on-board	
RAID	on-board SATA RAID 1 controller	
Hard disks/flash	hard disk, 3½-inch, 1 TB, in removable frame	hard disk up to 2 TB, SSD, CFast
Disk drive	–	multi DVD
Interfaces	2 x USB 3.0, 2 x USB 2.0, 1 x RS232	
Power supply	100…240 V AC	UPS
Operating system	–	Windows 10 IoT Enterprise, Windows Server 2016

Table 7 - Technical data of the IPC BECKHOFF C6670-0010.

5.7 Local Acquisition and Control System

The Local Acquisition and Control System performs the following tasks:

- acquiring the scientific data from the TDC and sending them to the ASTRI Array Data Acquisition System (Local Acquisition System)
- acquiring the housekeeping data from the CCU and sending them to the ASTRI Array Data Acquisition System (Local Monitoring System)
- controlling the start/stop of the acquisition and other subsystems, including the detector (temperature/voltage) and the filter wheel (Local Control System)

The ASTRI Array Data Acquisition System (ADAS) buffers the data transferred from the SI^3 Local Acquisition and Control System into a local storage and transfers them to the Local Bulk Repository of the ASTRI Mini-array site.

The software of the SI^3 Local Acquisition and Control System (Local Acquisition soft., Local Monitoring soft., Local Control soft.) that performs the tasks listed above will run on the IPC and will be described in detail in a separate document.

The Local Control System of SI^3 interfaces directly through OPC-UA with the SI^3 supervisor that is part of the Telescope Control System [RD6]. The start/stop of the acquisition of the instrument is issued remotely from the Supervisory Control And Data Acquisition (SCADA) system. SCADA performs also a check of the packet integrity through packet length and Cyclic Redundancy Check on the saved data. The Online Observation Quality System (OOQS) performs a quality check of the data (count rates on the four detector quadrants) and displays the housekeeping data in real time to give feedback to the Operator during the observations [RD6].

Data structure and products

The structure of the scientific data produced by SI^3 consists of a telescope identifier and the time tag of an event in a strongly compressed data format (5 bytes per event). The reconstructed uncompressed time tag is 17 bytes per hit and contains information on the detector identifier and some flags. This data model has the following scientific data products:

Data product	Description
DL0.SI3	Raw data (sequence of events) acquired and saved on disc
DL1.SI3	Reconstructed event lists
DL2.SI3	Event lists calibrated, cleaned and referred to Coordinated Universal Time (UTC)

DL3.SI3	Time coincidences
DL4.SI3	Diagram of the temporal correlation

Table 8 - ASTRI SI^3 data products.

Data Transfer

The transfer of the scientific data from the IPC to ADAS is done via FTP. The DL0 files are in telemetry format, one per each telescope and for each observation. Assuming that the raw timestamps of an event is 5 bytes, the maximum data transfer rate sustained by the system is 500 MB/s (4 Gbit/s). DL0 data are buffered to disc in compressed binary files of 150 GB at a maximum rate of 4 Gbit/s.

The physical link between the IPC and the ADAS system is provided by an optical fiber with a 10 Gbit/s SFP+ transceiver. Data is copied in a Local Bulk Repository at a lower data transfer rate.

The system will transfer off-site the ~110 TB of raw data acquired each month (see Section 5.8) before the start of the following observing run. Assuming an average data transfer rate of ~125 MB/s, all the data are transferred in ~10 days.

5.8 Science Data Processing System

The Science data processing system encompasses all the hardware, operations, and software programs needed for reducing and analyzing the raw data, for producing the DL1-DL4 data products (Table 8), and for simulating the performance of the instrument.

The TDC raw data will first be processed to produce reconstructed and calibrated event lists using the time reference signals from the TDU. The final photon time tags are referred to UTC. After removing unusable/low quality data by filtering them through suitable quality checks, the event lists are ready for the scientific analysis. They are then segmented in chunks of size adequate for being efficiently handled in the following steps. Then, coincidences are searched for in the arrival times at different telescopes varying the time delay between them. An efficient implementation of the entire procedure has been already developed and tested in the Asiago intensity interferometry experiment (Zampieri et al. 2021, MNRAS, in press). For the data volume of ASTRI SI^3 and scaling from the processing time required for the data of the Asiago experiment, we need to organize the threads and run them in parallel on machines with a suitable number (~1000) of cores and/or adapt the processing software for running on machines that perform hardware acceleration (GPUs). The final output will be the diagram of the temporal and spatial correlation of a star for any two telescopes of the array. Image reconstruction can eventually be performed from these data.

A typical monthly observing run totals 3 nights, each lasting 8 hours. The acquisition of bright stars (100 Mevents/second) is limited to 2 hours, while the remaining 22 hours are dedicated to observing average-brightness stars, with a typical event data rate of 20 Mevents/second. Then, the system will acquire ~110 TB of raw data per month produced in the typical-case data acquisition scenario (100 MHz event rate and 2 hours of observation plus 20 MHz event rate and 22 hours of observation per monthly run) with the full-array in operation and a packet size of 5 Bytes/event.

The following figures report the expected signal-to-noise ratio of the measurements of the correlation between any two telescopes achieved with ASTRI SI^3 as a function of filter width for stars with magnitude V=0 and V=2, respectively.

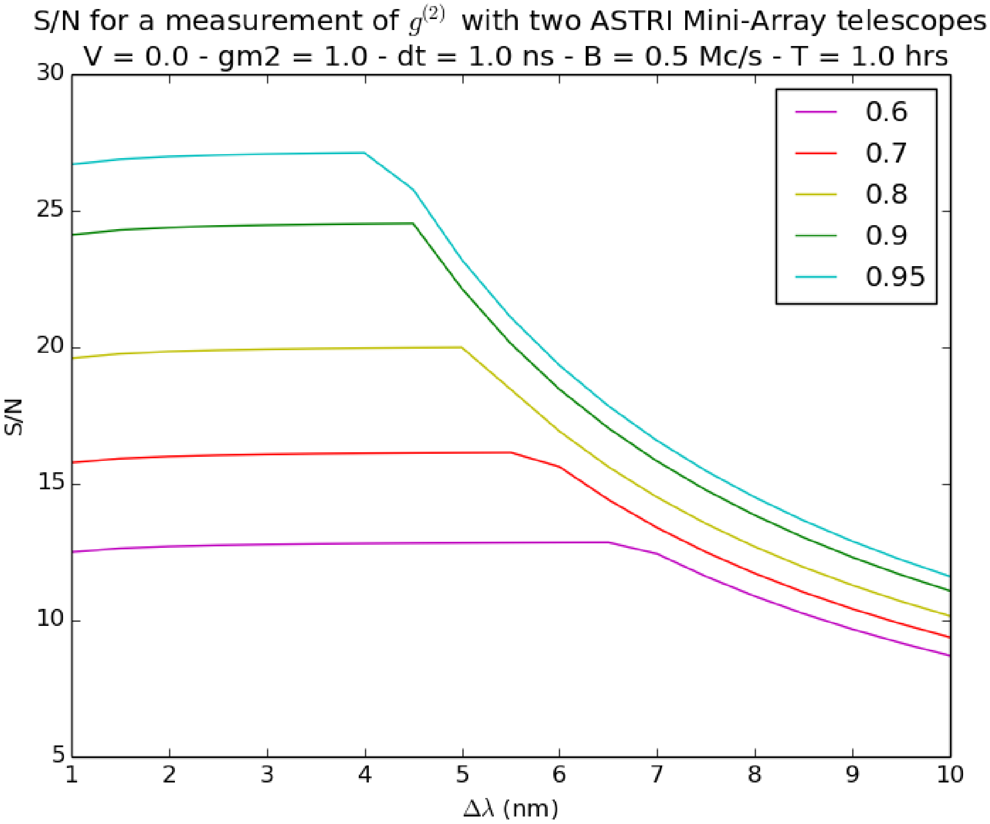


Figure 32: S/N ratio for a measurement of the discrete degree of coherence with two ASTRI telescopes as a function of the narrow band filter width and for different values of the efficiency of the focal plane optics module (from 0.6 to 0.95). The star magnitude is V=0 and the exposure time is 1 hour.

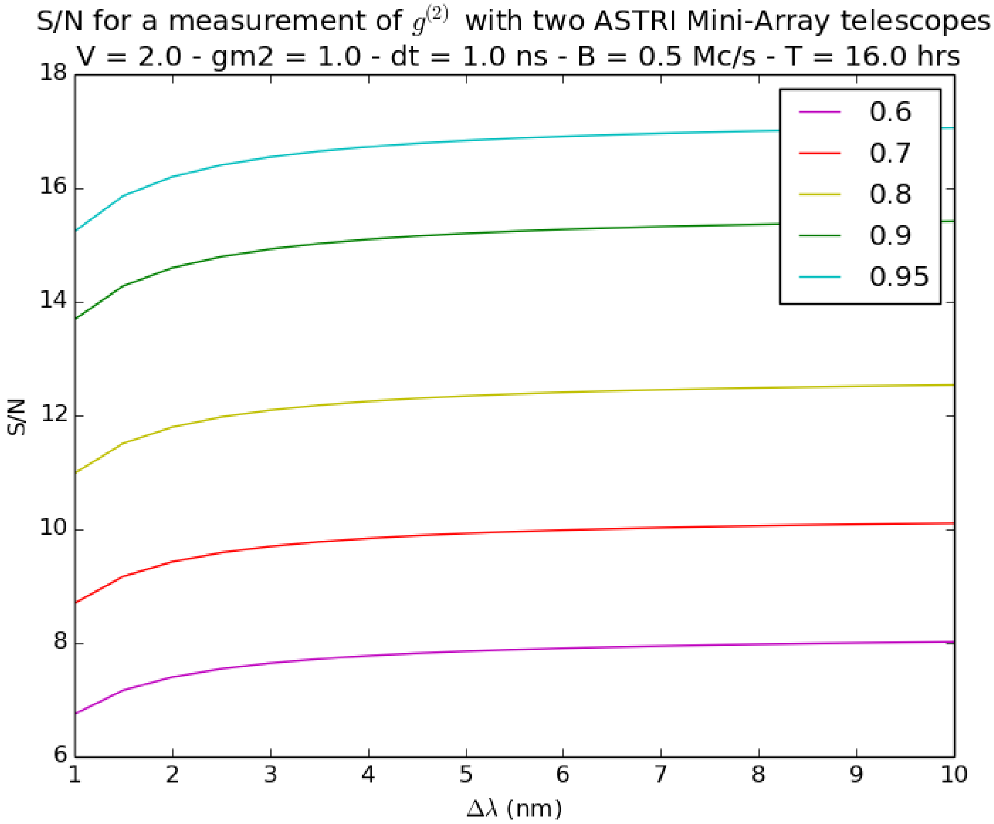


Figure 33: S/N ratio for a measurement of the discrete degree of coherence with two ASTRI telescopes as a function of the narrow band filter width and for different values of the efficiency of the focal plane optics module (from 0.6 to 0.95). The star magnitude is V=2 and the exposure time is 16 hours.