Programme: **ELT**

Project: **ELT MCAO Construction – MORFEO**

LGSO Technical Specifications

Document Number: E-MAO-PF0-INA-SPE-003

Document Version: 01

Document Type: Specification (SPE)

Released On: 2026-03-18

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Change Record from previous version

Date	Affected Section(s)	Changes / Reason / Remarks
2025-07-08	full	first draft
2025-08-08	full	All req IDs have been assigned
2025-10-03	full	Release for CfTRR review
2026-03-18	Full	Issue for cft

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1 Related Documents

1.1 Applicable Documents

MAO-PFH-1.6 Applicable documents

The following documents, of the exact version shown, form part of this document to the extent specified herein. In the event of conflict between the documents referenced herein and the content of this document, the content of this document shall be considered as superseding the others.

AD1 MORFEO Optics Common Requirements E-MAO-SF0-INA-SPE-004

AD2 E-MAO-PH0-INA-LIS-008 List of electrical cables between PFH and PH0 issue 1d2

AD3 ESO-193497 SAF-GEN-MAN-3444 ESO Safety Conformity Assessment Procedure, issue 5

AD4 ESO-192984 ESO Mechanical Standards, issue 2

AD5 ESO-191462 ESO Engineering Analysis Standard, issue 2

AD6 E-MAO-000-INA-SOW-006 MORFEO LGS Objective SOW, issue 1

AD7 E-MAO-000-INA-PLA-003 MAORY Product and Quality Assurance Plan, issue 3

AD8 E-MAO-PFH-ICD-DWG LGSO interface drawing, issue 3

1.2 Reference Documents

RD1 E-MAO-SF0-INA-MOD-002_02 OFDR MORFEO Zemax Model.zos

RD2 General Definitions and Basic Conventions Related to Interfaces ESO-193459 Version 2

2 Introduction

2.1 Scope

MORFEO (formerly known as MAORY) is the Adaptive Optics Module for ELT.

This document contains requirements and specifications for the LGSO subsystem.

This document contains two types of items: requirements and information. Requirements must be verified by the Vendor, whereas information items do not require verification. Both types are binding.

2.2 Naming Convention

Requirements are identified with a requirement tag following the format [MAO-PFH-XXX], where XXX is a unique, non-speaking number.

Section 7 specifies, for each requirement, the minimum verification method to be applied during the main project phases.

2.3 Abbreviations and Acronyms

AD	Applicable Document
AO	Adaptive Optics
AoI	Angle of Incidence
ARR	Acceptance Readiness Review
CNRS	Centre National de la Recherche Scientifique
CII	Core Integration Infrastructure
DER	Design Report
ELT	European Extremely Large Telescope
ESO	European Southern Observatory
FDR	Final Design Review
FoV	Field of View
HW	Hardware
IAA	Instrument Assembly Area
ICD	Interface Control Document
ICH	Instrument Control Hardware
ICSS	Instrument Control System Software
I-PXX/PFH	Interface between PXX subsystem and DMs subsystem
INAF	Istituto Nazionale di AstroFisica
INS	Instrumentation Software
INSU	Institut National des Sciences de l'Univers
IWS	Instrument Workstation
IORR	Instrument Operations Readiness Review
IPAG	Institut de Planétologie et d'Astrophysique de Grenoble
IRD	Interface Requirement Document

LCI	Local Communication Infrastructure
LCS	Local Coordinate System
LGS	Laser Guide Stars
LGSO	Laser Guide Stars Objective
LOR	Low Order and Reference
MAIT	Manufacturing Assembly Integration and Test
MORFEO	Multi conjugate adaptive Optics Relay For ELT Observatory
MCAO	Multi Conjugate Adaptive Optics
MCMT	Maximum Corrective Maintenance Time
MICADO	Multi-AO Imaging Camera for Deep Observations
MDT	Mean Down Time
MOI	Moment of Inertia
MTBF	Mean Time Between Failures
N/A	Not Applicable
NGS	Natural Guide Star
NP	Nasmyth Platform
NUIG	School of Physics at the National University of Ireland Galway
OAA	Osservatorio Astrofisico di Arcetri
OAAB	Osservatorio Astronomico d' Abruzzo
OAB	Osservatorio Astronomico di Brera
OACN	Osservatorio Astronomico di Capodimonte
OAPD	Osservatorio Astronomico di Padova
OAS	Osservatorio di Astrofisica e Scienza dello Spazio di Bologna
PAC	Preliminary Acceptance Review in Chile
PAE	Preliminary Acceptance Europe
PDR	Preliminary Design Review
PLC	Program Logic Controller
PFS	Primary Focal Station
PFH	MORFEO LGSO subsystem
PH0	MORFEO Instrument control Electronics Subsystem
PI	Principal Investigator
PM	Project Manager
PM0	MORFEO Main Support Structure Subsystem
PSF	Point Spread Function
PT	Product Tree
PR0	MORFEO RTC subsystem
PSO	MORFEO Software subsystem
PT0	MORFEO Thermal control subsystem
RAMS	Reliability, Availability, Maintainability and Safety
RBM	Rigid Body Motion
RD	Reference Document
RMS	Root Mean Square
RON	Read Out Noise
RTC	Real-Time Computer
SAT	System Architect Team
SCAO	Single-conjugate Adaptive Optics
SCS	Standard Coordinates System
SE	System Engineer
SET	System Engineering Team
SOW	Statement of Work
SMR	Spherical Mounted retroreflector
SMU	Sensor Monitor Unit
SR	Strehl Ratio

SRR	System Requirements Review
SRS	Standard Reference System
SW	Software
TBC	To Be Confirmed
TBD	To Be Defined
TBW	To Be Written
TP	Temperature Probe
WFS	Wavefront Sensor
WP	Work Package
WS	Workstation

2.4 Definitions

MAO-PFH-1.2.3.4: Definition of LGSO Subsystem *[info]*

LGSO subsystem is the Laser Guide Stars Objective, composed by four lenses and one flat mirror assembly, interfaced with the MORFEO MPO after the dichroic and a flat mirror and contains:

- LGSO Assembly
  - Optical elements (lenses and mirror)
  - Holders (mounting cells and assembly structure)
  - Kinematic Mount (delivered by the consortium)
  - Covers
- LGSO Unpacking handling and shipping tools
- LGSO Cleaning tools
- LGSO Test Equipment
- LGSO Dummy
- Spares

MAO-PFH-1.4.6: Definition of Handling *[info]*

Handling - It covers the handling of the LGSO during packing, assembling, testing and maintenance.

MAO-PFH-1.4.7: Definition of Accessibility *[info]*

Accessibility - It covers the access to the LGSO, including inside the main structure when necessary, for maintenance both at telescope and in the lab. It also covers all the auxiliary equipment providing access to the unit.

MAO-PFH-1.2.3.9: Definition of as built value *[info]*

In this document we refer to as-built value as the measured design value.

2.5 Coordinate System

The MORFEO coordinate system is centred in the E-ELT Focus B1 focal plane and has the same orientation of E-ELT Standard Coordinate System (SCS, see Table 1). The gravity orientation is parallel to the Z axis with opposite verse.

	X [mm]	Y [mm]	Z [mm]	α [deg]	β [deg]	γ [deg]
MORFEO SCS	27200	0	0	0	0	180

Table 1: Location of MORFEO SCS

The Local Coordinate System (LCS) of LGSO is referenced to the MORFEO SCS as defined in **MAO-PFH-1.2.3.1**.

MAO-PFH-1.2.3.1: Local Coordinate System LGSO
The LGSO LCS, expressed in the MORFEO SCS, shall be used for all deliverable drawings and 3D CAD models.

LGSO LCS is defined as follows:

- Origin: vertex of the first optical surface (lens or mirror) of the LGSO (where first means first to be met by light arriving from MPO)
- Z axis: along first element rotational axis , direction opposite to the light direction
- Y axis: parallel to gravity direction
- X axis: completing the right-handed triplet

The LGSO LCS (Figure 1) is obtained from the MORFEO SCS applying the translations in the table below and then the rotations of -180.000 deg around X, 57.700 deg around Y, and 90.000 deg around Z.

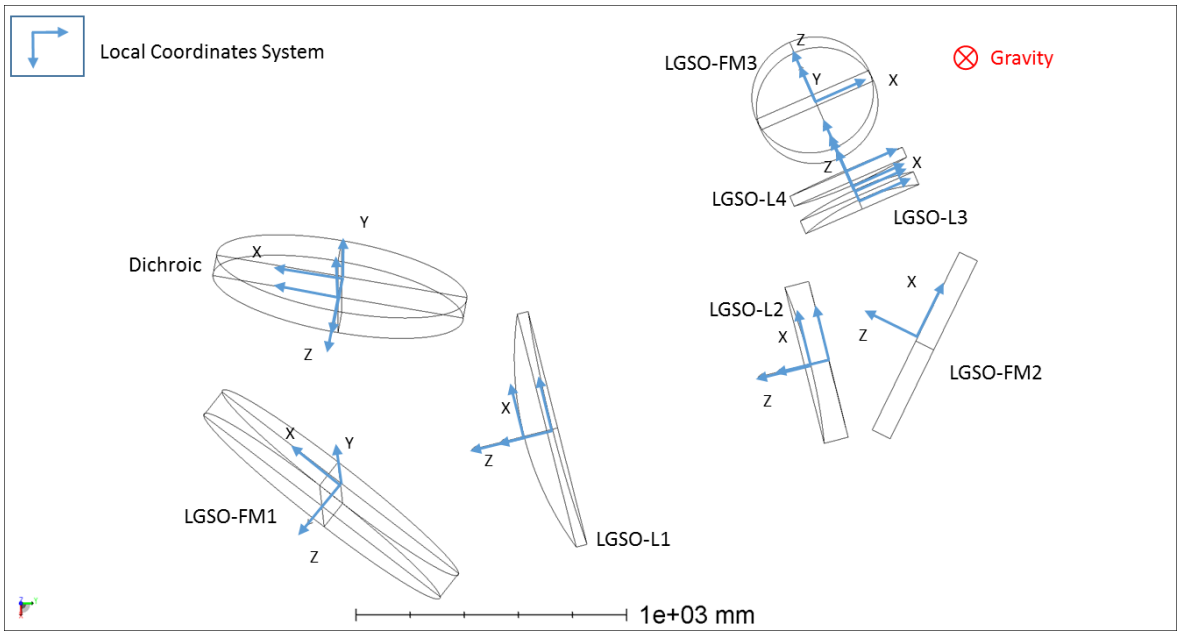


Figure 1: LGSO LCS

The three components of a vector expressed in the LGSO LCS can be represented in the MORFEO SCS applying the following roto-translation matrix to the vector (translations in [mm]):

Rotation			Translation
-0.969416411	0.000000000	0.245421722	-664.93
-0.245421722	0.000000000	-0.969416411	2345.96
0.000000000	-1.000000000	0.00000000	3751.56

3 Product Description

3.1 MORFEO overview

ELT (Extremely Large Telescope) is the world's largest telescope (39m diameter) under construction by ESO (https://elt.eso.org/) at Cerro Armazones in Chile. ELT is considered worldwide to be one of the highest priorities in ground based astronomy. MORFEO (http://wwwMORFEO.oabo.inaf.it/), as a first generation ELT instrument, will help compensate for the distortion of light caused by turbulence in the Earth's atmosphere. MORFEO is a Multi-Conjugate Adaptive Optics (MCAO) module that will allow spatially uniform adaptive optics compensation over a large field of view (about 1 arcmin^2) with high sky coverage. Wavefront sensing is performed by six Laser Guide Stars (LGS) and three Natural Guide Stars (NGS), for the measurement of high and low-order wavefront perturbations respectively.
The Post-Focal Relay Optics sub-system of MORFEO re-images the telescope focal plane to the exit ports (Figure 2 and Figure 3).

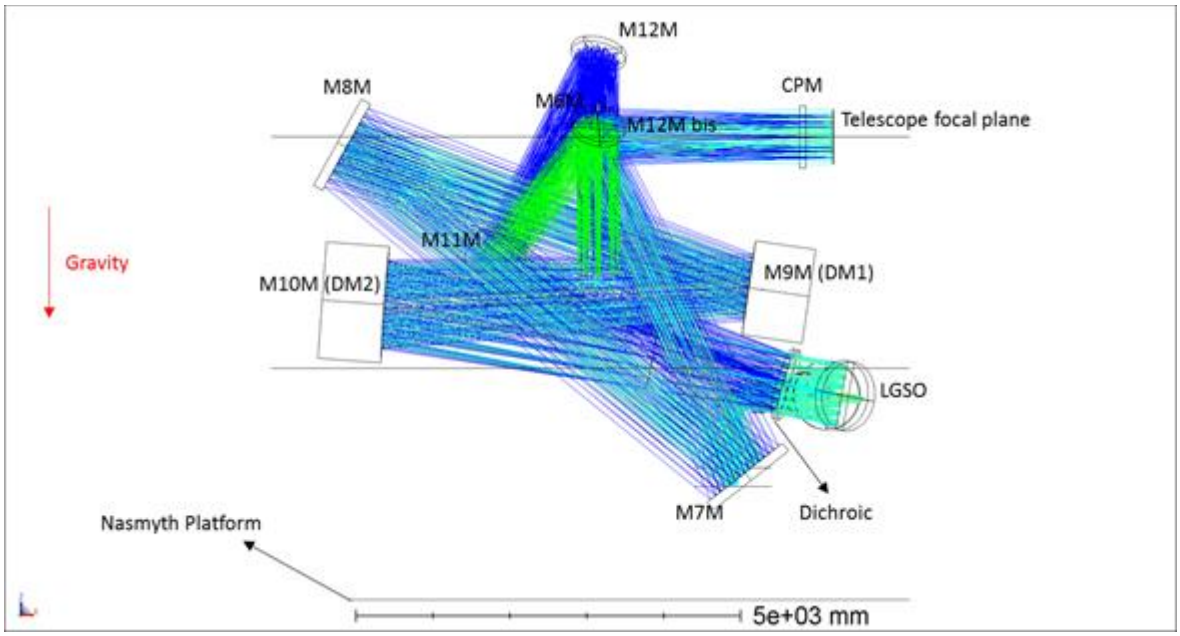


Figure 2: MORFEO optical design (side view)

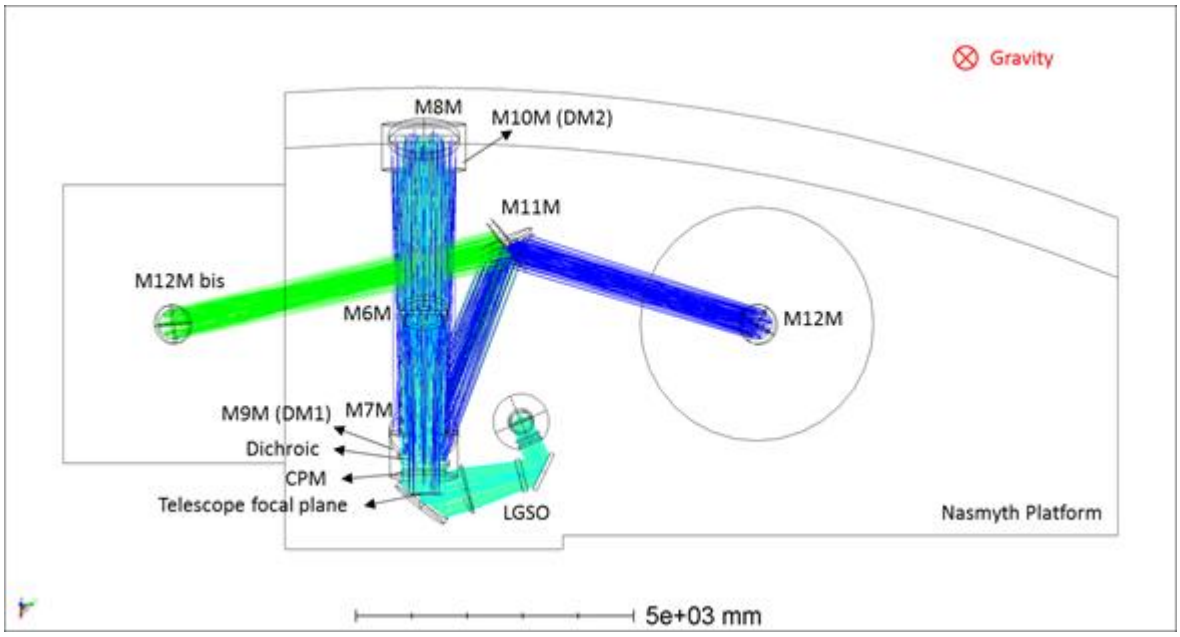


Figure 3: MORFEO optical design (top view)

The sub-system contains the following channels:

- Main Path Optics, which relay the telescope focal plane to the exit ports for the science instruments (MICADO and 2nd instrument);
- LGS Objective, which creates an image plane for the laser guide stars, used by the LGS WFS sub-system to measure in real-time the high-order wavefront aberrations for the MCAO mode of MORFEO.

The F/17.75 beam arriving from the ELT focal surface first passes through the CPM, a window that thermally separates the external and internal environments. The second surface of the CPM is aspherical, improving the optical quality for multiple object conjugation. Following the optical path, the beam encounters the first flat mirror, M6M, which folds it downward onto the first aspherical concave mirror, M7M. The beam is then reflected upward to the second aspherical concave mirror, M8M, and subsequently directed downward to the first deformable mirror (DM), M9M. This mirror has a spherical convex surface (conjugated to the meta-pupil at 17.5 km) and is the only convex surface along the main optical path. Next, the beam reflects off the second DM, M10M, which is spherical and concave, conjugated to the meta-pupil at 6.5 km. All optical surfaces downstream of M10M are flat. M10M is mounted on a hexapod and will be used to compensate for system misalignments such as defocus and astigmatism. After M10M, the pupil image is formed. Immediately beyond this point, the light is split into science/NGS and LGS paths by a dichroic filter (DICHROIC). The LGS light (589 nm) is transmitted, while the science and NGS light (600–2400 nm) is reflected. The reflected light then reaches M11M, a flat flip mirror mounted on a rotational axis (a MORFEO deliverable), which allows selection between the MICADO path and the second instrument path. The beam is subsequently reflected by a flat mirror—M12M (or M12M-bis)—mounted above MICADO (or the second instrument, respectively), and is brought to focus at the instruments' gravity-invariant

entrance focal plane. M11M and M12M can tip/tilt via motorized axes and are used to re-align the exit pupil and focal plane to MICADO.

The LGS Objective (LGSO) reduces the LGS beam F/# at 589 nm from approximately F/19 at the DICHROIC to F/5 at the entrance focal plane of the LGS WFS module. It consists of four silica spherical lenses (LGSO-L1 to L4) and one fold mirror (LGSO-FM2). The folding mirror is used to fit the optical train within the available envelope. The LGS asterism required by MORFEO is fixed at a 45-arcsecond field angle. As the ELT altitude angle varies (zenith angle from 0° to 60°), the LGS launchers maintain the LGS sources at a fixed 45-arcsecond angle on the sodium layer. Thanks to the telecentric beam and the constant F/# provided by the LGSO, the radial position of the LGS images on the LGSO focal surface remains constant, even as the apparent altitude of the sodium layer (ranging from 84 km to 180 km above the entrance pupil) changes. As a result, the LGS WFS module only needs to rotate about its central axis (to compensate for ELT altitude rotation) and move along the gravity vector (to compensate for varying sodium layer distances) in order to maintain correct focus.

3.2 Product Breakdown Structure

The items to be supplied by the contractor are defined in **MAO-PFH-1.2.3.4**

MAO-PFH-1.2.2.2: LGSO Product Breakdown shall comply with the one shown in Figure 4

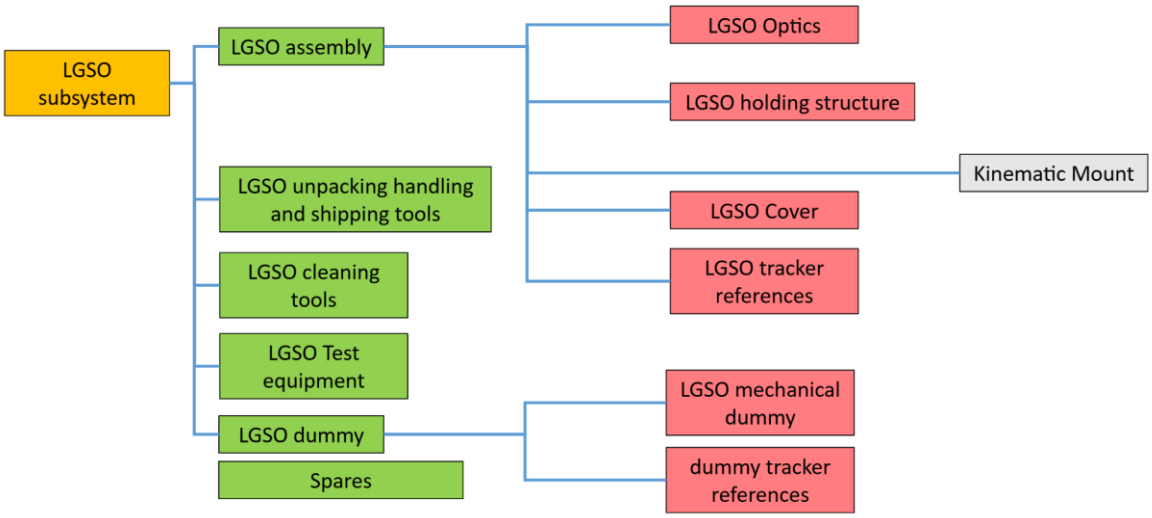


Figure 4: Product Breakdown Structure of LGSO[1]

[1] The white block will be provided by the consortium (TBC)

3.3 Interface Definition

The LGSO will interface with

- The Main support structure (PM0) that will provide mechanical support
- Thermal control system (PT0) that will provide temperature probe link

MAO-PFH-1.3.5.1: Interface with Thermal System

LGSO shall comply with I-PT0/PFH requirements as specified in 5.3 Thermal Interface: LGSO – MORFEO Instrument Thermal Control System

MAO-PFH-1.3.5.2: Interface with Instrument control Electronics

LGSO shall comply with I-PH0/PFH requirements as specified in 5.2 Electrical Interfaces: LGSO – MORFEO Instrument Thermal Control System

MAO-PFH-1.3.5.3: Interface with Main Structure

LGSO shall comply with I-PM0/PFH requirements as specified in 5.1 Mechanical Interface: LGSO– MORFEO Main Structure

4 Characteristics

4.1 Optical Interfaces and Performance Requirements

In this section, optical interfaces and performance requirements of the LGSO system as a whole are stated, defining the quantities to be evaluated, giving the acceptable ranges and describing the operative conditions for which the requirements have to be satisfied. The Optical Input Interface values are non-negotiable.

Optical Input Interface

As previously explained, LGSO has to produce an exit focal plane conjugated, through the MPO and the ELT optical path, with an atmospheric layer having an height varying between 84 and 180 km to the ground. The produced focal plane must be large enough to include images of points having positions ranging radially from 30 to 60 arcsec (on sky) from the centre of the field.

For this reason, LGSO has to be designed and tested using a specific input beam, with characteristics here reported, and reproducing the MPO and telescope beam, in terms of pupil dimension and size, field size and distance between pupil and focal plane. In particular, 3 configurations are defined, corresponding to 3 conjugation distance (84,100, and 180km), summarized in the following table.

Configuration	Conjugation distance	Note
1	84 km	

2	100 km	Main configuration for test
3	180 km	

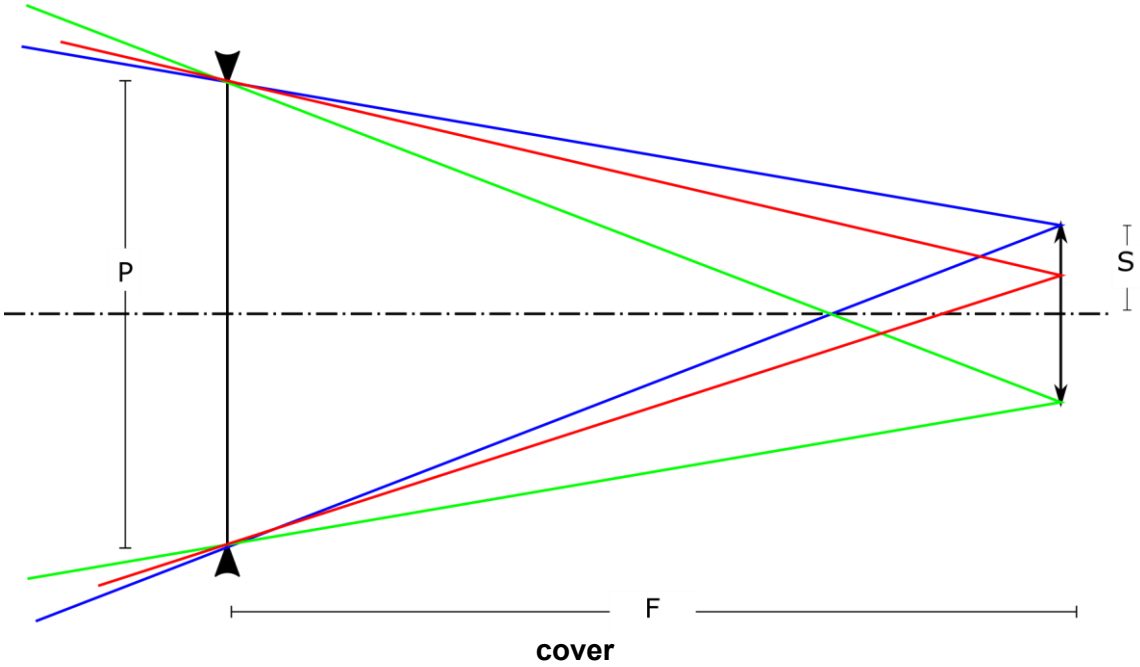


Figure 1: LGSO input beam (not in scale, one configuration)

MAO-PFH-1.3.2.1.: Input beam pupil diameter

The input beam shall present a pupil of P=810.55 mm diameter

MAO-PFH-1.3.2.2.: Input beam pupil position (distance wrt focal plane)

The distance (F) from the pupil to the input beam focal plane of the LGSO is varying with the configuration and it is summarized in the following table:

Configuration	F [mm]
1	23482.06
2	21320.96
3	17553.31

MAO-PFH-1.3.2.3.: Input beam field size and shape

The LGSO must be designed to correctly work for an input beam that if focused, would have a radial dimension (Sin, that corresponds to 60 arcsec in the sky) variable with the configuration, and summarized in the following table.

Configuration	S_{in} [mm]
1	325.23
2	295.25
3	243.01

MAO-PFH-1.3.2.4.: Input beam wavelength range

The input beam for the LGSO must be monochromatic with wavelength equal to 589 nm.

Optical Output Interface

As explained above, LGSO should transform the beam described in the previous section into a beam having a set of properties, described by the following requirements.

MAO-PFH-1.3.2.5: Output beam FoV size and shape

The size of the input beam FoV S_{in} must be transformed in the output beam FoV size S_{out} =56.06mm+/- 0.47mm, regardless of the layer configuration considered.

Moreover, the radial dimension of the image of a circle of input positions having radial distance from the FoV centre of ¾ S_{in} must be $S_{3/4}$=42.02mm+/- 0.47mm, regardless of the layer configuration considered. The actual value of $S_{3/4}$ must be measured (with an error < 50 micron) for at least 12 positions and layer configuration 2.

Anyway obtained values of S_{out} and $S_{3/4}$ slightly different that what is required due to geometrical distortion can be accepted after a discussion with the consortium.

Unless otherwise specified, the performance of the LGSO must be ensured within an annular field, with the input radial size ranging from Sin/2 to Sin.

For 12 input FoV positions having radial distance from the FoV centre of ¾ S_{in} performances will have to be verified by test, at least for input bean configuration 2. For remaining input beam configurations and for at least 12 positions of input FoV of distance S_{in}/2 and S_{in}, performances must be verified at least by design/analysis.

MAO-PFH-1.3.2.20: Output beam F#

F# of the output beam is defined by

$$F\# = \frac{1}{2 * sin\ sin\ (\alpha)}$$

Where α is the angle between the marginal ray and the LGSO optical axis.

The F# of the beam produced by LGSO must be 5.025 +/- 0.078%.

For 12 input FoV positions having radial distance from the FoV centre of ¾ S_{in} performances will have to be verified by test, at least for input bean configuration 2. For remaining input beam configurations and for at least 12 positions of input FoV of distance S_{in}/2 and S_{in}, performances must be verified at least by design/analysis.

MAO-PFH-1.3.2.7: Output beam exit pupil position

The exit pupil of the LGSO must be positioned at an infinite distance from the focal plane, i.e. the system must be image-side telecentric.

MAO-PFH-1.3.2.8: Chief Ray telecentricity error

The chief-ray of the beam for each point of the field and for each configuration, must be parallel to the optical axis of the system within an error angle of 26e-3 deg.

For 12 input FoV positions having radial distance from the FoV centre of ¾ S_{in} performances will have to be verified by test, at least for input bean configuration 2. For remaining input beam configurations and for at least 12 positions of input FoV of distance S_{in}/2 and S_{in}, performances must be verified at least by design/analysis.

MAO-PFH-1.3.2.9: Output beam exit pupil circularity error

Pupil circularity error must be lower than 0.078%.

For each point of the field, pupil circularity error is defined as the average over couples of marginal rays of the departures from 1 of

$$D = (tan\,(|\alpha 1|) + tan\,(|\alpha 2|)\,)/0.2$$

Where α1 and α2 are the angles between the chief ray and the two opposite marginal rays (see fig 2).

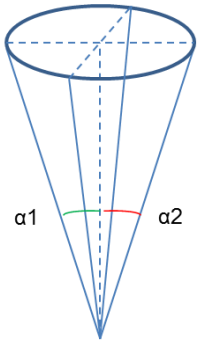


Figure 2

This requirement can be verified by analysis only, for all the input beam configurations and for at least 12 positions of input FoV of distance $S_{in}/2$, $S_{3/4}$ and S_{in}.

MAO-PFH-1.3.2.10: Output beam telecentricity error

Telecentricity error must be lower than 0.078%.

Telecentricity error is defined as the average over couples of marginal rays of

$$\Delta = \left| \frac{\left(\frac{|tan\,(\alpha 1)|}{0.1} - 1\right) - \left(\frac{|tan\,(\alpha 2)|}{0.1} - 1\right)}{2} \right|$$

Where α1 and α2 are the angles between the chief ray and the two opposite marginal rays (see fig 2).

This requirement can be verified by analysis only, for all the input beam configurations and for at least 12 positions of input FoV of distance $S_{in}/2$, $S_{3/4}$ and S_{in}.

MAO-PFH-1.3.2.11: Output beam WaveFront Error

The RMS wave front error, after tip/tilt and defocus subtraction, shall be less than 200nm @ $S_{3/4}$ for all configurations.

The RMS wave front error, after tip/tilt and defocus subtraction, shall be less than 300nm @ S_{in} and $S_{in}/2$ for all configurations.

For 12 input FoV positions having radial distance from the FoV centre of ¾ S_{in} performances will have to be verified by test, at least for input bean configuration 2. For

remaining input beam configurations and for at least 12 positions of input FoV of distance $S_{in}/2$ and S_{in}, performances must be verified at least by design/analysis.

MAO-PFH-1.2.4.9: LGSO throughput (@ 589nm)

LGSO shall have a Beginning Of Life throughput higher than 93.0% (goal 95.0%) at 589nm from Sin/2 to Sin.

MAO-PFH-1.2.4.11: LGSO elements reflectivity and transmissivity

The reflectivity and transmissivity of LGSO single elements measurements shall be done on witness samples coated together with the elements itself. Measurement shall consider proper AOIs for each optical element. Measurements shall be performed at 589nm.

MAO-PFH-1.2.4.12: **Coating durability**

The durability of the coating shall be the one specified in E-MAO-SF0-INA-SPE-004 MAO-SF0-2.6.1.1 (15 years). No recoating activity is allowed.

MAO-PFH-1.2.4.14: **Coating degradation estimation**

It shall be provided an estimation of the degradation of the transmission/reflectivity curve considering the cleanliness specified in E-MAO-SF0-INA-SPE-004 MAO-SF0-2.5.12.3.3 ISO 7.2 (median) and ISO 8 (90% percentile)

MAO-PFH-1.3.2.22: Baffling

A baffling could be necessary pending on MORFEO straylight analysis: the baffling dimensions and characteristics will be defined by the Consortium during phase C (see SOW AD6). An attachment interface for a baffle shall be foreseen.

MAO-PFH-1.3.2.12: enclosure

A protective enclosure shall be foreseen for straylight, cleanliness and protection purposes, details to be agreed with the consortium during phase C

MAO-PFH-1.3.2.21: Microroughness (clear aperture)

The micro-roughness (spatial bandwidth upper limit 1 mm^{-1}) of each optical surface inside the clear aperture shall not exceed Rq=2 nm rms.

MAO-PFH-1.3.2.6: Polished surface characteristics

Surface flaws over each polished surface shall comply with ISO 10110 part 7: 5/6x0.4; L2x0.025 for any area of 0.20 m^2 and 5/2x0.4; L2x0.025 for any area of 5000 mm^2.

MAO-PFH-1.3.2.13: Max Volume and its position wrt Input beam pupil

LGSO total envelope volume shall be the one specified in the file CAD [AD 8] and shown in Figure 3.

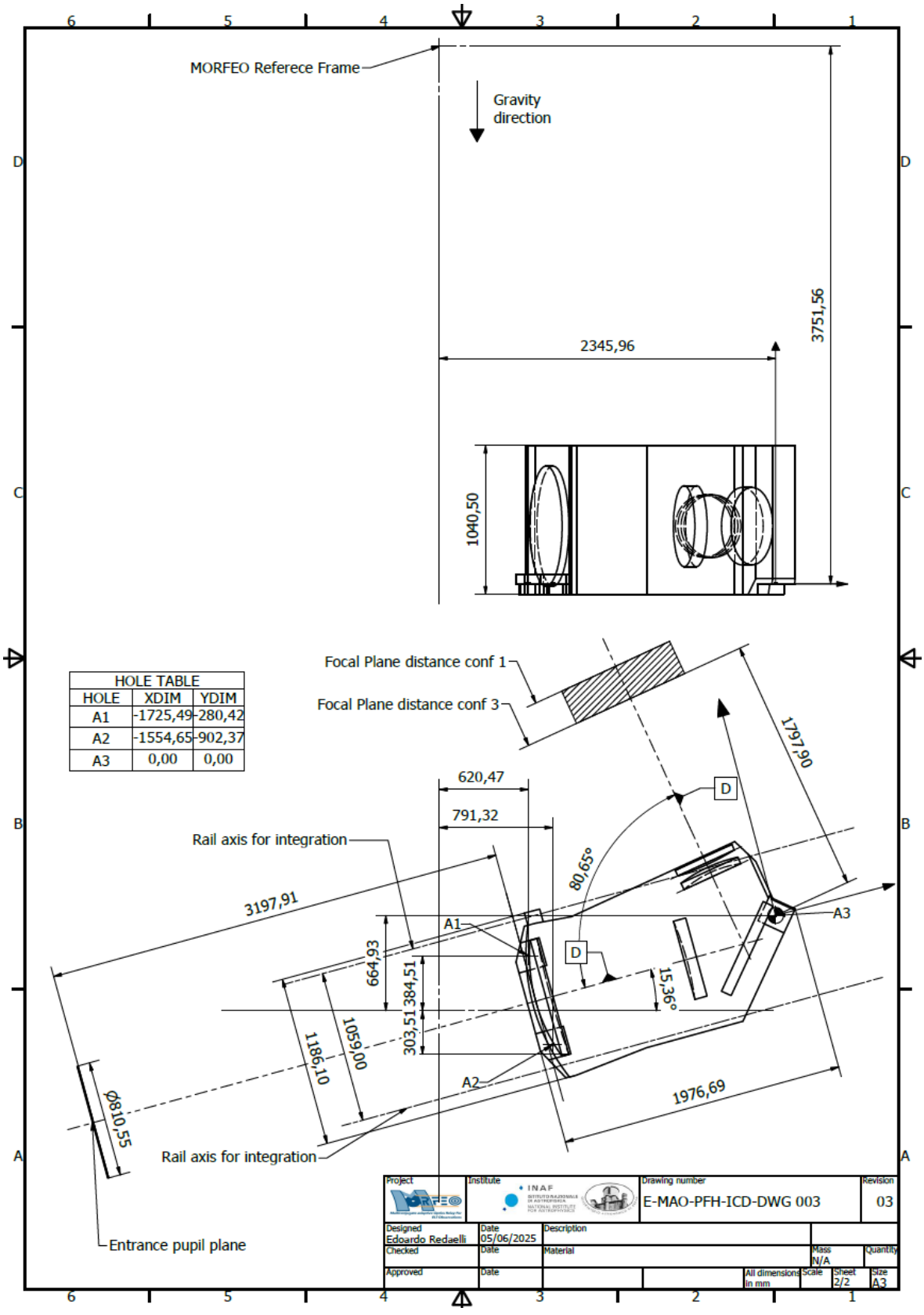


Figure 3: LSGO Allowed Volume

MAO-PFH-1.3.2.14: focal plane positioning

Position of the focal plane varies depending on the configuration. The center of the focal plane shall be located along the line D indicated in Figure 3 and within the volume specified by V in Figure 3. All the information is contained in the CAD file [AD 8].

MAO-PFH-1.3.2.15: focal plane Curvature

The Output Focal Plane may be flat or curved. If curved, the radius of curvature (concave or convex) shall be equal or larger than 4000 mm. The radius may vary between different layer configurations, but in all cases must comply with this minimum value.

MAO-PFH-1.3.2.16: Pupil position variation accommodation

LGSO shall comprise an integrated alignment tool to accommodate a variation of the Pupil distance of +/-11mm. An example of such an alignment tool may be the axial movement of an element of the system. The system shall comprise an integrated alignment tool with an accuracy of 0.3 mm of the pupil distance. All the requirements shall be met after the compensations.

MAO-PFH-1.3.2.17: Clear apertures oversizing

Clear apertures of the LGSO elements shall be oversized wrt the nominal footprint. The diameter percentage of oversizing shall be >6.5%.

MAO-PFH-1.3.2.18: Acceptance of design

The manufacturer is free to propose his own LGSO design [RD1], that may be different from the consortium one or the consortium design itself. In any case, the manufacturer shall assure performances of the system and the design itself shall be discussed with, and accepted by, the consortium.

MAO-PFH-1.3.2.19: Evaluation of the design with the Nominal MPO Morfeo Design

A further verification by analysis of the performances of the proposed design shall be done integrating the proposed design in the nominal MORFEO optical design [RD 1].

4.2 Proposed design

In this section, the LGSO design devised by the consortium is described as information for the manufacturer, reporting foreseen performances.

Reference Zemax file : RD1

Configurations regarding LGSO are number 6, 7 and 8.

4.2.1 Design description

The system is composed by four spherical lenses and a flat mirror, coupled with the MPO with a first flat mirror (LGSO FM1), and with the exit focal plane and the LGS wavefront sensor (LGSWFS) with a further flat mirror (LGSO FM3), both not part of the LGSO system.

The geometrical properties of the elements are reported in the following table and illustrated in the following layout.

The first surface of L1 is placed 3197.98 mm from the input beam pupil.

Element	Thickness [mm]	Radius [mm]	Diameter [mm]	Glass	Comment
L1	108	1210.00	838	Silica	Convex
		5621.00	838		Concave
L1-L2 dist	984				
L2	70	2077.00	564	Silica	Concave
		inf	564		Flat
L2-FM2 dist	340				
Rotation around x					- 40.32554
FM2		inf	690x540		Elliptical Flat
Rotation around x					- 40.32554
FM2-L3 dist	550				
L3	40	746.70	436	Silica	Concave
		1031.50			Convex
L3-L4 dist	20				
L4	60	1831.50	434	Silica	Convex
		4943.00			Convex

Table 1: LGSO elements geometric properties and mutual positioning

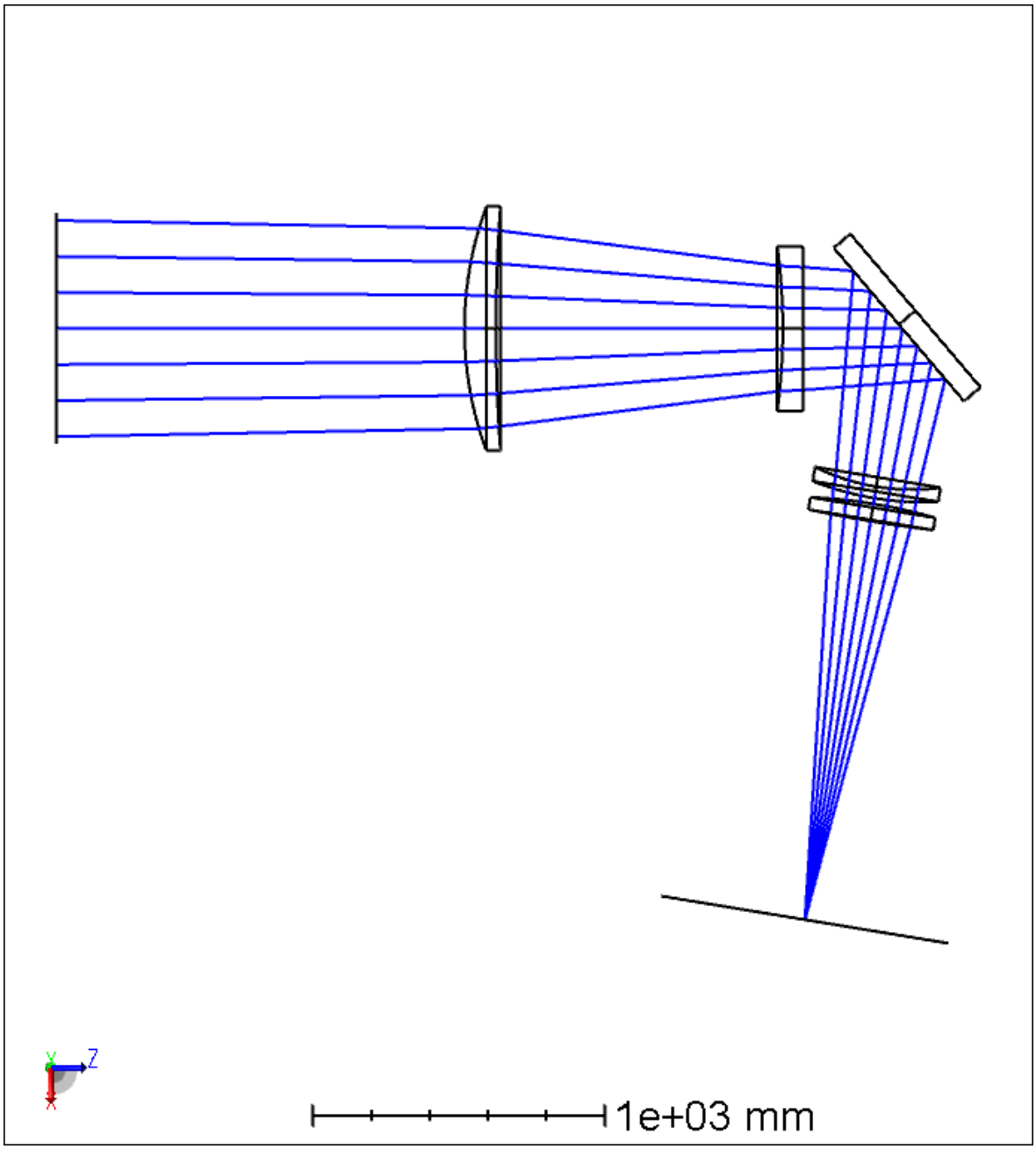
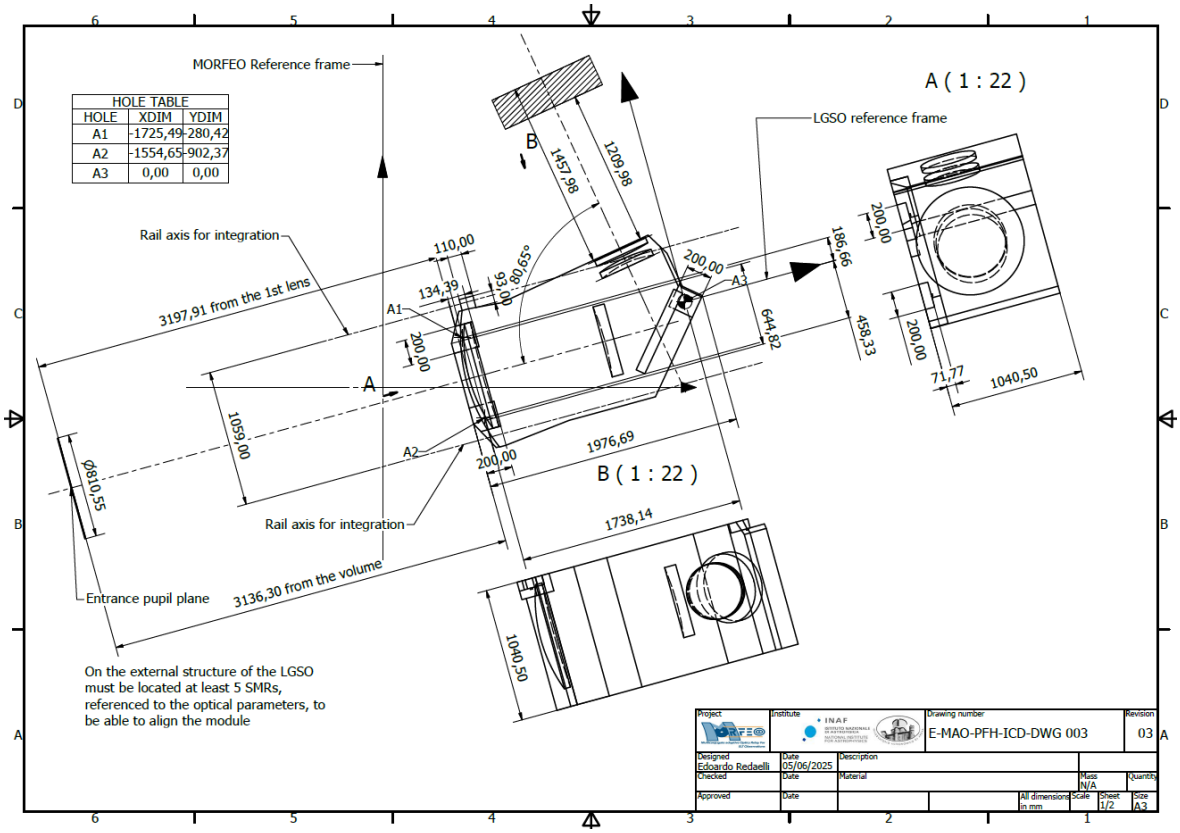


Figure 4 LGSO Layout (only central field)



The proposed system, when illuminated with a beam as the one described in previous section, produces a focal plane at a distance from L4 last surface variable as reported in the following table, where the radii of curvature of the focal plane (concave toward L4) are also reported

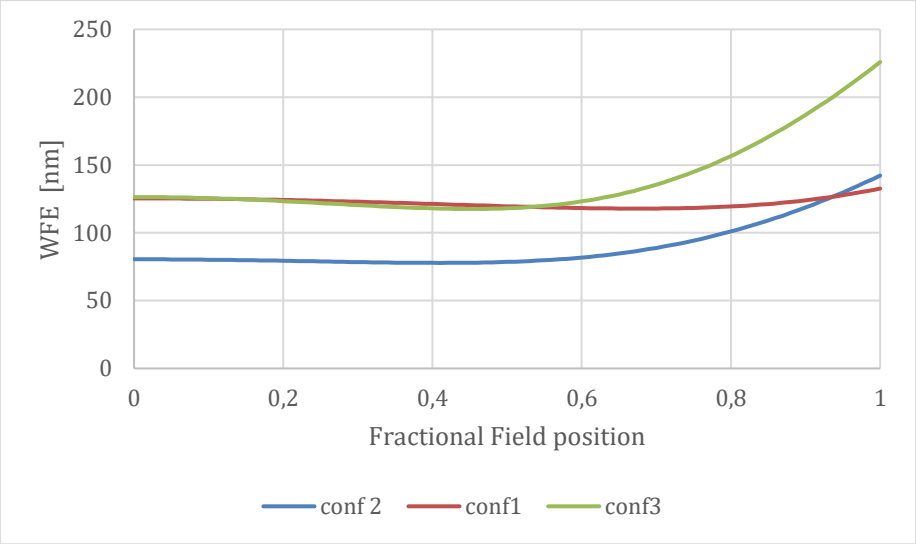
Configuration	Distance [mm]	RoC [mm]
1	1457.752	5770.341
2	1386.517	5486.481
3	1220.299	4947.238

4.2.2 Design performances

The design described above has the following nominal performances

WFE RMS

Wave front error RMS remains for all configurations and essentially for all the FoV smaller than 200nm as can be appreciated in the following plot.



FoV size

$S_{3/4}$ S =42.26mm and S_{out} =56.34mm, in specifications as requested. Being essentially a rotationally symmetric design, so is the dimension of the field. The nominal value differs by the paraxial one because of the geometrical distortion.

Pupil circularity error

Pupil circularity error is between -0.008% and 0.004%, depending on configuration and field radial position.

Telecentricity error

Telecentricity error is between 0.004% and 0.008%, depending on configuration and field radial position.

The design has been the subject of a tolerances analysis, assuming the following parameters

Radius of Curvature (spherical elements)	0.1% 0.05% for L1 surfaces
Index of refraction	5 10^{-4} (uniform over the element volume)
Abbe number	0.7 (about 1%)
Thickness	1 mm
Wedges of lenses faces	6 10^{-3} degrees both in X and Y direction About 100 um runouts for 1 meter diameter element
Positioning errors	100 micrometres for x, y, z displacement 6 10^{-3} degrees both in tx and ty direction

Figure error	50 nm for each surface, distributed in Zernike modes 5-11 (18.9 nm per mode)
Flat elements non planarity (Z4)	100 nm

Toleranced design assured required performances in essentially all realizations and configurations. As an example, here is reported the WFE (sampled at several FoVpositions, all at 45''distance from FoV center) in configuration 2.

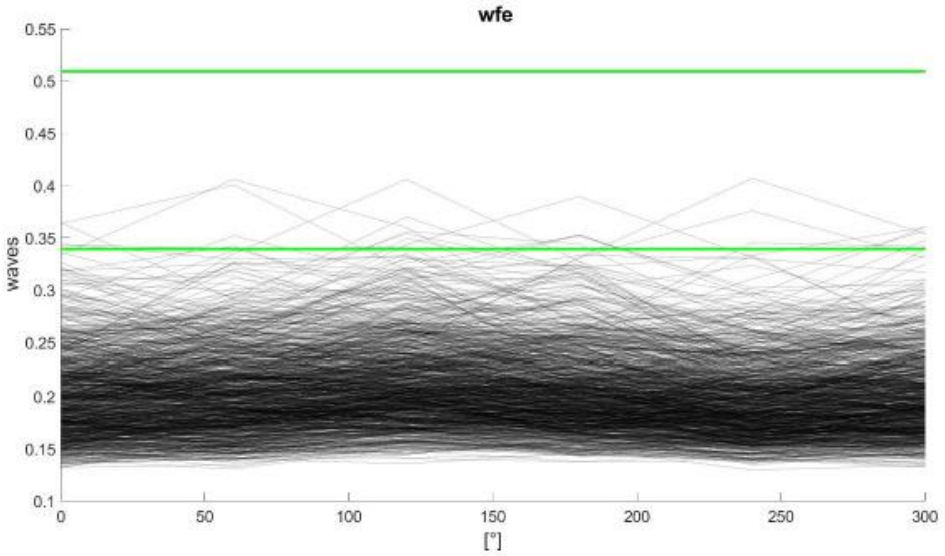


Figure 105. WFE of the 1000 MC files as function of the azimuthal angle.

4.3 Positioning

MAO-PFH-1.2.4.10: Mechanical reference LGSO

LGSO shall have five (TBC) Spherical Mounted Retro reflector (SMR) nest holders. It shall be possible to retrieve the as-built LGSO position with respect to the optical input beam from the acquisition of the SMR within the following tolerance:

Dx ±0.8 mm

Dy ±0.8 mm

Dz ±0.1 mm

Rx ±0.3 arcmin

Ry ±0.3 arcmin

Rz ±5 arcmin

The position of the SMRs must be referenced also with respect to the kinematics interfaces.

The preferable position is around the edge of the glass of LGSO cell and will be agreed with the customer in the design phase (as proposed in AD8).

note: the fitting procedure shall be agreed with the vendor.

4.4 Physical Characteristics

MAO-PFH-1.2.1: Common requirements applicability

LGSO shall comply with all requirements in AD1 and a compliance and verification matrix shall be produced. Non applicable requirements must be marked as NA.

MAO-PFH-1.2.2.3: Optics Material

Materials of LGSO shall be Zerodur for the mirror and Silica for the lenses, or thermoelastic compatible optical glass (in this case the consortium shall approve the alternative proposed material).

MAO-PFH-1.2.4.13: LGSO thermal induced distortion

All the requirements shall be met in the full temperature range of operational conditions (0°-15°C).

Note: It is preferable to demonstrate by test performance and system-parameter measurements at multiple temperatures within the operational range (0°-15 °C). However, it is also acceptable to demonstrate performance and system-parameter measurements in the operational range through a thermo-mechanical-optical model correlated with measurements at a minimum of two temperatures (not necessarily within the operational range), provided that this correlation is sufficient to demonstrate compliance with the requirements.

4.5 Environmental Conditions

4.5.1 General

MAO-PFH-1.1.4: Telescope dynamics for performance requirements

Functional requirements shall be met considering: Telescope Azimuth Speed up to 2 degrees/s and Azimuth axis acceleration up to 0.1 deg/s2. Both velocity and acceleration ranges apply independently and concurrently.

MAO-PFH-1.1.3: Telescope dynamics for functional requirements

Performance requirements shall be met considering: Telescope Azimuth Speed up to 16 arcsec/s and Azimuth axis acceleration up to 30 arcsec/s2. Both velocity and acceleration ranges apply independently and concurrently.

4.5.2 Nominal Operating Conditions

MAO-PFH-1.1.1: General applicable conditions

Unless otherwise specified all the requirements in this document and its applicable documents shall be met under the provisions specified in section 4 of AD1**.**

4.5.3 Specific Operating Conditions

MAO-PFH-1.1.2: Specific conditions for LGSO

In addition to section 4 of AD1, the following conditions shall be further considered:

- Air pressure in Europe AIV is 1045 mbar
- Europe operative temperature 20-25°
- Europe operative humidity 50%-80%
- No wind effects will load the LGSO units
- Earthquake quasi static accelerations are ax=± 3.3g, ay=± 3.3g, az=± 2.185g (expressed in the MORFEO SCS)
- Gravity orientation during integration could vary up to 180 with respect to the nominal position
- MORFEO operating reference temperature for the specifications verification, if not elsewhere specified, is 9°C.

4.6 Optical Tests

MAO-PFH-1.2.6.1: Definition of Test Equipment *[info]*

The Test Equipment shall include:

- the unit Optical Test Stand as needed for supporting the LGSO under optical test at the final destination.
- all Custom qualification Items
- Custom prototypes if any
- Integration and maintenance stand

MAO-PFH-1.2.6.2: Coating hardness and adherence

It shall be possible to clean the optical surfaces. To allow this by trained staff, the LGSO coatings shall be compliant to DIN-ISO 9211 part 3, category C, for Abrasion and adhesion. It shall withstand the following durability tests:

- ISO 9211-4, Abrasion, severity 01
- ISO 9211-4, Adhesion, severity 01

The compliance shall be demonstrated on witness samples coated together with the optical surfaces. A standard coating qualification plan shall be provided by the vendor.

MAO-PFH-1.2.6.3: Optical test with interferometry

Unless otherwise specified, optical measurements shall be done by interferometry (after coating deposition).

MAO-PFH-1.2.6.4: Include measurement errors in optical verifications

The error budget shall include the measurement errors with a confidence level of at least 2.5 sigma.

MAO-PFH-1.2.6.5: Include thermal and turbulence effects in optical verifications

Thermal and turbulence effects in the optical test setup shall be taken into account in the testing errors. The verification of thermal conditions effects during tests shall be based on optical analysis and validated by optical tests.

MAO-PFH-1.2.6.6: Europe performance estimate

A detailed performance estimate of Europe operative conditions shall be produced by the vendor (by analysis is acceptable)

5 Interfaces

5.1 Mechanical Interface: LGSO – MORFEO Main Structure

I-PM0/PFH-1.2.1.1: LGSO Mass

The mass of LGSO on the bench shall be lower than 450 Kg (contingency included)

I-PM0/PFH-1.2.1.2: LGSO Volume allocation

The volume reserved for LGSO unit as specified in MAO-PFH-**1.3.2.12** is defined in AD8

I-PM0/PFH-1.2.1.4: LGSO mounting

The LGSO unit mounting interface to PM0 shall be compliant to AD8

I-PM0/PFH-1.2.1.6: MOI *[Info]*

The LGSO moment of inertia shall be provided by the vendor.

For the time being the dimensioning of the MORFEO structure assumed the following values:

X(Kgmm^2) TBD

Y(Kgmm^2) TBD

Z(Kgmm^2) TBD

I-PM0/PFH-1.2.1.7: CoG

The LGSO Center of Gravity wrt MORFEO SCS shall be provided by the vendor.

For the time being the dimensioning of the MORFEO structure assumed the following values:

	SCS
X [mm]	-323
Y [mm]	1482

Z [mm]	-3363

Any deviation shall be discussed and agreed with the Consortium.

I-PM0/PFH-1.2.1.8: Acting forces

If not elsewhere specified, values coming from earthquake analysis shall be used as acting forces for dimensioning the mechanical interface.

I-PM0/PFH-1.2.1.9: LGSO Unit Structural frequency

The lowest eigenfrequency of the LGSO shall be higher than 30Hz. The corresponding analytical verification shall assume infinitely rigid interfaces.

I-PM0/PFH-1.2.1.11: LGSO Access

The access to the LGS OBJECTIVE shall be:

- from the front of the optical surface for cleaning, cover
- from the back of the optical surface for handling tool installation and removal,
- from the front for alignment fine tuning and fixation.

the integration of the LGS OBJECTIVE will be, as a baseline,

- from the left (Micado) side of the Main structure in Bologna,
- from the left (Micado) side of the Main structure in the Armazones Integration assembly
- from the left (Micado) side of the Main structure in Nasmyth platform

I-PM0/PFH-1.2.1.12: LGSO Interface Material

The bench interface material will be steel (foreseen steel alloy is S355JR for the pipes and WELDOX700 for plates, TBC).

I-PM0/PFH-1.2.1.13: LGSO Alignment (info)

The kinematic interface, provided by the Consortium, will allow the remaining correction required with an accuracy of

Dx, Dy	± 0.05 mm TBC
Dz	± 0.01 mm TBC
Rx, Ry	± 2 arcsec TBC

MAO-PFH-1.2.4.26: LGSO mounting repeatability

The LGSO mountings interface to the main support structure shall guarantee a remounting repeatability of 50um (in decentering and piston) on any of the connection

points on short time scales. The optical performance defined in **MAO-PFH-1.2.4.1**, **MAO-PFH-1.2.4.2**, **MAO-PFH-1.2.4.3**, **MAO-PFH-1.2.4.10**, **MAO-PFH-1.2.4.13**, and **MAO-PFH-1.2.4.25** shall be granted.

5.1.1 LGSO vibration requirements

I-PM0/PFH-1.2.1.10.1: Vibration allowed

The vibrations in Table 2 shall be considered as limit for the allowed vibration induced from LGSO to its interface. Final values are pending on MORFEO vibration analysis that will be done in phase C and communicated to the vendor.

	Frequency Range [Hz]		
Nasmyth Instruments	1-4,45	4.45-56	56-110
(Force (x,y,z) [N] RMS per one-third octave frequency bands)	0,25	0,1	0,5

Table 2 Vibration specification

I-PM0/PFH-1.2.1.10.2: Vibration received

if not specified elsewhere the level of vibrations that the LGSO receives from its interface are defined in the following table. Final values are pending on MORFEO vibration analysis that will be done in phase C, and will be communicated to the vendor.

	Frequency Range [Hz]		
Nasmyth Instruments	1-4,45	4.45-56	56-110
(Force (x,y,z) [N] RMS per one-third octave frequency bands)	3	1	3

Table 3 Vibration specification

5.2 Electrical Interfaces: LGSO – MORFEO Instrument Control Hardware

I-PH0/PF0-1.4.2.3: LGSO TP cables

The LGSO Temperature probe (number still to be defined) will be connected to MORFEO Control Electronics racks through the cable defined in AD2

5.3 Thermal Interface: LGSO – MORFEO Instrument Thermal Control System

I-PT0/PFH-1.2.3.1: Probes location

One temperature probe will be located on each glass and one on the mounting. The precise location will be agreed with the contractor before the LGSO FDR.

I-PT0/PFH-1.2.3.2: Temperature sensors accuracy

The temperature sensors shall be PT100 1/3 DIN.

5.4 Handling and integration

MAO-PFH-1.2.2.1: Optomechanics dummy

The supplier shall provide a mechanical dummy of LGSO. The dummy shall preserve:

- volume
- mechanical interface to the structure (according to what defined in I-PM0/PFH)
- handling points
- COG, with a maximum error of 1 cm distance
- mass
- position of SMR

with respect to the real ones.

MAO-PFH-1.4.2: LGSO Covers

The supplier shall provide covers for the optical surfaces and other sensitive areas of the LGSO. The mounting and removal of the covers shall be possible without risking damage, e.g. by the use of guides.

The covers shall weigh less than 15 kg and, when mounted onto LGSO, shall not exceed the allowable volume.

MAO-PFH-1.4.3: LGSO Handling tools

The supplier shall provide proper and safe tools for all LGSO activities. As a minimum this shall include the following activities:

- Packing and unpacking
- Lenses Cleaning
- Lenses Handling in integration room
- Lenses Maintenance and test

Additional interfaces for the tools will be defined and agreed during final design phase

The tools needed for Mirror mounting on MORFEO main structure will be in charge of the consortium according to the interfaces defined in **MAO-PFH-1.4.12.**

MAO-PFH-1.4.4: First integration time and personnel constraint

LGSO manufacturer shall define together with MORFEO Consortium the LGSO installation procedure such that it will minimise the person hours needed.

MAO-PFH-1.4.5: Dismounting time and personnel constraint

LGSO manufacturer shall define together with MORFEO Consortium the LGSO dismounting procedure such that it will minimise the person hours needed.

MAO-PFH-1.4.9: Access for inspection and maintenance

The LGSO shall provide full access to the unit volume, including inside the unit itself, for inspection, cleaning and preventive maintenance of all its subsystems.

MAO-PFH-1.4.10: packing requirements

Packing recommendations of LGSO units will be provided to the vendor at the beginning of phase C.

MAO-PFH-1.4.11: Packaging reusable

The packing and transport container used for delivery to the consortium shall be reusable for the shipping to the telescope site (note that the time estimated between the delivery to the consortium and the shipping in Chile is at least 4 years).

MAO-PFH-1.4.12: Handling interfaces

When integrated into MORFEO the LGSO will be fixed to the MORFEO integration tools according to the interfaces defined in AD8

MAO-PFH-1.4.14: Level of disassembly before packing

The LGS Objective shall be shipped fully integrated.

note : If for any reason the vendor needs to ship the optical elements and holder separately, this shall be agreed with the consortium. It shall be anyway guaranteed and demonstrated that the remounting in any of the conditions defined in AD1 and **MAO-PFH-1.1.2** will fulfil all the optical performance defined in and **MAO-PFH-1.1.2** will fulfil all the optical performance defined in **MAO-PFH-1.2.4.1**, **MAO-PFH-1.2.4.2**, **MAO-PFH-1.2.4.3**, **MAO-PFH-1.2.4.10**, **MAO-PFH-1.2.4.13**, and **MAO-PFH-1.2.4.25**. The vendor shall also provide enough support and training to the consortium to execute the reintegration of Mirror to the holder. In any case this possibility has to be discussed and agreed with the consortium.

MAO-PFH-1.4.15: bonding compatibility with cleaning

The adhesive material selected for the bonded pads of the finished LGSO shall not degrade due to exposure to CO2 snow, alcohol, acetone, detergents and water used for regular cleaning of the mirror.

MAO-PFH-1.2.4.27: Cleaning

The procedures and all required tools and documentation for the cleaningWashing, shall be developed, tested and delivered with LGSO. Proper training shall be given to the consortium and/or ESO personnel.

MAO-PFH-1.2.4.28: LGSO-FM3 Dismounting
It shall be possible to remove the folding mirror without dismounting the full lgso to guarantee the internal cleaning of the lgso inside the main structure, it shall be possible to remove the mirror through normal crane. The remounting shall not degrade the performance defined in and **MAO-PFH-1.1.2** will fulfil all the optical performance defined in **MAO-PFH-1.2.4.1**, **MAO-PFH-1.2.4.2**, **MAO-PFH-1.2.4.3**, **MAO-PFH-1.2.4.10**, **MAO-PFH-1.2.4.13**, and **MAO-PFH-1.2.4.25**. .

6 Product Assurance

MAO-PFH-1.2.5.34: Engineering standards

To facilitate the integration ,operation and maintenance of the LGSO in the ELT observatory the vendor shall follow the design guidelines reported in AD3 AD4 AD5.

6.1 Requirements Verification

MAO-PFH-1.5.1.8 RAMS starting point

The compliance of all RAMS requirements shall be evaluated starting from the Preliminary Acceptance Europe reported in AD6 sec 2.1.

MAO-PFH-1.2.5.11: LGSO safety active when powered off

Functions necessary for the safety of the LGSO units when the system is in non-operational non- ready shall be active.

MAO-PFH-1.5.1.1: General RAMS requirements

Unless otherwise specified LGSO shall comply with section 9 of AD1.

A compliance and verification matrix shall be produced (included in the verification of MAO-PFH-1.2.1). Non applicable requirements must be marked as NA.

MAO-PFH-1.5.1.2: LGSO includes safety and integrity measures

LGSO shall include safety measures that the unit needs to undertake in order to ensure its own integrity and safety (hardware, software, and human safety) under all conditions and safety requirements specified herein. Human safety shall be guaranteed at all times.

MAO-PFH-1.5.1.3: No human intervention

Safety of the LGSO Units itself shall not require human intervention if the Units are powered off by up to 24 hours.

MAO-PFH-1.5.1.4: Witness tests

Witness samples (described in AD7 , 4.2.3, 4.2.5, 4.3) can be agreed for all critical processes and materials

MAO-PFH-1.5.1.5: Analysis code and references

Any code used in Engineering calculations shall be indicated and references for formulas, assumptions, material data, etc. shall be provided.

MAO-PFH-1.5.1.6: Development test

Development tests shall be performed where needed to determine component characteristics or to validate analysis methods and assumptions.

MAO-PFH-1.5.1.7: Qualification of components before system tests

Qualification tests shall preferably be performed at component level as needed if system level tests will not be sufficient to simulate worst case conditions.

MAO-PFH-1.5.3.1: Cleaning duration

LGSO cleaning time shall be lower than 1h (not including the time required to install and remove any structure to access the optic)

MAO-PFH-1.5.3.2: staff limit

Each preventive/predictive maintenance action shall require at most 2 trained technicians.

MAO-PFH-1.4.13: LGSO Accessibility

The LGSO shall be designed to ensure adequate accessibility to its individual opto-mechanical components for maintenance, repair, and part replacement, in order to minimize downtime and reduce the risk of hardware damage.

7 Requirement Verification

ID requirement	FDR Verification	ARR Verification
MAO-PFH-1.1.1	Design	Design
MAO-PFH-1.1.2	Design	Design
MAO-PFH-1.1.3	Design	Design
MAO-PFH-1.1.4	Analysis	Analysis
MAO-PFH-1.2.1	Design	Design
MAO-PFH-1.2.2.1	Design	Inspection
MAO-PFH-1.2.2.2	Design	Inspection
MAO-PFH-1.2.2.3	Design	Inspection
MAO-PFH-1.2.3.1	Design	Design
MAO-PFH-1.2.4.9	Design Analysis	Test
MAO-PFH-1.2.4.10	Analysis	Test
MAO-PFH-1.2.4.11	Analysis	Test

MAO-PFH-1.2.4.12	Design	Test
MAO-PFH-1.2.4.13	Analysis	Analysis (Test goal)
MAO-PFH-1.2.4.14	Analysis	Test
MAO-PFH-1.2.4.26	Design	Test
MAO-PFH-1.2.4.27	Design	Test
MAO-PFH-1.2.4.28	Design	Test
MAO-PFH-1.2.5.11	Design	Test
MAO-PFH-1.2.5.34	Design	Test
MAO-PFH-1.2.6.2	Design	Test
MAO-PFH-1.2.6.3	Analysis	Test
MAO-PFH-1.2.6.4	Analysis	Test
MAO-PFH-1.2.6.5	Analysis	Test
MAO-PFH-1.2.6.6	Analysis	Test
MAO-PFH-1.3.2.1.	Design	Test
MAO-PFH-1.3.2.2.	Design	Test

MAO-PFH-1.3.2.3.	Design	Test
MAO-PFH-1.3.2.4.	Design	Test
MAO-PFH-1.3.2.5	Design	Test
MAO-PFH-1.3.2.6	Design	N/A
MAO-PFH-1.3.2.7	Design	Test
MAO-PFH-1.3.2.8	Analysis	Test
MAO-PFH-1.3.2.9	Analysis	N/A
MAO-PFH-1.3.2.10	Analysis	N/A
MAO-PFH-1.3.2.11	Analysis	Test
MAO-PFH-1.3.2.12	Design	Inspection
MAO-PFH-1.3.2.13	Design	Test
MAO-PFH-1.3.2.14	Design	Test
MAO-PFH-1.3.2.15	Design	Test
MAO-PFH-1.3.2.16	Analysis	Test
MAO-PFH-1.3.2.17	Design	Test
MAO-PFH-1.3.2.18	Design Analysis	Test

MAO-PFH-1.3.2.19	Analysis	Test
MAO-PFH-1.3.2.20	Design	Test
MAO-PFH-1.3.2.21	Design	Test
MAO-PFH-1.3.2.22	Design	Test
MAO-PFH-1.3.5.1	Design	Design
MAO-PFH-1.3.5.2	Design	Design
MAO-PFH-1.3.5.3	Design	Design
MAO-PFH-1.4.10	Design	Inspection
MAO-PFH-1.4.11	Design	Inspection
MAO-PFH-1.4.12	Design	Test
MAO-PFH-1.4.13	Design Analysis	Test
MAO-PFH-1.4.14	Design	Test
MAO-PFH-1.4.15	Design	Test
MAO-PFH-1.4.2	Design	Inspection
MAO-PFH-1.4.3	Design	Inspection
MAO-PFH-1.4.4	Analysis	Test

MAO-PFH-1.4.5	Analysis	Test
MAO-PFH-1.4.9	Design	Inspection
MAO-PFH-1.5.1.1	Design Analysis	Analysis
MAO-PFH-1.5.1.2	Design	Inspection
MAO-PFH-1.5.1.3	Design	Test
MAO-PFH-1.5.1.4	Design	Test
MAO-PFH-1.5.1.5	Design	Test
MAO-PFH-1.5.1.6	Design	Test
MAO-PFH-1.5.1.7	Analysis	Test
MAO-PFH-1.5.1.8	Analysis	Test
MAO-PFH-1.5.3.1	Analysis	Test
MAO-PFH-1.5.3.2	Analysis	Test

Table 1 PFH tech spech Verification table

ID requirement	FDR Verification	ARR Verification
I-PM0/PFH-1.2.1.1	Design	Test

I-PM0/PFH-1.2.1.2	Design	Inspection Test
I-PM0/PFH-1.2.1.4	Design	Inspection
I-PM0/PFH-1.2.1.7	Design	Design
I-PM0/PFH-1.2.1.8	Analysis	Analysis
I-PM0/PFH-1.2.1.9	Analysis	Analysis
I-PM0/PFH-1.2.1.10.1	Analysis	Analysis
I-PM0/PFH-1.2.1.10.2	Analysis	Analysis
I-PM0/PFH-1.2.1.11	Design	Inspection
I-PM0/PFH-1.2.1.12	Design	Inspection
I-PM0/PFH-1.2.1.13	Analysis	Test
I-PH0/PFH-1.4.2.3	Design	Inspection
I-PT0/PFH-1.2.3.1	Design	Inspection
I-PT0/PFH-1.2.3.1	Design	Inspection

Table 2 Interface Verification table