ASTRI Mini-Array

PMC and SQM Detailed Design Document

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DOCUMENT HISTORY		
Issue	**Date**	**Modification**
1.0	18/01/2022	Initial Draft

1. Introduction

The ASTRI Mini-Array (MA) is an INAF project aimed to observe astronomical sources emitting at very high-energy in the TeV spectral band and perform Stellar Intensity Interferometer of bright stars. The ASTRI MA consists of an array of nine innovative Imaging Atmospheric Cherenkov telescopes that are an evolution of the two-mirror ASTRI-Horn telescope successfully tested since 2014 at the Serra La Nave Astronomical Station of the INAF System of Catania. Each telescope will be equipped with the new version of the Cherenkov Camera based on Silicon photomultiplier detectors. The main science goals of the ASTRI MA in the gamma-ray high energy band, encompass both galactic and extragalactic science. The nine telescopes will be installed at the Teide Astronomical Observatory, operated by the Instituto de Astrofisica de Canarias (IAC), on Mount Teide (~2400 m a.s.l.) in Tenerife (Canary Islands, Spain). The ASTRI MA will be operated by INAF on the basis of a host agreement with IAC.

1.1. Purpose

This document details the design of the Telescope Auxiliary Systems consisting in:
- The Pointing Monitoring Camera (PMC) which provides information about the telescope pointing direction in the sky.
- The Sky Quality Monitor (SQM) which provides information about Night Sky Background

1.2. Scope

This document describes:
- the PMC+SQM mechanical design;
- the PMC and SQM measuring devices;
- the PMC+SQM power and ethernet connections
- the PMC data acquisition hardware;
- the PMC data acquisition software;
- the PMC local data processing software;
- the PMC data input output;

The description of the SQM acquisition and control software is outside the scope of this document.

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	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
FMECA	Failure Mode Effects and Criticality Analysis
HW	Hardware
HS	Heating System
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
PA	Product Assurance
PBS	Product Breakdown Structure
PCB	Printed Circuit Board
PDM	Photon Detection Module
PDR	Preliminary Design Review
PMC	Pointing Monitoring Camera
PR	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	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
SQM	Sky Quality Monitor
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 Instrument) 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.

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
[AD7] ASTRI Mini Array -Telescope - PMC/SQM Assembly ICD - PMC ICD ASTRI-INAF-ICD-7510-001

2.2. Reference Documents

[RD1] ASTRI Mini Array Telescope Design Report -
[RD2] ASTRI Mini Array Top Level architecture - ASTRI-INAF-DES-2100-001

[RD3] FLIR FLEA3 GigE Vision Data Sheet
[RD4] FLIR FLEA3 GigE Vision Technical Reference
[RD5] SQM-LE Operator Manual

3. Overview and Functional requirements

Each Telescope of the ASTRI MA foresees a set Auxiliary Systems to be mounted on the back of the telescope secondary mirror.

The Pointing Monitoring Camera shall acquire images of the sky and perform an astrometry analysis in order to determine the telescope pointing direction. The sky image acquisition could be either on request or at regular intervals. The main output from the PMC are the coordinates of the measured pointing direction and the angular error with respect to the commanded pointing direction.

The Sky Quality Monitor shall provide a measure of the Night Sky Background in a wide angle.

The PMC and the SQM are arranged within the same mechanical assembly and present a single mechanical and electrical interface with the telescope mount [AD7].

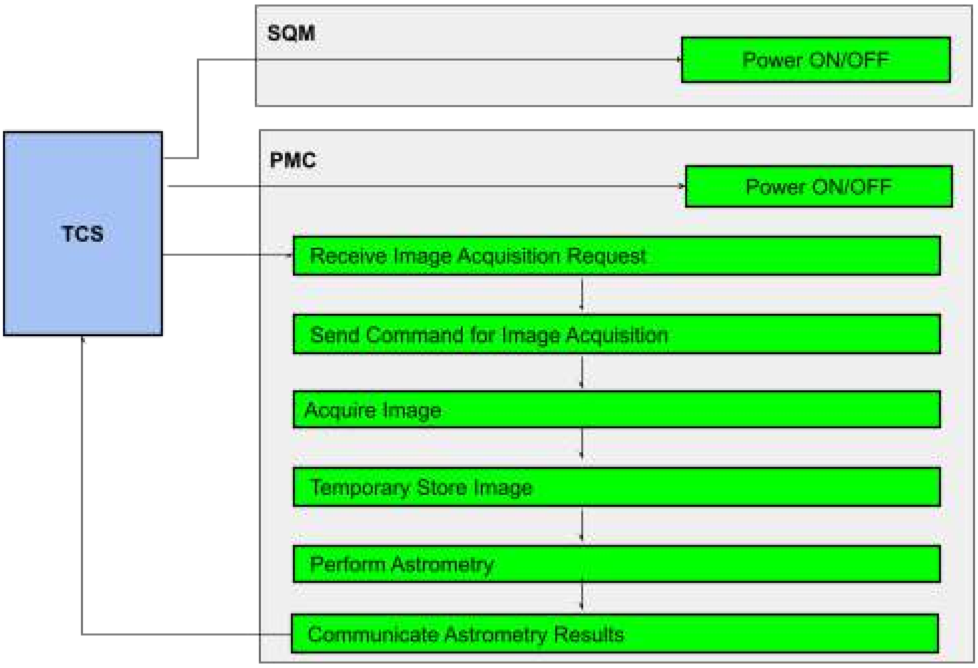


Figure 1. PMC and SQM functional decomposition.

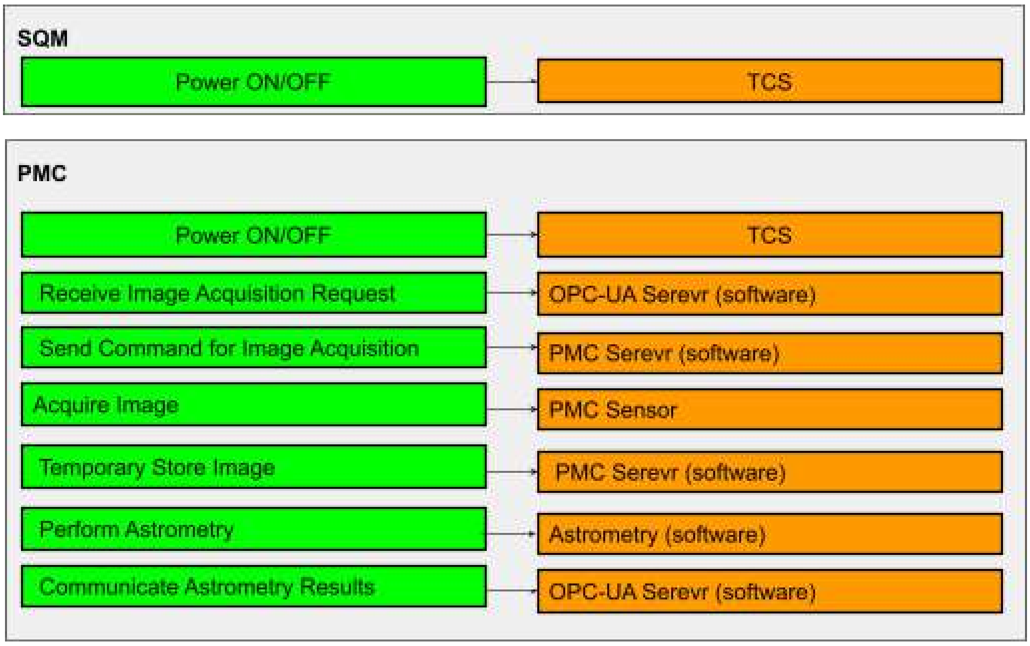


Figure 2. Association between PMC and SQM functions and components.

The SQM functions are decoupled from the PMC ones and all its acquisition and control features are described elsewhere, for the purpose of this document the SQM can be considered a host inside the PMC mechanical structure. The PMC and SQM functional decomposition is shown in Figure 1, while the associations between function and software or hardware components are shown in Figure 2.

4. Design Options Considered

The PMC is needed for each telescope the Night Sky Background is measured by the SQM in a wide field of view, making the measurement with each telescope of the Mini Array largely redundant.

While each telescope could potentially be provided with both a PMC and a SQM only a few (2) of them will be actually instrumented with a SQM device.

5. Baseline Design

The baseline design described here includes both a PMC and a SQM, in some of the telescopes the SQM measuring device will not be installed.

5.1. Mechanical Design

The mechanical assembly (Figure 1 top)hosting the SQM and the PMC is organised in a single cylindrical container where the two measuring devices are installed. Both PMC and SQM are integrated in the telescope in order to point in the same direction where the structure is pointing.

The internal part of the mechanical assembly is made of an L shaped frame intended to hold the PMC and SQM in position (Figure 1 bottom). All the internal parts of the assembly made of metal are painted black to minimise light reflections.

Figure 3. SQM/PMC assembly (top). Main mechanical frame (bottom).

5.1.1. SQM /PMC Mechanical Interface

The assembly will be integrated on the M2 back structure. The mounting frame, shown in Figure 3, is mounted on the M2 Support Structure.

Three holes ⌀10 mm in diameter, positioned 120° from each other on a radius of 220.5 mm are the fixing points of the frame.

Figure 4 shows the requested position of the three holes (indicated with E, F, and G in Figure 5) to be drilled on the M2 Support Structure.

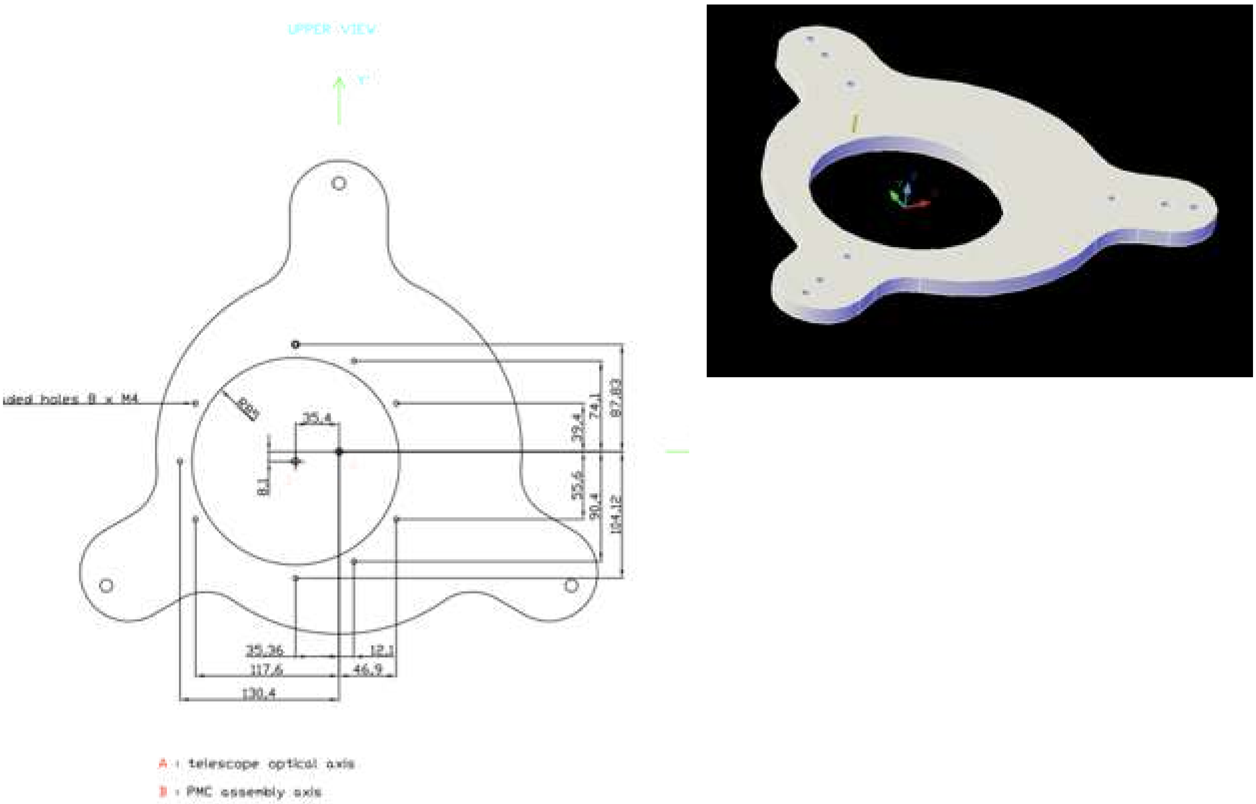


Figure 4. SQM/PMC interface flange.

In order to have the desired match between the two frames in correspondence with the holes the M2 Support Structure shall be milled on a 30 mm diameter in order to have the requested planarity. The three pads, where the SQM/PMC frame will be mounted, shall be maintained perpendicular to the Z axis. Figure 5 shows a 3D drawing of the PMC/SQM assembly mounted on the back of M2.

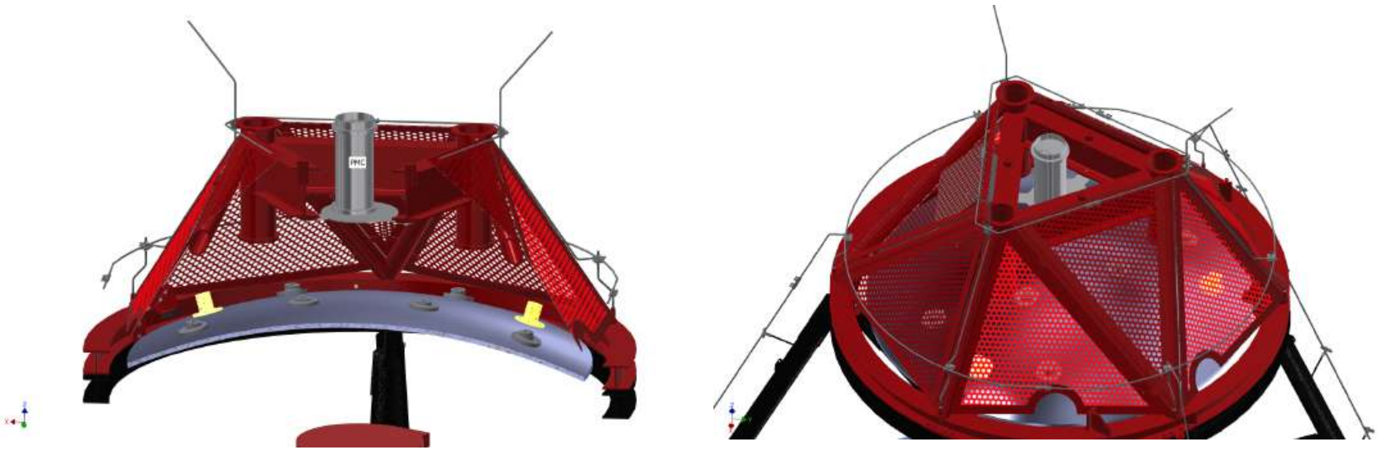


Figure 5. 3D drawing of the PMC assembly mounted on the M2 shield.

5.1.2. Optical Windows

As shown in Figure 1 the assembly shall have one optical window for each measuring device. The Optical windows of choice are from *Edmund Optics* (https://www.edmundoptics.com/):

- PMC: *75mm DIA., 4mm THICK, MgF2 COATED λ/4 N-BK7 WINDOW*
- SQM: *50mm DIA., 4mm THICK, MGF2 COATED λ/4 N-BK7 WINDOW*

The PMC and SQM Optical Windows differ by their diameter only. The PMC Optical Window main characteristics are listed in Table 1 while the drawing is shown in Figure 6. The corresponding information for the SQM Optical Window is shown in Table 2 and Figure 7 respectively.
The Optical Windows are manufactured with an anti-reflection coating whose performance are shown in Figure 8.

Table 1. PMC Optical Window characteristics.

Abbe Number (v_d):	64.17	**Clear Aperture (%):**	90
Diameter (mm):	75.00 +0.0/-0.25	**Thickness (mm):**	4.00
Coating:	MgF_2 (400-700nm)	**Coating Specification:**	R_{avg} ≤1.75% @ 400 - 700nm
Coefficient of Thermal Expansion CTE (10^{-6}/°C):	7.1	**Knoop Hardness (GPa):**	610
Young's Modulus (GPa):	82	**Density (g/cm^3):**	2.51
Index of Refraction n_d:	1.516	**Parallelism (arcmin):**	1.00
Poisson's Ratio:	0.206	**Substrate:**	N-BK7
Surface Flatness:	λ/4	**Surface Quality:**	60-40
Thickness Tolerance (mm):	±0.20	**Type:**	Protective Window
Typical Energy Density Limit:	10 J/cm^2 @ 532nm, 10ns	**Wavelength Range (nm):**	400 - 700

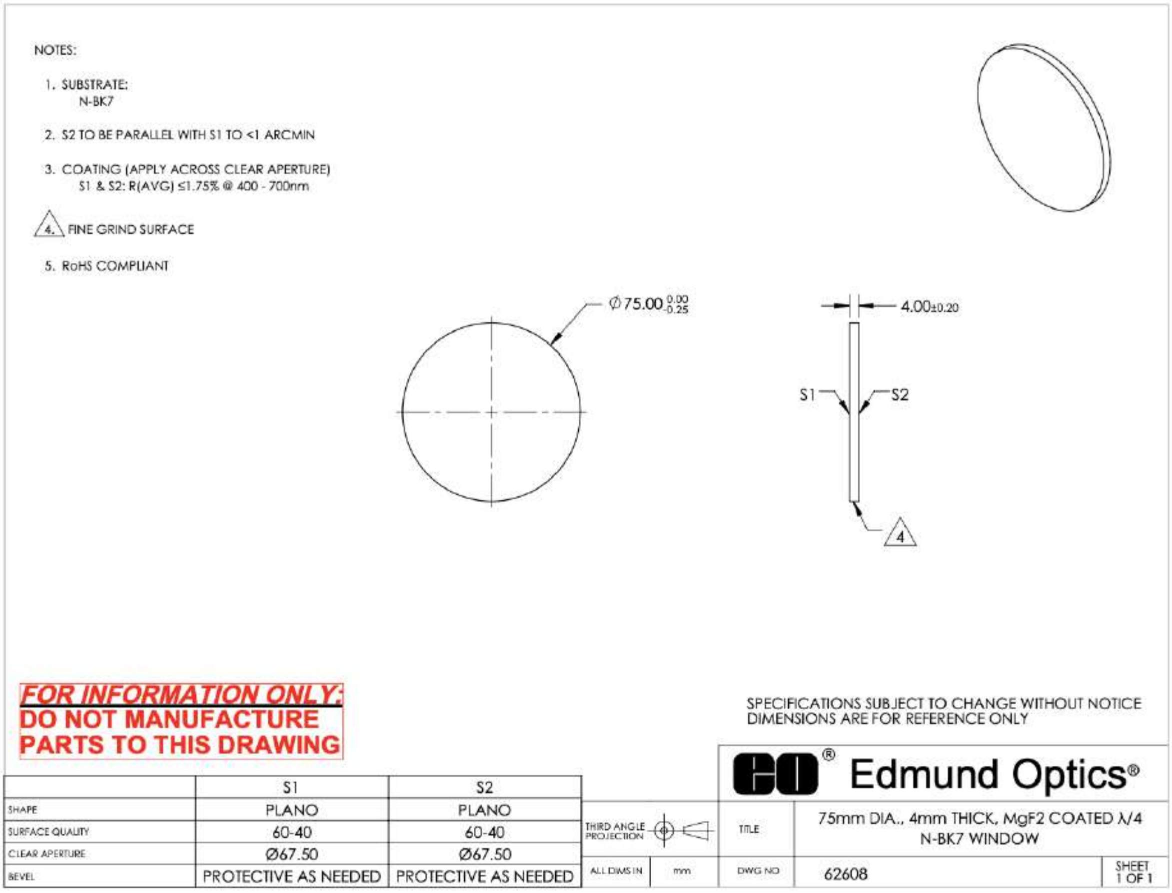


Figure 6. PMC Optical Window drawing.

Table 2. SQM Optical window characteristics.

Abbe Number (v_d):	64.17	**Clear Aperture (%):**	90
Diameter (mm):	50.00 +0.0/-0.25	**Thickness (mm):**	4.00
Coating:	MgF_2 (400-700nm)	**Coating Specification:**	R_{avg} ≤1.75% @ 400 - 700nm
Coefficient of Thermal Expansion CTE (10^{-6}/°C):	7.1	**Knoop Hardness (GPa):**	610
Young's Modulus (GPa):	82	**Density (g/cm³):**	2.51
Index of Refraction n_d:	1.516	**Parallelism (arcmin):**	1.00
Poisson's Ratio:	0.206	**Substrate:**	N-BK7
Surface Flatness:	λ/4	**Surface Quality:**	60-40
Thickness Tolerance (mm):	±0.20	**Type:**	Protective Window
Typical Energy Density Limit:	10 J/cm² @ 532nm, 10ns	**Wavelength Range (nm):**	400 - 700

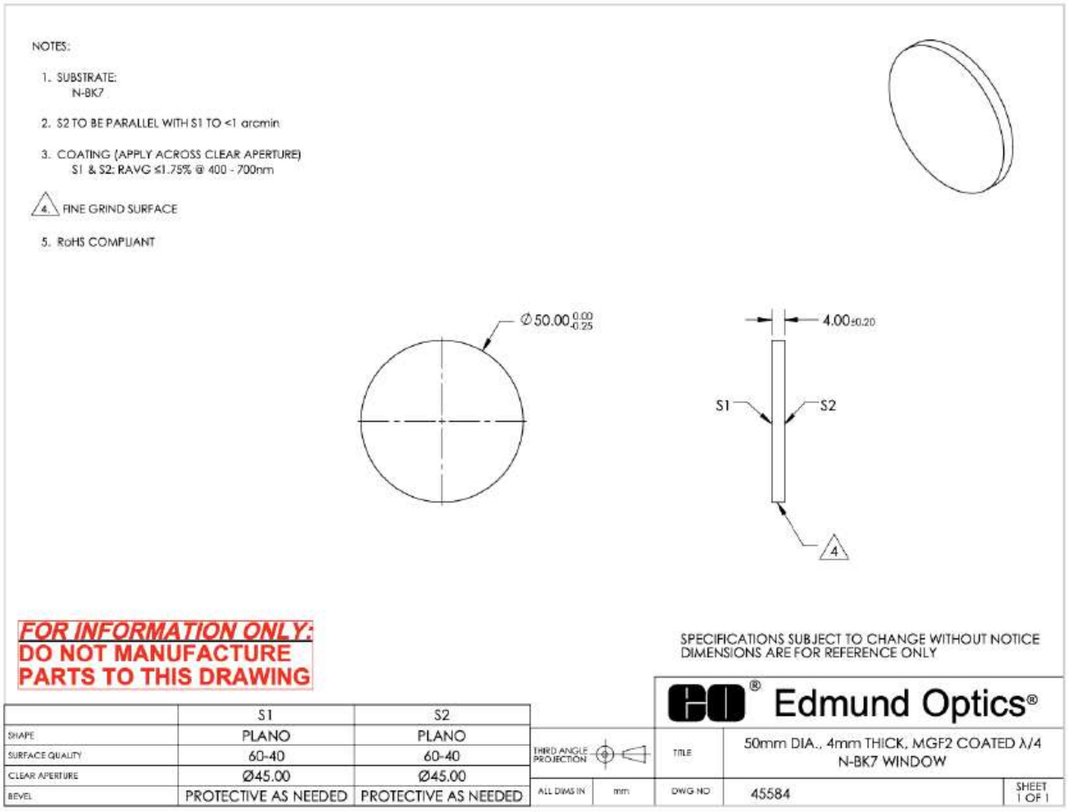


Figure 7. SQM Optical Window drawing.

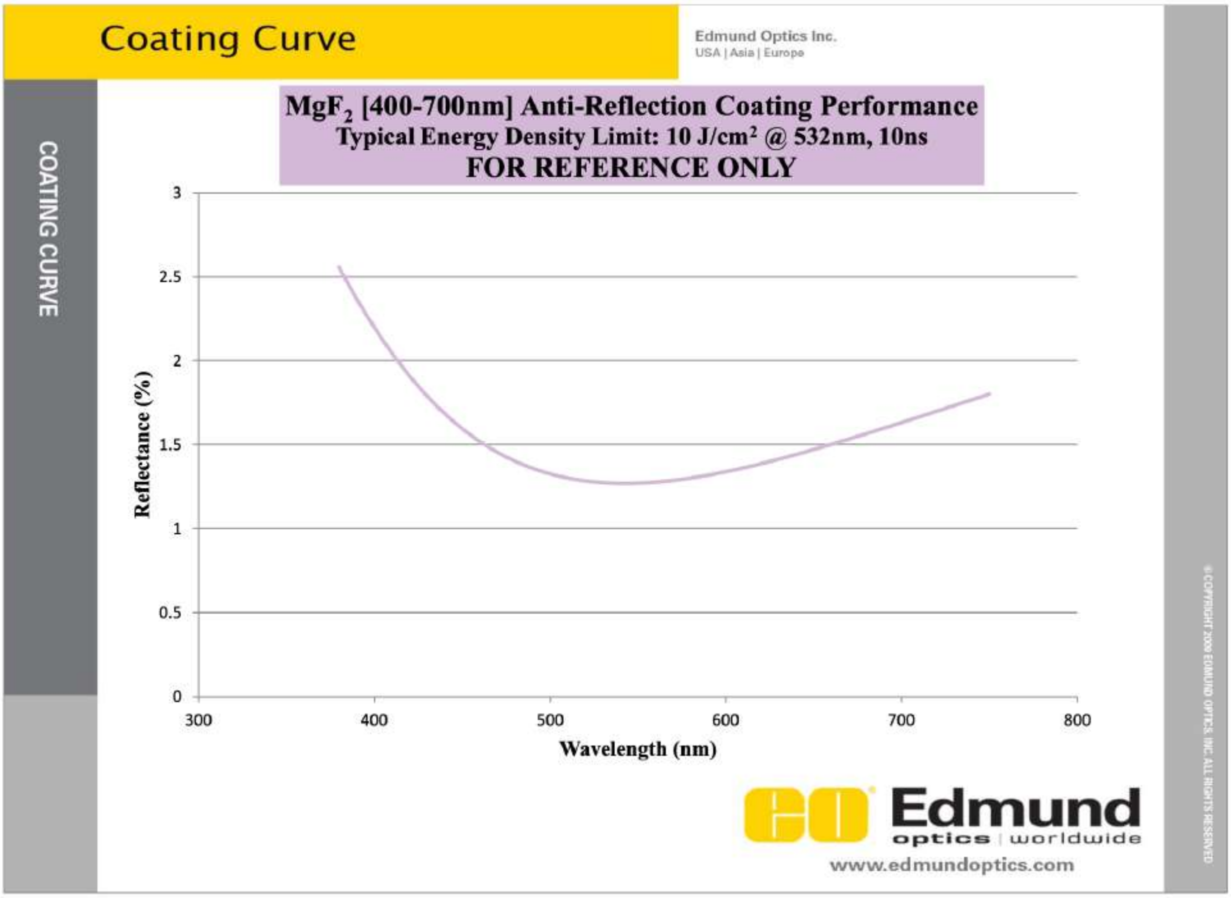


Figure 8. PMC and SQM Optical Windows reflectance.

5.1.3. SQM /PMC Assembly Heater

In order to avoid the optical window to be clouded by moisture with low temperature, a Heating System (HS) is present on the metal plate hosting the windows.

The HS, as shown in Figure 9, is based on two *Arcol* 47 Ohm 25 W resistors with Aluminum housing and a *Honeywell* Thermostatic Switch (P.N. 2455R 9082-461 L25C) which closes at a temperature of 15°C or below. The HS input voltage is 24 V and the circuit schematics are shown in Figure 9 as well.

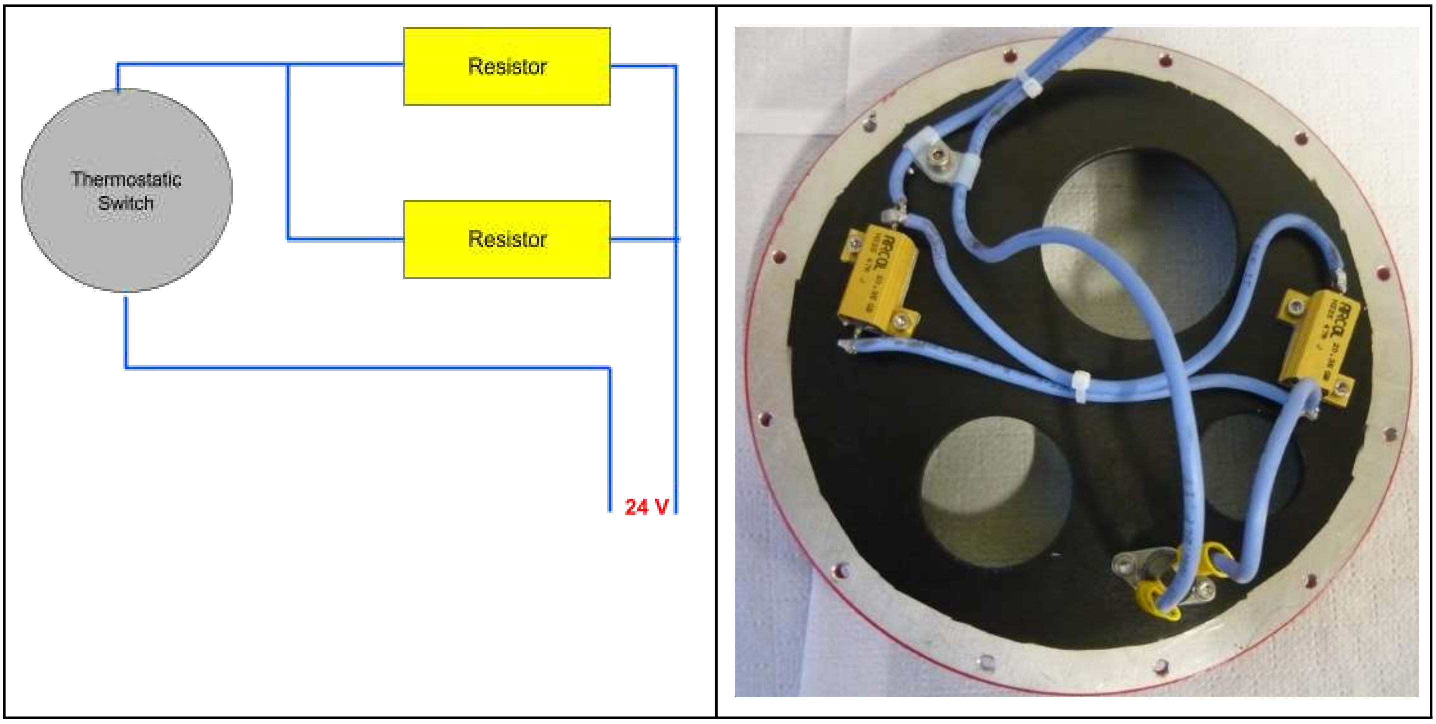


Figure 9. The Heating System circuit schematics (left) and the picture of the back of the metal plate hosting the Optical Windows with the main HS components and wiring.

5.1.4. SQM /PMC Electrical Interface

In the SQM/PMC assembly there are three independent power lines:

- 24V for the PMC
- 5V for the SQM
- 24V for a heater that can be switched on in case of mist formation on the optical windows.

The selected connector (Figure 5) is an Amphenol Limited, 62GB 14 Way Flange Mount MIL Spec Circular Connector Receptacle, Pin Contacts, Shell Size 12, Bayonet. Identi- fication codes and the link to on-line information are available in Table 2.

The selected connector is an EPIC Circon M23 12 poles 1mm wire gauge (Figure 5). The connector on the SQM/PMC assembly will be a Female connector.

Figure 10. Amphenol Limited, 62GB 14 Way Flange Mount MIL Spec Circular Connector Receptacle, Pin Contacts, Shell Size 12, Bayonet Connector

Table 3. Amphenol Limited, 62GB 14 Way Flange Mount MIL Spec Circular Connector Receptacle, Pin Contacts,Shell Size 12, Bayonet Connector details

Link	https://it.rs-online.com/web/p/connettori-circolari-militari/8139749/
RS Code	**813-9749**
Man. Code	**62GB-50T12-14PN**

The corresponding female connector (which will be provided) is the Amphenol Limited, 62GB 14 Way Cable Mount MIL Spec Circular Connector Plug, Socket Contacts, Shell Size 12 Bayonet, which is shown in Figure 10 and whose details are available in Table 4.

Figure 11. Amphenol Limited, 62GB 14 Way Cable Mount MIL Spec Circular Connector Plug, Socket Contacts,Shell Size 12, Bayonet corresponding to the male connector mounted on the PMC/SQM assembly plate.

Table 3. Amphenol Limited, 62GB 14 Way Cable Mount MIL Spec Circular Connector Plug, Socket Contacts,Shell Size 12, Bayonet Connector details

Link	https://it.rs-online.com/web/p/connettori-circolari-militari/8139847/
RS Code	**813-9847**
Man. Code	**62GB-56T12-14SN**

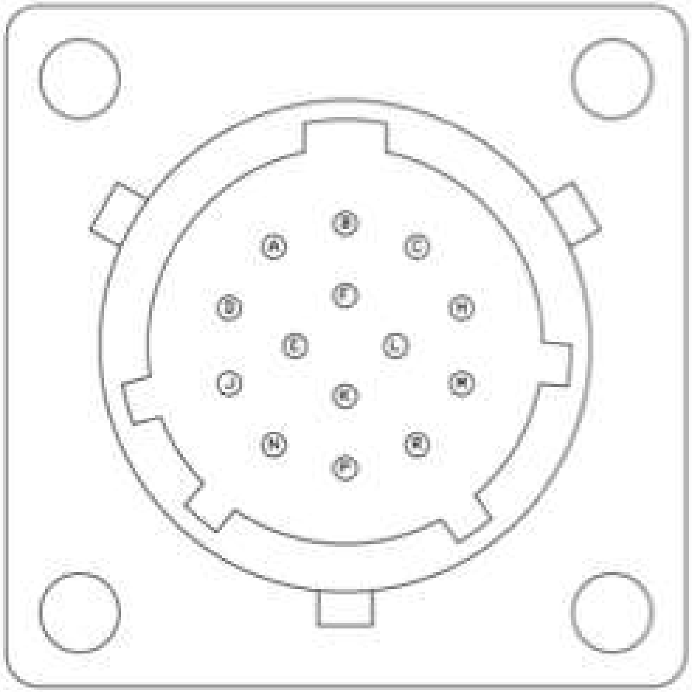


Figure 12. Pin naming scheme for the Amphenol panel mount male Connector (Am- phenol Limited, 62GB 14 Way Flange Mount MIL Spec Circular Connector Receptacle, Pin Contacts, Shell Size 12, Bayonet)

Table 4 lists the pin out for the power connector and the power budget is shown in 5.

Table 4. Pin out of the Amphenol connector.

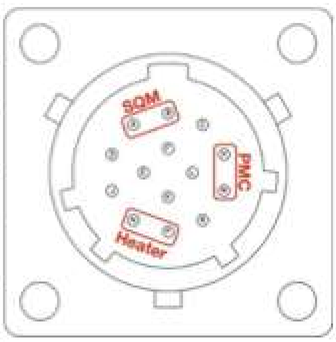
Pin	Signal	Note	
A	+5 Volt	SQM Power	
B	Ground	SQM Grounding	
C	Spare		
D	Spare		
E	Spare		
F	Spare		
H	+24 Volt	PMC Power	
J	Spare		

Table 5. Power Bugdet for the PMC/SQM assembly

Device	Volt	Current	Power
SQM	Min 5 Max 6	0,3 A	1,8 W
PMC	Min 12 max 24	0,21 A max	< 2,6 W
Heater	24 V	2 A	50 W
			P total max +10%margin 58 W

Each SQM and PMC subsystem needs an Ethernet connection. The selected connectors are Ethernet IP67 connections “receptacle (Figure 6).

5.1.5. SQM /PMC Communication Interface

Both PMC and SQM are connected directly to the Telescope Switch or the Local Control PC and there is no SW interface between the assembly and the telescope structure.

Each SQM and PMC subsystem needs an Ethernet connection. The selected connectors are the Amphenol, Female Cat5e RJ45 Panel Mount Connector shown in Figure 8. Fig- ure 9 shows the corresponding cable mount connector (provided) and Table 6 lists the Amphenol Cat5e RJ45 details not for the Panel and Cable mount connectors.

Figure 13. Receptacle Connector on Camera Assembly for Ethernet connection

5.2. Pointing Monitoring Camera

The PMC image acquisition device is composed of:

- a camera;
- a photographic lens.

The production of both the Camera and the Lens used in the ASTRI-Horn prototype have been discontinued, details about the selected replacements are reported below. The available options and the rationale behind the selected ones, together with the specifications from the ASTRI-Horn prototype are discussed in Appendix A

5.2.1. Camera

The chosen camera is a *FLIR* Blackfly S GigE (Model: BFS-PGE-63S4M-C) with a 6.3 Mpixel Monochromatic Sony IMX178 C-Mos sensor. The camera is shown in Figure 13 with the full list of details available in Table 6.

The camera in the ASTRI PMC system is powered through the GPIO pins (Figure 14) while the control and acquisition is performed through the ethernet connection. The mechanical drawings are shown in Figure 15.

Figure 14. The FLIR Blackfly S GigE (Model: BFS-PGE-63S4M-C) camera chosen as the PMC sensor.

Color	Pin	Line	Function	Description
Green	1	3	Power / Input	+12 V DC Camera Power / Non-isolated input
Black	2	0	Opto Input 1	Opto-isolated input
Red	3	2	NC / +3.3 V / GPIO	+3.3 V output. Current 120 mA (nominal) Firmware enabled / Non-isolated I/O
White	4	1	Opto Output 1	Opto-isolated output
Blue	5	N/A	Opto GND	Ground for opto-isolated I/O, not connected to camera ground
Brown	6	N/A	GND	DC camera power ground

Figure 15. The FLIR Blackfly S GigE (Model: BFS-PGE-63S4M-C) GPIO pinout.

Table 6. Characteristics of the FLIR Blackfly S GigE (Model: BFS-PGE-63S4M-C) camera chosen as the PMC sensor.

	BFS-PGE-63S4M
Firmware Version	1811.3.3.0
Resolution	3072 x 2048
Frame Rate*	19.0 FPS
Megapixels	6.3 MP
Chroma	Mono
Sensor	Sony IMX178, CMOS, 1/1.8"
Readout Method	Rolling shutter with global reset
Pixel Size	2.4 µm
Lens Mount	C-mount
ADC	10-bit / 12-bit/ 14-bit
Minimum Frame Rate	1 FPS
Gain Range	0 to 47 dB
Exposure Range	25 us to 30 s
Acquisition Modes	Continuous, Single Frame, Multi Frame
Partial Image Modes	Pixel binning, ROI
Image Processing	Gamma, lookup table, and sharpness
Sequencer	Up to 8 sets using 5 features
Image Buffer	240 MB
User Sets	2 user configuration sets for custom camera settings
Flash Memory	6 MB non-volatile memory
Opto-isolated I/O	1 input, 1 output
Non-isolated I/O	1 bi-directional, 1 input
Serial Port	Supported
Auxiliary Output	3.3V, 120 mA maximum
Interface	GigE
Power Requirements	Power over Ethernet (PoE); or 12 V nominal (8 - 24 V)
Power Consumption	2.6 W (POE); 2.1 W (GPIO) maximum
Dimensions/Mass	29 mm x 29 mm x 30 mm / 36 g
Machine Vision Standard	GigE Vision v1.2
Compliance	CE, FCC, KCC, RoHS, REACH. The ECCN for this product is: EAR099.
Temperature	Operating: 0°C to 50°C Storage: -30°C to 60°C
Humidity	Operating: 20% to 80% (no condensation) Storage: 30% to 95% (no condensation)
Warranty	3 years

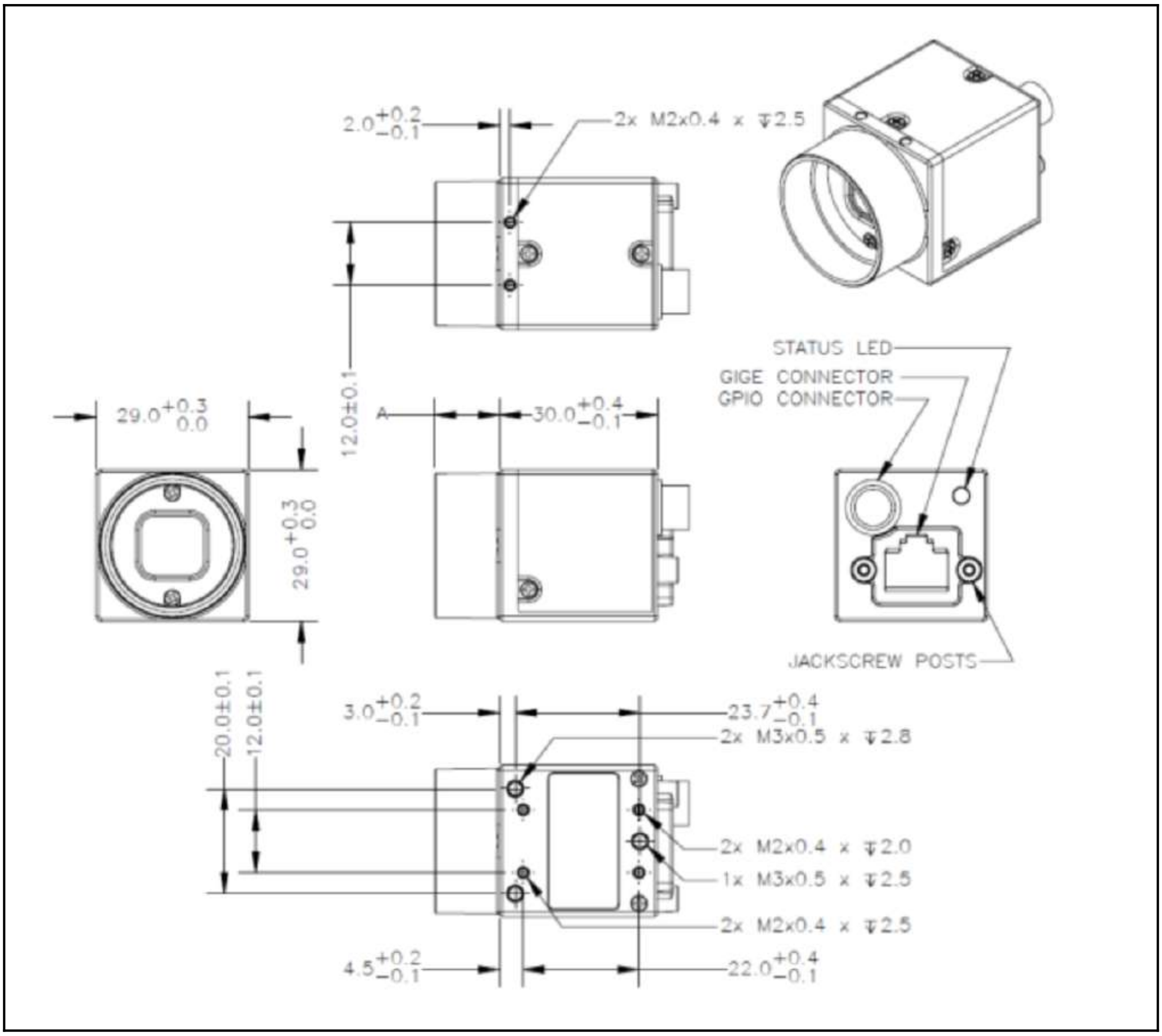


Figure 16. Drawings of the FLIR Blackfly S GigE (Model: BFS-PGE-63S4M-C) camera chosen as the PMC sensor.

5.2.2. PMC Lens

The chosen lens for the PMC sensor is the *Computar* M7528-MPW3 (https://computar.com/product/1466/M7528-MPW3 https://computar.com/resources/files_v2/1731/M7528-MPW3_11-19.pdf)

whose main characteristics are shown below. The lens drawings are shown in Figure 16.

M7528-MPW3

f = 75mm F 2.8
For 2/3 type Cameras
C-Mount

Model No.		M7528-MPW3		Effective Lens Aperture	Front	ϕ 26.1mm	
Focal Length		75mm			Rear	ϕ 15.8mm	
Max. Aperture Ratio		1:2.8		Distortion	2/3 type(Y=5.5mm)	0.33%	
Max. Image Format		8.8mm x 6.6mm(ϕ 11mm)			1/1.8 type(Y=4.5mm)	0.21%	
Operation Range	Iris	F2.8 - 16.0			1/2.5 type(Y=3.55mm)	0.12%	
	Focus	0.4m – inf.		Back Focal Length		14.6mm	
Control	Iris	Manual		Flange Back Length		17.526mm	
	Focus	Manual		Mount		C-Mount	
Object Dimension at M.O.D.	2/3 Type	47.0 x 35.2 mm		Filter Size		M34 P=0.5mm	
	1/1.8 Type	38.4 x 28.8 mm		Dimensions		ϕ 36mm x 75mm	
	1/2.5 Type	30.4 x 22.9 mm		Weight		102g	
Angle of View	D	2/3 type	8.4°	1/1.8 type	6.9°	1/2.5 type	5.4°
	H		6.7°		5.5°		4.3°
	V		5.0°		4.1°		3.3°
Operating Temperature		-10°C - +50°C					

2/3 type

C

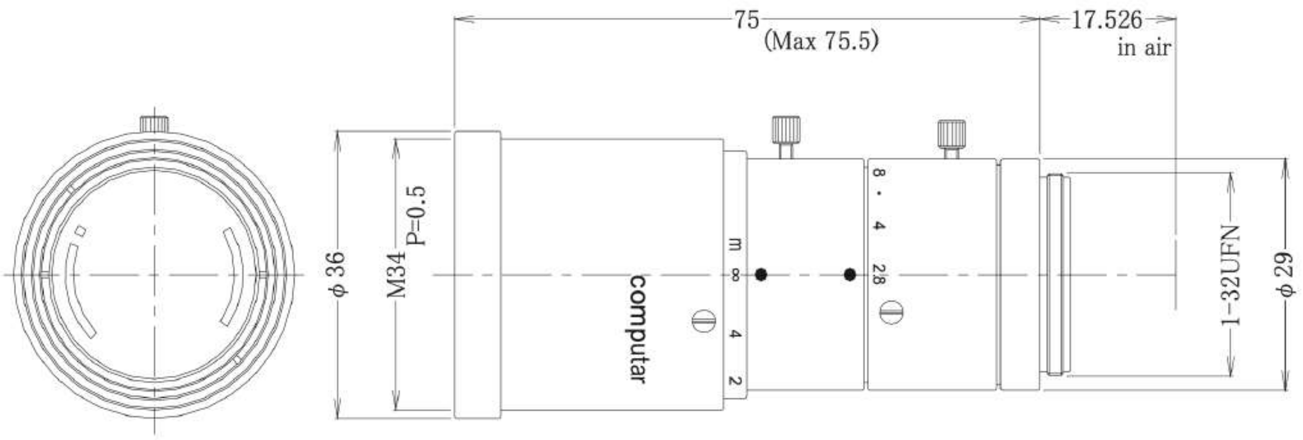


Figure 17. Mechanical drawings of the Computar M7528-MPW3 lens chosen for the PMC.

5.2.3. Camera/Lens Mechanical support

The camera is equipped with a tripod adapter used to connect it to a metal cylinder which in turn is screwed onto the main mechanical frame to hold the camera and lens in place (Figure 18).
As shown in Figure 18 (centre and right), the upper part of the lens is held in place with a metal bearing anchored to the main mechanical frame as well.

Figure 18. A picture of the PMC Camera and Lens assembled together with the metal cylinder used to anchor the camera to the main mechanical frame (left). The PMC/Lens while being mounted on the internal mechanical frame (centre and right).

5.2.4. PMC Optical Seal

In order to avoid mechanical damages and to screen the camera from stray light rays an optical seal made of balck foam is sandwiched between the end of the PMC lens and the Optical Window as shown in Figure 18.

Figure 18. The PMC optical seal (left) and the Optical windows with the optical seals and devices below (right).

5.3. Sky Quality Meter

The Sky Quality Monitor, based on the *Unihedron* SQL-LE device (http://unihedron.com/projects/sqm-le/), is shown in Figure 16.

Figure 17. The SQM measuring device (Unihedron SQL-LE)

The SQM is powered with the 5V input provided by the general electrical interface discussed above.

The SQM is connected to an external ethernet switch, the SQM data acquisition and processing is outside the scope of this document.

5.3.1. SQM Mechanical support

The SQM is held in position close to the optical window with two metal bands screwed onto the main mechanical frame as shown in Figure 18.

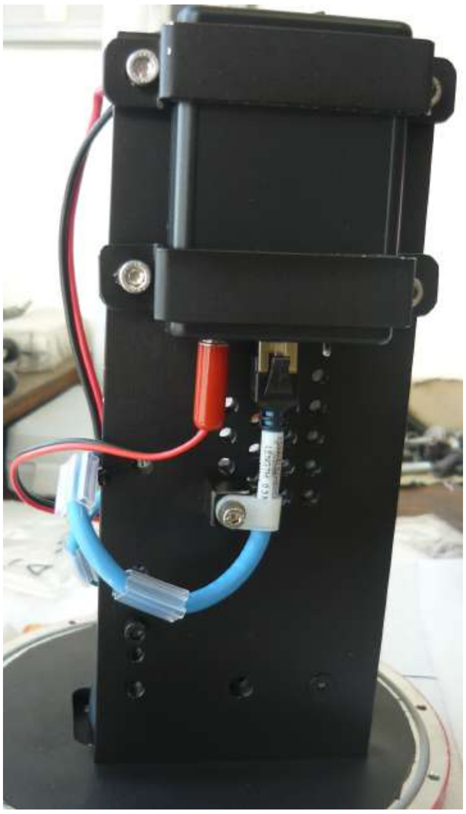


Figure 18. The SQM anchoring on the main mechanical frame.

5.3.2. SQM optical seal

The SQM sensor is coupled to the Optical Window through an optical seal similar to the PMC one. Both optical seals are shown in Figure 19.

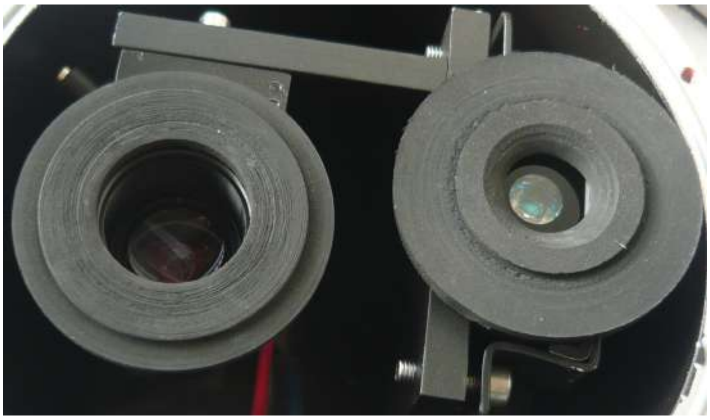


Figure 19. The PMC and SQM optical seals.

5.4. Local Control PC

The Local Control PC shall be placed inside the telescope service cabinet and shall run a Linux based operating system (Ubuntu) to receive the input commands and information, to acquire data from the PMC, to perform the astrometry and to return the requested output.

The chosen PC is **SHC / Comitec** (see Figure 20) with the following main characteristics:

- PC SHC FANLESS J1900 2.0GHZ
- RAM 4GB
- SSD120GB
- 4*GBLAN (INTEL I211AT)
- 4*USB
- VGA 1Y

Table 7 lists the technical details for the chosen Local Control PC.

Figure 20 : The PMC Local Control PC: SHC J1900 form Comitec

Table 7. Details of the characteristics of the PMC Local Control PC, SHC J1900 form Comitec.

Temperature	-10/+70
Chassis	Aluminum alloy
CPU	Intel Celeron Processor J1900 (Quad-Core 2M Cache, 2 GHz, up to 2.42 GHz)
RAM	4GB DDR3 1600MHz SODIMM 1.20V (1*4GB)
SSD	120GB 2.5" SATA3 6GB/S
GPU	Intel HD Graphics
Network card	4*GBlan NICs 10/100/1000 Intel Controller I211AT
Mount	VESA:100 x 100 mm
Power	External 10W 12V
USB 3.0	1
USB 2.0	2
VGA	1
RJ45	4
Dimensions	128 x 156 x 47 mm3
Mass	1.15 kg

5.4.1. PC Boot

The Local Control PC BIOS is configured to automatically boot as soon as the power is restored or available.

5.4.2. Local Control PC Connections

The Local Control PC is equipped with 4 1Gb ethernet ports with Rj45 connectors numbered from 1 to 4.
In the baseline design, as shown in Figure 21, only two ports will be used:

- The ethernet port N. 1 shall be connected to the ethernet switch to communicate with other Telescope subsystems;
- The port N. 2 shall be directly connected to the camera which will be isolated from the rest of the network and it will be only reachable through the Local Control PC.

The Local Control PC is configured to act as a DHCP server which will assign an IP to any device connected to the port N. 4. The default IP settings are listed in Table 8.

Table 8. Default PMC internal LAN IPs according to the DHCP server configuration.

Device	IP
LC PC port 4	192.168.11.1
Camera	192.168.11.10

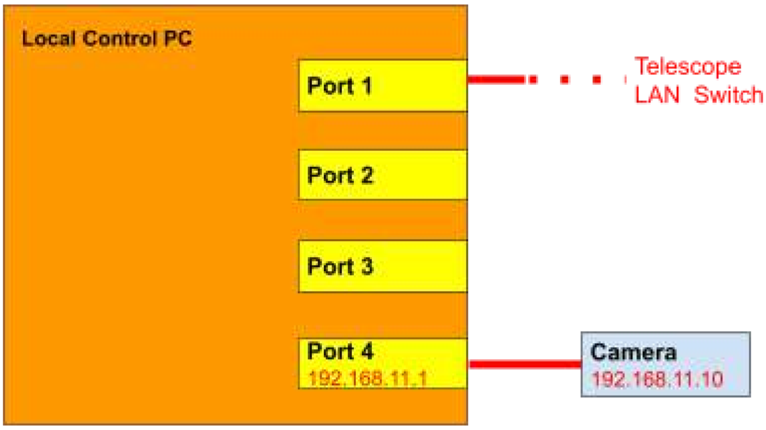


Figure 21. Schematics of the PMC system ethernet connections.

5.5. PMC Local Control Software

The functional diagram of the PMC software is sketched in Figure 21. The main software components are:

- OPC-UA Server;
- PMC Server;
- Astrometry.

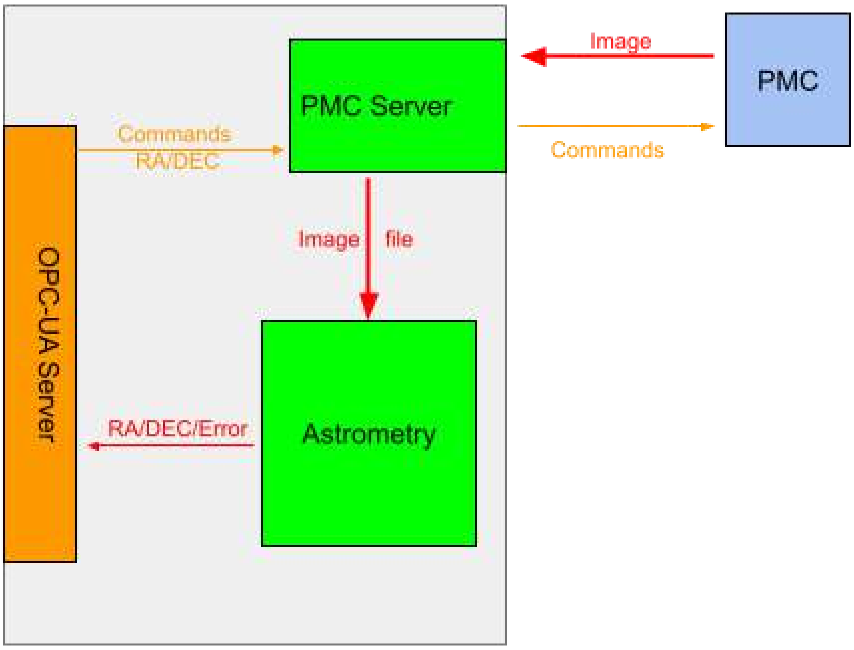


Figure 22. Functional diagram of the PMC Local Control Software.

5.5.1. OPC-UA Server

The OPC UA-Server is the Local Control Software interface with the external systems, it receives commands and the Telescope RA/DEC pointing information from the TCS and it propagates them to the PMC Server. The OPC UA-Server can configure, reset and restart the PMC Server. The OPC UA-Server also retrieves the Astrometry results and propagates them to the TCS.

The OPC UA-Server is Java based and it is built on top of the prosys-opc libraries[1].

5.5.2. PMC Server

The PMC Server is the part of the server that directly interacts with the camera device, it controls the hardware and acquires images. The PMC Server implements an internal Finite State Machine (FSM). The PMC Server and the OPC UA-Server are launched at boot and they interact with each other via a socket based communication to exchange commands, data and FSM state information.

The FSM diagram is presented in Figure 22.

[1] https://prosysopc.com

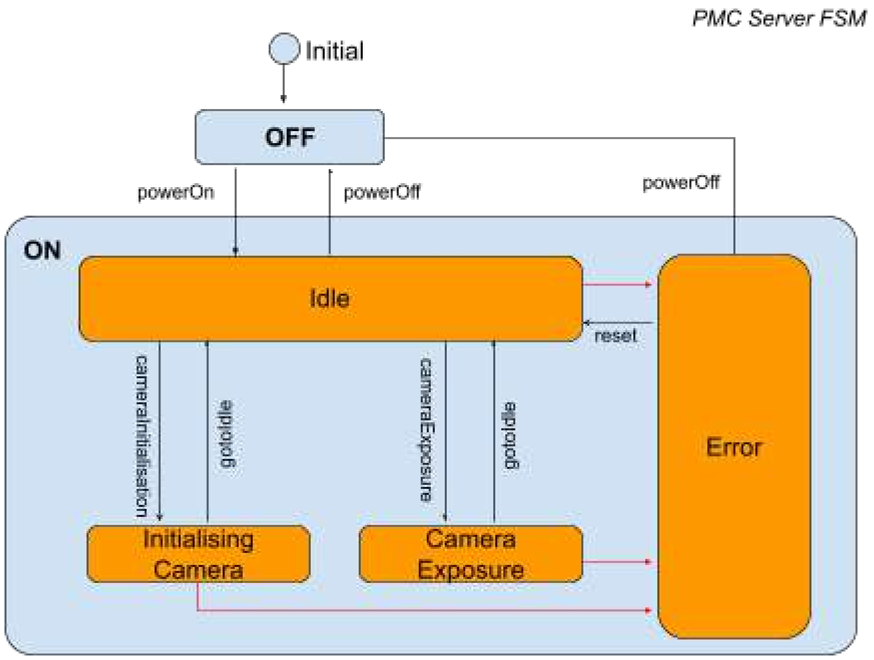


Figure 22. The PMC Server Finite State Machine diagram.

The acquired image is saved as a FITS file with the following information stored in the header (Table 8):

Table 8. Metadata stored in the header of the FITS file produced by the PMC Server.

Keyword	Description
DATE-OBS	Exposure Start Date and Time (UTC).
DATE-END	Exposure End Date and Time (UTC).
DATE	File Creation Date and Time (UTC).
EXPOSURE	Total Exposure Time (us)
RA0	Commanded Telescope RA (degree)
DEC0	Commanded Telescope DEC (degree)

The PMC Server is a C++ based software which uses the Spinnaker SDK[2] API libraries to interact with FLIR Camera.

5.5.3. Astrometry

The Astrometry process is based on the Astrometry.net[3] package

The Astrometry, is a standalone, C based, executable which is ran by the OPC-UA Server, it reads the image file acquired by the PMC Server and performs an astrometric analysis to measure the RA and DEC coordinates of the field centre and the corresponding error with respect to the expected telescope pointing direction. The results are stored in the image fits file header and in a *txt* Astrometry file for the OPC UA-Server consumption.

Table 9. Metadata stored in the header of the FITS file after the Astrometry update.

Keyword	Description
DATE-OBS	Exposure Start Date and Time (UTC).
DATE-END	Exposure End Date and Time (UTC).
DATE	File Creation Date and Time (UTC).
EXPOSURE	Total Exposure Time (us)
RA0	Commanded Telescope RA (degree)
DEC0	Commanded Telescope DEC (degree)
RA	Astrometry RA
DEC	Astrometry DEC

[2] https://www.flir.eu/products/spinnaker-sdk/
[3] http://astrometry.net/doc/index.html

Table 10. Information stored in the Astrometry output file.

Vale Description
Astrometry Success Status OK (0/1)
Astrometry RA
Astrometry DEC
Astrometry Azimuth
Astrometry Elevation
RA Error
DEC Error
Azimuth Error
Elevation Error

5.5.4. System Startup and Configuration

The operations automatically performed at boot are:

- DHCP Server service start (from standard DHCP configuration);
- PMC Server start from a script executed through crontab configuration;
- OPC-UA Server start from a script executed through crontab configuration.

5.5.5. Astrometric Measurement Process

The logical processing steps of the PMC Local Control Software and its interaction with the TCS for the basic astrometric measurement are sketched in Figure 23 and explained in Table 11.

Table 11. Description of the logical processing steps of the PMC basic astrometric measurement.

Step N.	Step Description	Communication
1	The TCS through an *OPC-UA Client* sends a *Measurement Request* and the commanded *Telescope RA/DEC* to the *PMC OPC-UA Server*	TCP/IP

2	The *PMC OPC-UA Server* propagates the *Measurement Request* and the commanded *Telescope RA/DEC* to the *PMC Server*	socket
3	The *PMC Server* state is set to *Camera Exposure* (the *PMC OPC-UA Server* regularly monitors the *PMC Server* state)	internal-socket
4	The *PMC Server* sends the *Image Acquisition* command to the *Camera*	TCP/IP
5	The *PMC Server* retrieves the *Image Data* from the *Camera*	TCP/IP
6	The *PMC Server* saves the *Image Data* into a *FITS Image File* on disk with a unique name (and optionally a jpg file).	
7	The *PMC Server* state is set to *Idle*, the *PMC OPC-UA Server* regularly monitors the *PMC Server* state and detects the change.	internal-TCP/IP
8	The *PMC Server* runs the script executing the *Astrometry* (passing the input FITS file information)	
9	The *Astrometry* process reads the *FITS Image File*, it also retrieves the commanded Telescope RA/DEC from the header.	
10	The *Astrometry* computes the *Field RA/DEC*.	
11	The *Astrometry* saves the *Field RA/DEC* and the measured *Error* on the commanded Telescope *RA/DEC* into a txt Astrometry File with a unique name based on the input FITS file name. The *Astrometry* also updates the header of the *FITS Image File* with the *Field RA/DEC* and the *Telescope RA/DEC Error*.	
12	The *PMC OPC-UA Server* detects the presence of a new *Astrometry* file and reads its content.	
13	The *PMC OPC-UA Server* sends the Astrometry results information to the TCS *OPC-UA Client.*	TCP/IP

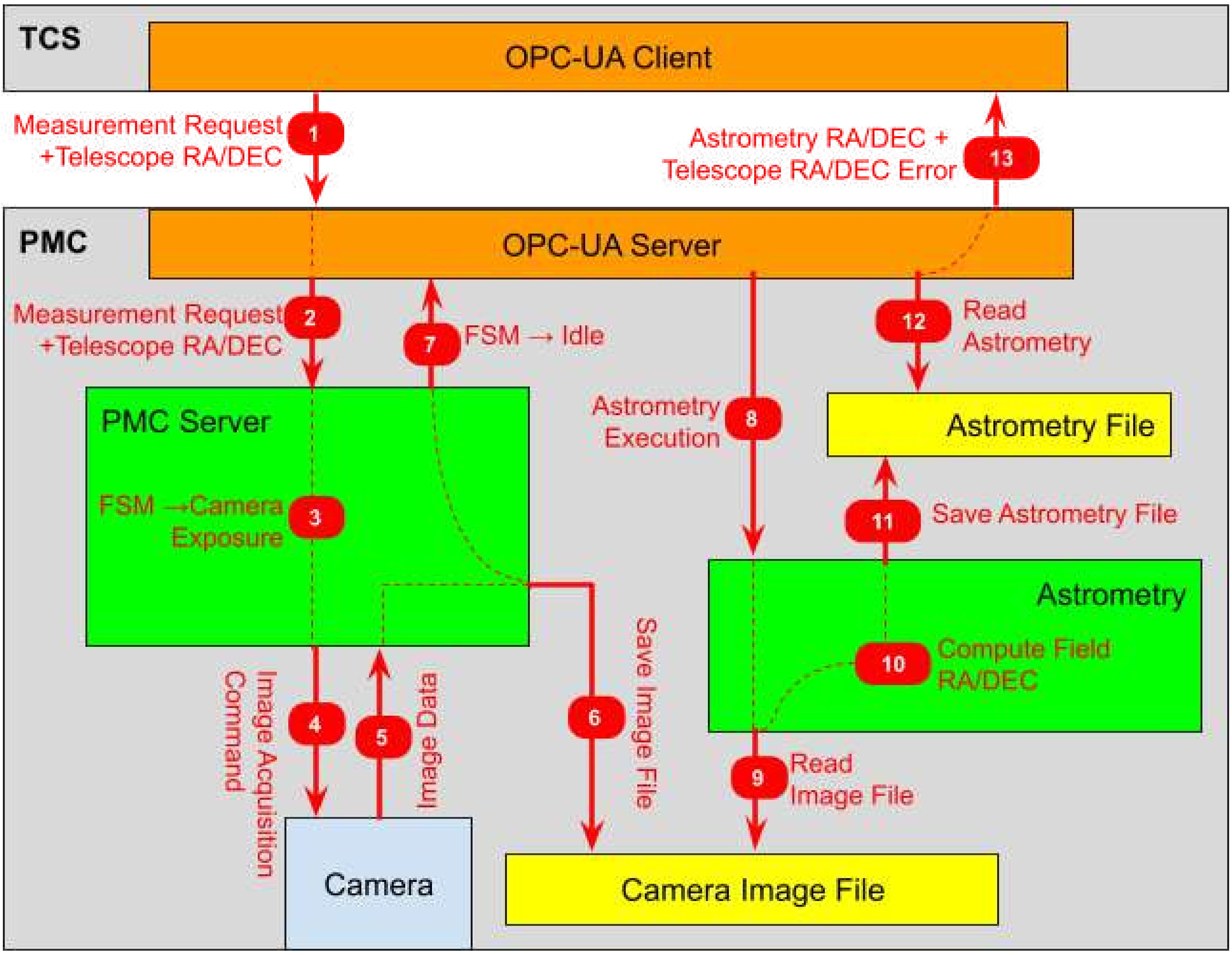


Figure 23. Logical processing steps of the PMC basic astrometric measurement.

5.5.6. Engineering GUI

An Engineering Graphical User Interface (GUI) will be available for the PMC system to be used during Factory Acceptance Tests, AIV and Commissioning and Maintenance.

The Engineering GUI will allow users to interact with one or all the PMC systems through their OPC-UA Server. Through the PMCGUI interface is possible to test all functionalities of the PMC availables at OPC-UA level. Also it provides a set of tools useful during the commissioning of the telescopes.

An example of the GUI appearance is shown in Figure 24.

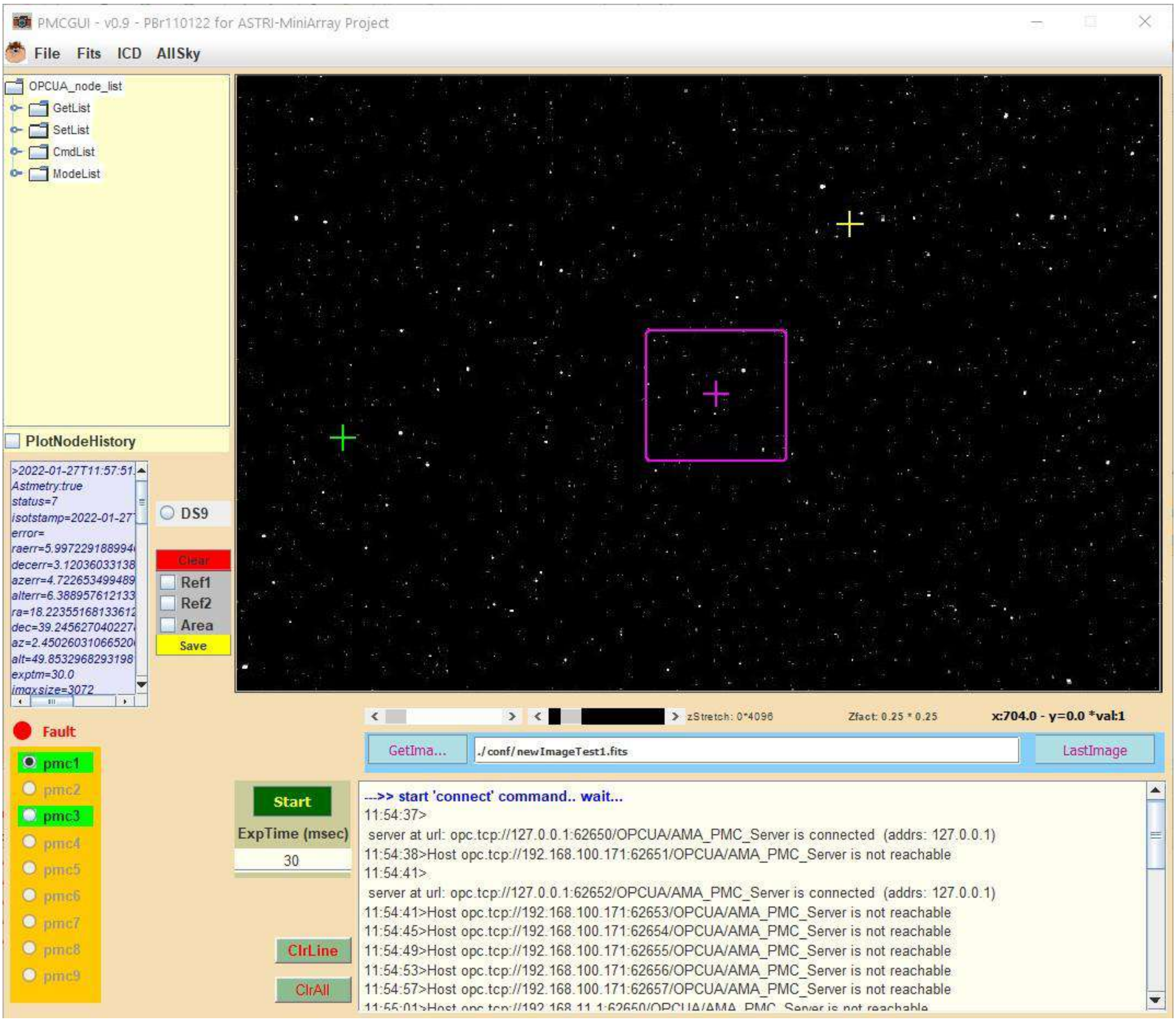


Figure 24. The PMC Engineering GUI.

6. Astrometry Test

In order to demonstrate that the Lens and Camera changes in the PMC design will not have a negative impact on the Astrometric measurements a test has been performed on images acquired with one of the production *FLIR* cameras (BFS-PGE-63S4M-C) and the corresponding *Computar* (M7528-MPW3) lens.

The tests have been performed installing a set of PMC Camera+Lens on the structure of the 80 cm Telescope at the Observatory of Coloti (Figure 25) which has been used for the pointing and the sky position tracking during the acquisition of the PMC camera images used for the Astrometry test.

Figure 25. The Telescope at the Observatory of Coloti (Montone, PG) with the PMC Camera and Lens mounted on the structure. The red box highlights the PMC components position.

Figure 26 shows an image acquired with 20 s exposure after the lens focus has been optimised.
Figures 27 and 28 show the recognised stars in the image and the Astrometry.net log file respectively.

As it can be seen from the log file (Figure 28) the RA and DEC coordinates of the field centre has been measured and the field size has been recognised to be 5.60 x 3.74 degrees, corresponding to a pixel scale of approximately 6.6 arcsec/pixel which is compatible with the expectations and it can be compared with the 7.3 arcsec/pixel of the ASTRI-Horn prototype.

*Figure 26. Example of a 10 s exposure image taken with the FLIR (*BFS-PGE-63S4M-C*) camera and the Computar (M7528-MPW3) lens.*

*Figure 27. Sources recognised in a 10 s exposure image taken with the FLIR (*BFS-PGE-63S4M-C*) camera and the Computar (M7528-MPW3) lens.*

```
Reading input file 1 of 1: "/home/astri/coloti/images/pmc/testAcquisition-Exposure-20000000us-21225965-2021-07-28T21-02-35.jpg"...
Extracting sources...
Downsampling by 2...
simplexy: found 4007 sources.
Solving...
Reading file "/home/astri/coloti/images/pmc/testAcquisition-Exposure-20000000us-21225965-2021-07-28T21-02-35.axy"...
mo field stars:
  star 1; field_xy 2105.0,727.3, field_orig 2105.0,727.3
  star 5; field_xy 2699.6,1420.9, field_orig 2699.6,1420.9
  star 0; field_xy 2170.4,1042.2, field_orig 2170.4,1042.2
  log-odds ratio 638.752 (2.54962e+277), 94 match, 0 conflict, 97 distractors, 99 index.
  RA,Dec = (283.631,32.0046), pixel scale 6.57163 arcsec/pix.
  Hit/miss:   Hit/miss: ++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++-+-+--+++--++++-++++-+-+--++++-++----+-
Field 1: solved with index index-4111.fits.
Field 1 solved: writing to file /home/astri/coloti/images/pmc/testAcquisition-Exposure-20000000us-21225965-2021-07-28T21-02-35.solved to indicate this.
Field: /home/astri/coloti/images/pmc/testAcquisition-Exposure-20000000us-21225965-2021-07-28T21-02-35.jpg
Field center: (RA,Dec) = (283.629936, 32.005469) deg.
Field center: (RA H:M:S, Dec D:M:S) = (18:54:31.185, +32:00:19.689).
Field size: 5.6039 x 3.73983 degrees
Field rotation angle: up is -34.1078 degrees E of N
Field parity: neg
Creating new FITS file "/home/astri/coloti/images/pmc/testAcquisition-Exposure-20000000us-21225965-2021-07-28T21-02-35.new"...
Creating index object overlay plot...
Creating annotation plot...
Your field contains:
  Part of the constellation Lyra (Lyr)
  The star ν1Lyr
  The star ν2Lyr
  The star Sheliak (βLyr)
  The star Sulafat (γLyr)
  The star λLyr
  The star 17Lyr
```

*Figure 28. Example of the Asstrometry.net log file generated processing a 10 s exposure image taken with the FLIR (*BFS-PGE-63S4M-C*) camera and the Computar (M7528-MPW3) lens.*

7. Appendix A - Optics and Camera design updates with respect to the prototype

1. ASTRI-Horn Lens

The PMC for the ASTRI-Horn prototype mounts a Computar E5Z2518C-MP Lens

- https://computar.com/resources/files_v2/800/E5Z2518C-MP_spec_sheet.pdf
- https://computar.com/product/1115/E5Z2518C-MP

whose mechanical dimensions and technical characteristics are shown in Figure 29 and Table 12 respectively.

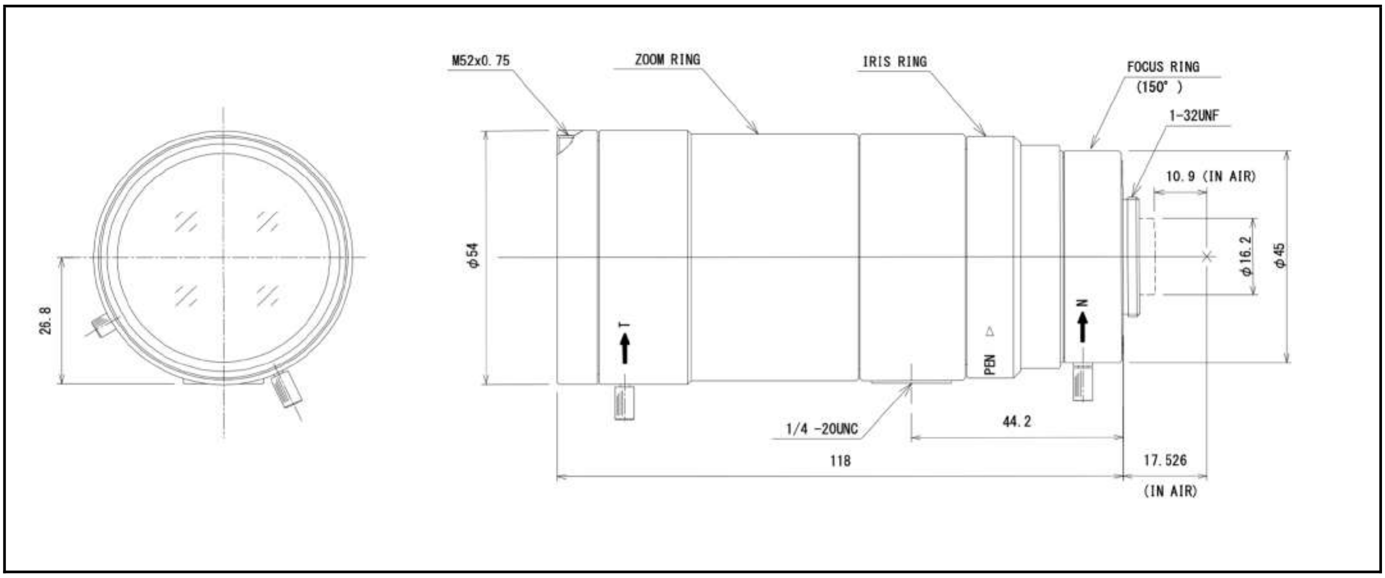


Figure 29. Mechanical dimensions of the Computar E5Z2518C-MP for the ASTRI-Horn PMC.

Table 12: Technical specifications of the Computar E5Z2518C-MP for the ASTRI-Horn PMC.

E5Z2518C-MP

5X 25mm-135mm F1.8
for 1/1.8 type Megapixel Cameras, Vari-focal Manual Iris
C-Mount

Model No.		E5Z2518C-MP		Effective Lens Aperture	Front	φ44.5mm	
Focal Length		25mm - 135mm			Rear	φ12.2mm	
Max. Aperture Ratio		1:1.8		Back Focal Length	Tele	12.0mm	
Max. Image Format		5.3mm x 7.1mm(φ8.9mm)			Wide	16.4mm	
Operation Range	Iris	F1.8 - F16C		Flange Back Length		17.526mm	
	Focus	1.5m - Inf.		Mount		C-Mount	
	Zoom	25mm - 135mm		Tripod Screw		1/4 -20UNC	
Control	Iris	Manual		Filter Size		M52 x 0.75	
	Focus	Manual		Dimensions		φ54 x 118	
	Zoom	Manual		Weight		411 g	
Angle of View	D	1/1.8 type	20.7° - 3.9°	1/2 type	18.4° - 3.5°	1/3 type	13.6° - 2.6°
	H		16.2° - 3.1°		14.5° - 2.8°		10.8° - 2.1°
	V		12.0° - 2.4°		10.8° - 2.1°		8.1° - 1.6°
Operating Temperature		−10℃ - +50℃					

2. Alternative Lenses

No Lens was available with the same optical characteristics among the production catalogue choices which would fit inside the mechanical constraints imposed by the PMM cylindrical container (Figure 3) the two available options where:

- Computar M7528-MPW3 (the chosen options)
- Computar M6Z1212-3S
    - https://computar.com/resources/files_v2/599/M6Z1212-3S_Spec1207.pdf
    - https://computar.com/product/712/M6Z1212-3S

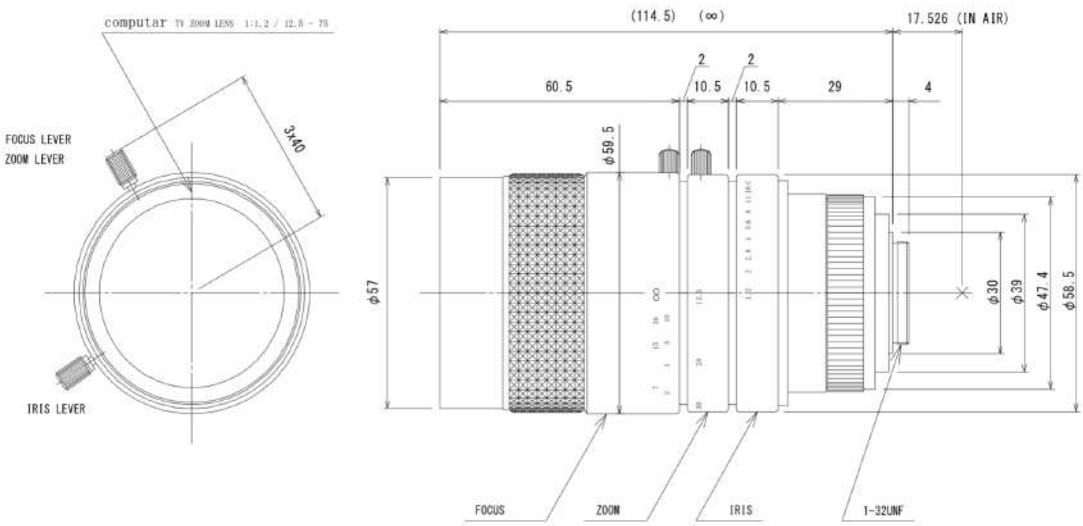


Figure 30. Mechanical dimensions of the Computar M6Z1212-3S.

Table 13. Technical specifications of the Computar M6Z1212-3S.

M6Z1212-3S

6X 12.5mm-75mm F1.2
for 2/3type Cameras,Manual Zoom
C-Mount

Model No.		M6Z1212-3S		Effective Lens Aperture	Front	ϕ46.5mm	
Focal Length		12.5mm - 75mm			Rear	ϕ15.6mm	
Max.Aperture Ratio		1:1.2		Back Focal Length		15.4mm	
Max.Image Format		8.8mm x 6.6mm(ϕ11mm)		Flange Back Length		17.526mm	
Operation Range	Iris	F1.2 - F16C		Mount		C-Mount	
	Focus	1m - Inf.		Filter Size		M55 P=0.75mm	
	Zoom	12.5mm - 75mm		Dimensions		ϕ59.5mm x 114.5mm	
Control	Iris	Manual		Weight		483g	
	Focus	Manual					
	Zoom	Manual					
Angle of View	D	2/3type	46.9° - 8.3°	1/2type	35.1° - 6.2°	1/3type	26.6° - 4.7°
	H		38.3° - 6.7°		28.3° - 5.0°		21.3° - 3.8°
	V		29.2° - 5.1°		21.3° - 3.8		16.1° - 2.8
Operating Temperature		-20℃ - +50℃					

A summary of the most relevant parameters is shown in Table 14.

Table 14. Comparison of the relevant parameters for the different Lens options.
The exposure time for ASTRI-MA is extrapolated.

Model	Application	Focal Length	fstop	Field of view	Aperture	Area	Exposure Time
E5Z2518C-MP	ASTRI-Horn	135 mm	F1.8	3.1x2.4 deg	44.5 mm	15.5 cm2	3 s
M7528-MPW3	ASTRI-MA	75 mm	F2.8	5.5x4.1 deg	26.1 mm	5.3 cm2	10 s
M6Z1212-3S	ASTRI-MA (*excluded option)*	75 mm	F1.2	6.7x5.1 deg	46.5 mm	17 cm2	3 s

All the available options have a 75 mm focal length instead of the 135 mm for the ASTRI-Horn prototype. The fixed focal length option has a smaller aperture potentially leading to a longer exposure time.

3. Camera Update

The camera used for the ASTRI-Horn prototype is the:
FLIR Flea3 GigE (FL3-GE-28S4M-C: 2.8 MP, 15 FPS, Sony ICX687, Mono)
https://www.flir.it/products/flea3-gige/?model=FL3-GE-28S4M-C
which mounts a CCD sensor.

CCD sensors have been discontinued and have been replaced by CMOS.
Due to the change in the lens and it's image size the new camera model features a smaller pixel size.

The chosen model for the ASTRI Mini Array PMC is the:
FLIR Blackfly S GigE (BFS-PGE-63S4M-C: 6.3 MP, 19 FPS, Sony IMX178, Mono)
https://www.flir.it/products/blackfly-s-gige/?model=BFS-PGE-63S4M-C

The main technical characteristics of the two camera models are listed in Table NN while details related to the camera-lens combination are listed in Table MM

Table 15. Comparison between the PMC cameras for the ASTRI-Horn and ASTRI-MA.

Model	**FL3-GE-28S4M-C** (ASTRI-Horn)	**BFS-PGE-63S4M-C** (ASTRI-MA)
Sensor Format	1/1.8”	1/1.8”
Pixel Size	3.69 µm	2.4 µm
Megapixels	2.8	6.3
Resolution	1928 × 1448	3072 × 2048
Quantum Efficiency	79 (% at 525 nm)	77.07 (530nm)

Table 16. Comparison of the angular pixel size for the three different options of camera-lens combination.

Model	Application	Image Size (experimental)	Image Size (1/f)	Image Size (AoV/Pixels)
E5Z2518C-MP	ASTRI-Horn	7.25” / pixel	12.1”/pixel	5.8 “ / pixel
M7528-MPW3	ASTRI-MA	6.6” / pixel	13.2”/pixel	6.4” / pixel
M6Z1212-3S	ASTRI-MA (*excluded option)*		7.3”/pixel	7.8” /pixel