



<b>Publication Year</b>	2022
<b>Acceptance in OA</b>	2025-03-04T16:06:12Z
<b>Title</b>	MORFEO at ELT: system engineering activity up to preliminary design review
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<b>Publisher's version (DOI)</b>	10.1117/12.2630353
<b>Handle</b>	<a href="http://hdl.handle.net/20.500.12386/36415">http://hdl.handle.net/20.500.12386/36415</a>
<b>Serie</b>	PROCEEDINGS OF SPIE
<b>Volume</b>	12187

# MORFEO@ELT: SYSTEM ENGINEERING ACTIVITY UP TO PRELIMINARY DESIGN REVIEW

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## ABSTRACT

MORFEO (formerly known as MORFEO) an adaptive optics module able to compensate the wavefront disturbances affective the scientific observation. It will be installed on the straight-through port of the telescope Nasmyth platform to serve the first-light instrument MICADO and with the provision for a future second instrument. The module underwent the Preliminary Design Review in 2021 and is expected to be commissioned in 2029.

In this paper we present a synthesis of the System Engineering approach adopted to manage the development of the instrument. We will discuss the evolution of the architecture towards the requirements. We will detail the criticalities of the system engineering with a particular focus onto the management of the interfaces between subsystems and external systems (Telescope, other instruments...). We will also make a brief description of way in which we implemented Model Based System Engineering and the tools adopted in order to manage requirements, use cases and interfaces.

**Keywords:** Adaptive optics, ELT, MORFEO, MBSE, Preliminary Design Review

## 1. INTRODUCTION

MORFEO (Multiconjugate adaptive Optics Relay For ELT Observations), as first generation ELT instrument, will help compensating for the distortion of light caused by turbulence in the Earth's atmosphere which make astronomical images blurry. It is a Multi-Conjugate Adaptive Optics (MCAO) module that will allow to achieve spatially uniform adaptive optics compensation over a large field of view (about 1 arcmin<sup>2</sup>) 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. Finally, the wavefront error compensation is performed by two adaptive post focal Deformable Mirrors (DMs) located inside MORFEO (the core of the instrument), which work together with the telescope's adaptive and tip-tilt mirrors M4 and M5 respectively. The MORFEO MCAO mode has to be available at the first light with at least one deformable mirror (DM), with provision for a second DM as an upgrade. This imply that MORFEO, although funded for only one DM, has to be designed for two DM from the beginning, with one deformable mirror being possibly replaced by a rigid mirror.

The MORFEO project recently passed the Preliminary Design Review (PDR), whose formal closure is expected by early next October. Subsequently, the Project will enter the final design phase (12-18 months) and then in the manufacturing and test phase in Europe. The first light at the ELT Nasmyth platform is expected by the end 2028.

A general overview of the MORFEO global architecture and functional overview as presented at the PDR are illustrated in Figure 1 and Figure 2 respectively. The main hardware subsystems indicated in the figure are complemented by the electronics[1] at system and sub-systems level, instrument control software[2] and real time computer[2].

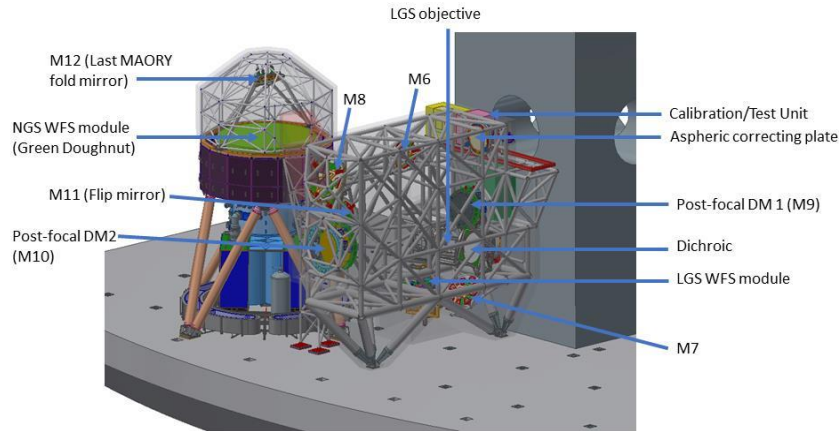


Figure 1 General overview of the MORFEO instrument (thermal cover in transparency) installed on the Nasmyth platform with MICADO

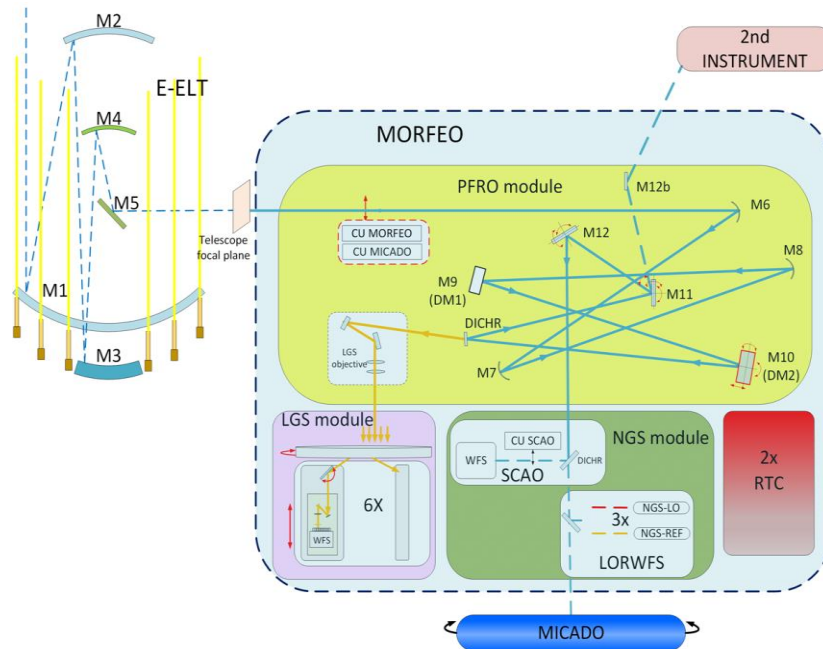


Figure 2 Functional overview of the MORFEO module in the context of the ELT and MICADO client instrument

Both the LOR WFS [9] and SCAO modules are hosted in the same structure, the so-called Green Doughnut (GD). The data produced by the cameras of the LGS WFS and of the NGS WFS are collected by the MORFEO Real Time Computer, which drives the deformable mirrors, i.e. the telescope's M4/M5 adaptive/tip-tilt mirrors and two post-DMs inside MORFEO itself. All the wavefront sensors in MORFEO are placed downstream of the deformable mirrors ensuring optical feedback.

The final MORFEO main path optics baseline[3] has 8 reflections: 2 aspheric concave mirrors, 2 spherical deformable mirrors (one convex and one concave), 1 dichroic and 3 fold mirrors. The optical layout is shown in Figure 3. In the current configuration, according to the technical specification, the MORFEO baseline provides for the presence of only one DM (convex shape with an optical diameter of 880 mm, M9 DM1 in Figure 3) while the second concave DM (M10 DM2 in Figure 3) is replaced by a rigid mirror.

- The sub-system contains the following channels:
- Main path optics, which relay the telescope focal plane to the exit port for the science instruments

LGS Objective, which create 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.

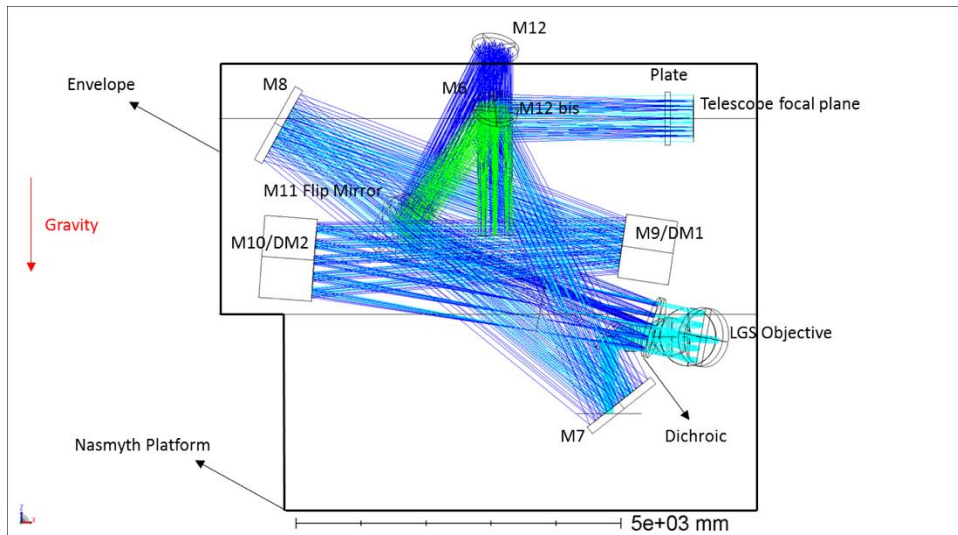


Figure 3 MORFEO Optical Layout

## 2. KEY ELEMENTS OF THE SE ACTIVITY

MORFEO Systems Engineer is responsible for overseeing the overall design of the MORFEO instrument up to commissioning. SE manages and maintains part of MORFEO document to identify all documents (requirements, plans, etc.) needed by the project.

One of the critical activities in systems engineering is the requirements managing. This involves the MORFEO requirements break-down to subsystems level and from here down to subsystems procurements specifications. To simplify requirements, we decompose the MORFEO system into subsystems, which are defined following the Top Level Product Breakdown (See Figure 4).

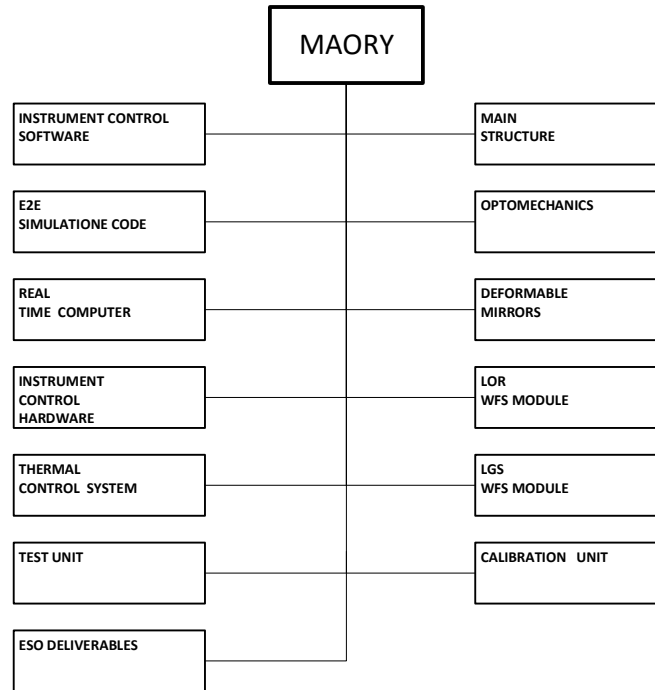


Figure 4 Morfeo PBS

We illustrate the role of MORFEO technical budgets to derive requirements on subsystems. One task of the System Engineering is to manage the technical budgets at system level combining the contributors at subsystems level to meet the overall requirements.

The system engineering activities has been organized adopting the Model Based System Engineering method (MBSE) to manage the key elements:

- Requirements
- Use Cases
- Budgets
- Interfaces

### 3. MORFEO MBSE MODEL

It has been developed a hybrid Model Based Systems Engineering (MBSE) approach to keep control without imposing to the participants' procedures and methods that may be seen as a bureaucratization. In the first phase, starting from the top-level requirements we deployed all the flow down to subsystem, including requirement generated by different use cases (calibration, AIV, ...) and interfaces. This approach allowed us to have under control not only the requirement tracing, but also all the instrument operations "from cradle to grave". The way to communicate with all the team has been identified in Excell spreadsheets. They are easy to edit and update from non MBSE users, and allow the model editors to "easy" implement the modification.

The model is organized in a fractal way. From Figure 5 is possible the context as entry point. Then at System level are modelled:

- Requirements
- Structure
- Use cases
- Analysis

This approach is then replicated inside each subsystem, and potentially could be replicated in lower levels. The interface management is kept at system level as imply agreement between subsystems

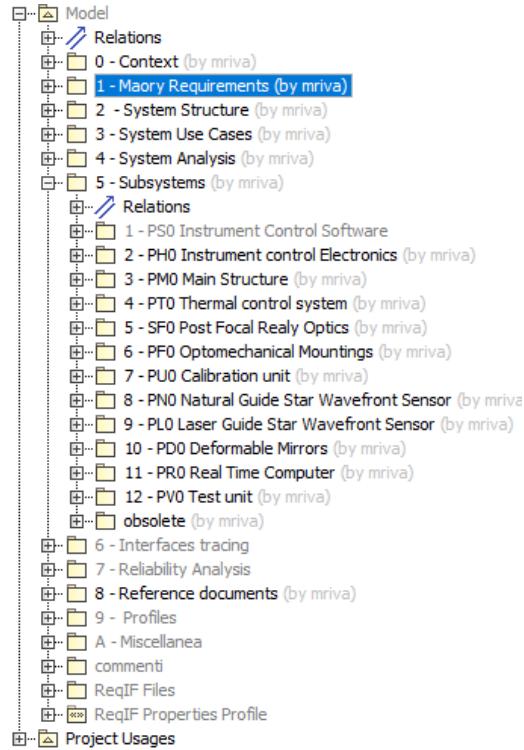


Figure 5 Backbone of the System model

The modeling of the context shown in Figure 6 has been the very first step to identify all the relation of the Modeled system (Morfeo) with the other systems (stakeholder and environment).

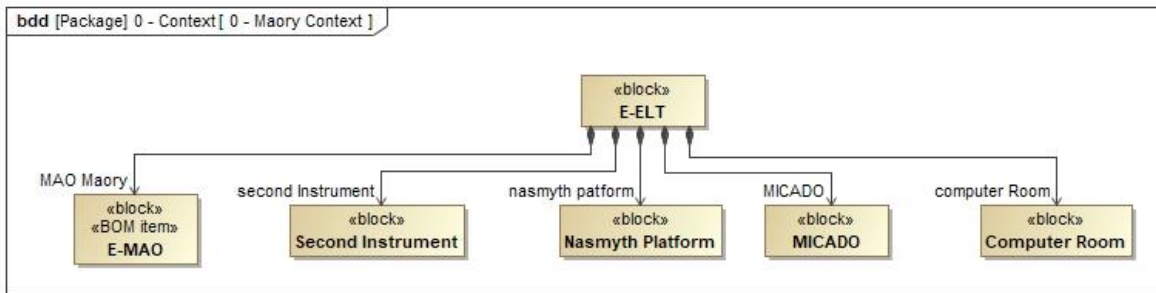


Figure 6 Morfeo context BDD

The system structure has been deployed thanks to block element at different levels. In Figure 7 is shown the system level Block definition diagram.

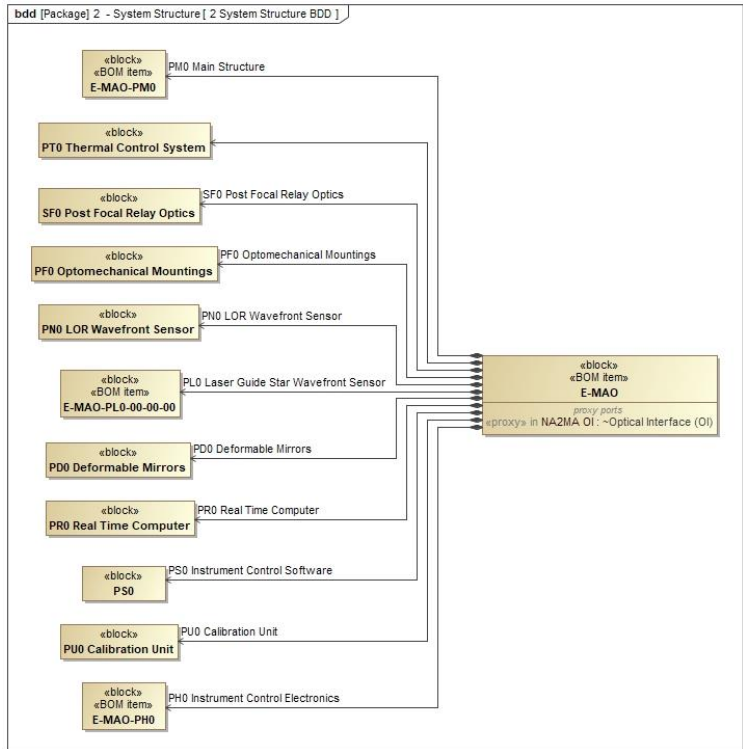


Figure 7 system structure

A direct link between the system Bill of Material [10] has been deployed (tested but not implemented at all levels yet) with the system model structure. In next phases of the project the system structure will be fully representative and connected with the BOM and its properties. The procedure directly import and keep synchronized the excel BOM Figure 8 with the system structure Figure 7

MAORY Bill of Materials										
Each WP shall fill in data in the corresponding section. Columns P and Q are reserved to Glossary Team										
RESPONSIBILITY OF SE/PA										
RESPONSIBILITY OF WP Managers										
Name	L1	L2	L3	L4	L5	L6	L7	Name Acronym	Type	Description
<b>SM0 - SYSTEM MAIV ENGINEERING</b>										
E-MAO-SM0-00-00-00-00	E	MAO	SM0					E-MAO-SM0		System MAIV
E-MAO-SM0-01-01-00-00	E	MAO	SM0	MHT1	HT			E-MAO-SM0-MHT1-HT	Assembly	Mounting Handling Tool Main Bench Structure Top Part 1
E-MAO-SM0-02-02-00-00	E	MAO	SM0	MHT2	HT			E-MAO-SM0-MHT2-HT	Assembly	Mounting Handling Tool Main Bench Structure Top Part 2
E-MAO-SM0-03-03-00-00	E	MAO	SM0	Legs	HT			E-MAO-SM0-Legs-HT	Assembly	Mounting Handling Tool Main Bench Legs
E-MAO-SM0-04-04-00-00	E	MAO	SM0	NDI	SEq			E-MAO-SM0-NDI-SEq	Assembly	Nasmyth Dummy Interface on the floor, to connect the bench legs
E-MAO-SM0-05-05-00-00	E	MAO	SM0	BAS_S	SEq			E-MAO-SM0-BAS_S-SEq	Integration	Bench Alignment System Sensor, to measure displ. of MAO wrt PFS
E-MAO-SM0-06-06-00-00	E	MAO	SM0	BAS	SEq			E-MAO-SM0-BAS-SEq	Integration	Bench Alignment System, to move and align the overall MAORY bench
E-MAO-SM0-07-07-00-00	E	MAO	SM0	MHS	SEq			E-MAO-SM0-MHS-SEq	Assembly	Micado Holding Structure MHS (height reduced for Chile) including derotator and M12 support
E-MAO-SM0-08-08-00-00	E	MAO	SM0	MHSL	SEq			E-MAO-SM0-MHSL-SEq	Assembly	Legs to increase the height of the MHS for integration in Bologna
E-MAO-SM0-09-09-00-00	E	MAO	SM0	PN0	HT			E-MAO-SM0-PN0-HT	Assembly & Maintenance	HT to position the LOR on the Micado Dummy Support
E-MAO-SM0-10-10-00-00	E	MAO	SM0	PL0	HT			E-MAO-SM0-PL0-HT	Assembly & Maintenance	HT to position the LGS on the MAORY Bench based on movable lifting pump
E-MAO-SM0-11-11-00-00	E	MAO	SM0	PU0	HT			E-MAO-SM0-PU0-HT	Assembly & Maintenance	HT to position the Calibration Unit on the MAORY Bench

Figure 8 grab screen of the BOM

#### 4. REQUIREMENT MANAGEMENT

The most intensive use of the model is related to the requirement management. A requirement model has been set up to:

- Keep Verification Cross-Reference Matrices, and Verification Activities under control.

- maintain a list of Applicable and Reference Documents including standards and linking these with requirements. This allows visibility into where and how modifications to documents will affect the requirements.
- Adoption of a graphic derivation tree representation gives excellent visibility to the requirements and links between requirements across the MORFEO project.

The capturing of the requirement started from the stakeholder requirement that included mainly three documents:

- MORFEO -ELT MCAO- Technical Specification
- Common Requirements for ELT Instruments
- Common ICD between the ELT Nasmyth Instruments and the Rest of the ELT System.

In Figure 4 is sketched the flow down of requirements, from ESO documents (pink blocks) and external interfaces (grey and violet blocks) to the subsystem technical specification. in case of requirement to be budgeted, the same philosophy is applied. The budget analysis (purple package) is refining the main requirement, from which subsystem requirement (budget allocation) are derived.

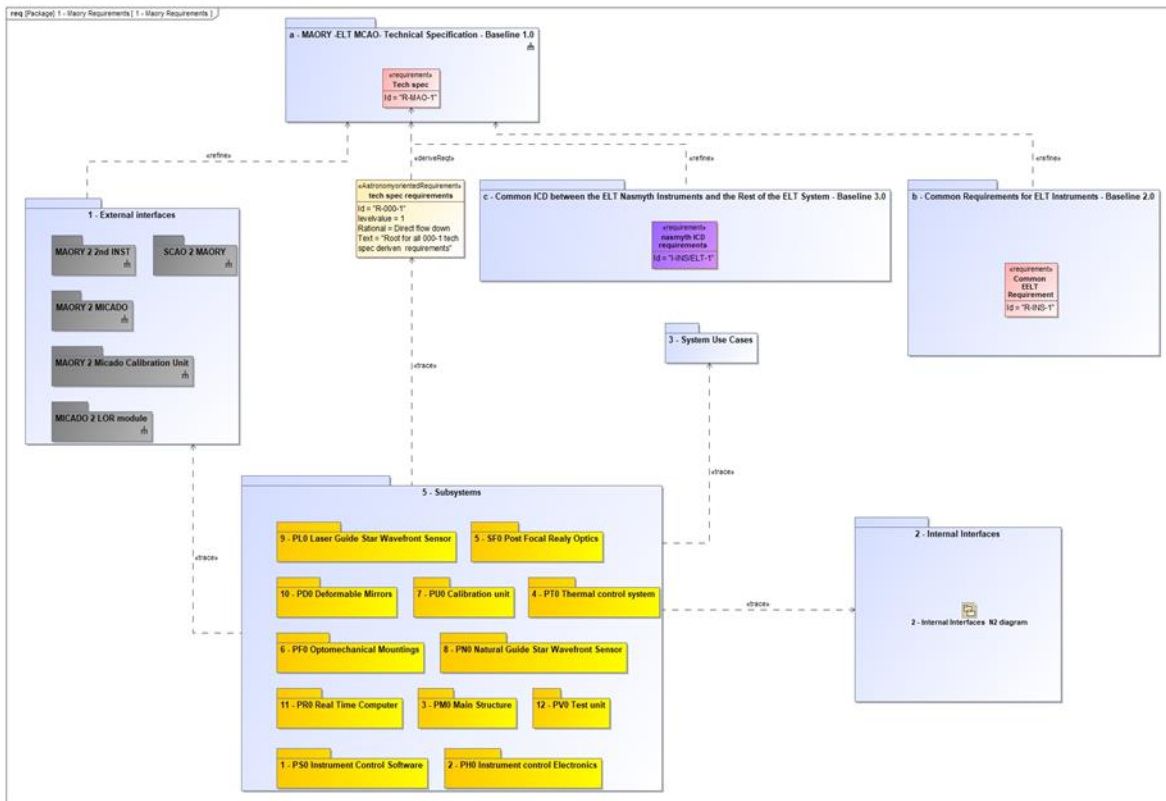


Figure 9 system level Requirement flow down diagram

From the system level requirements then subsystem level have been derived.

In Figure 10 is shown a typical subsystem requirement tree. The main root is made by the subsystem tech-specs. The main root branches out to subsystem requirements of different type:

- Physical
- Functional
- performance
- operational

- interfaces

This root branches also to set of requirements like the one derived by ESO documents (dark pink block in Figure 10).

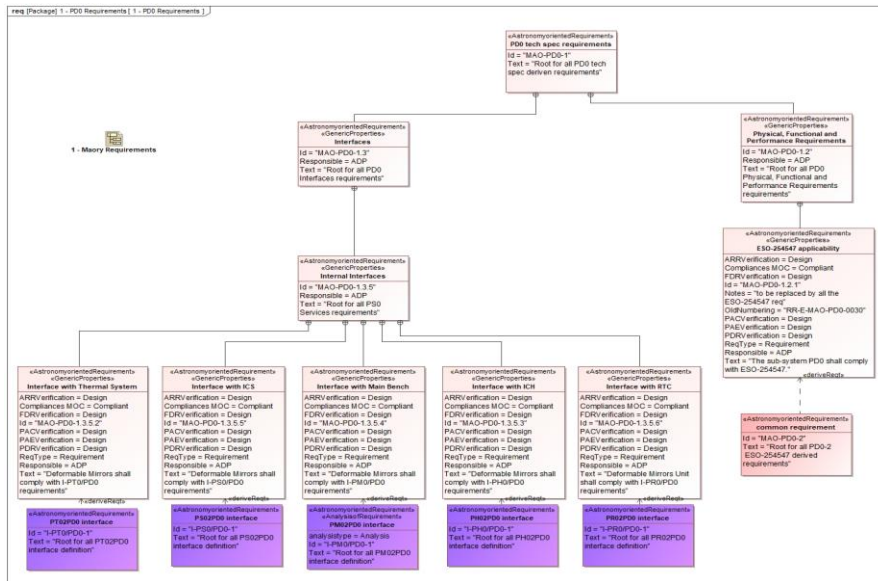


Figure 10 subsystem req tree

A more detailed description of the requirement management which is under standardization within the more general ASTROMBSE project can be found in [12]

## 5. USE CASES MANAGEMENT

All the system use cases them have been modeled and visualized in through Use cases and activity diagrams. They have been also synthesized in tables, in order to have a clear simplified view of all the procedures. These use cases have been imported in the model thanks to the collaboration of various actor, AIV, Calibration, RAMs managers. And then related documents have been generated by compiling the model. In this way we can keep all the procedure under control of the model, and synchronize them with the paper documents.

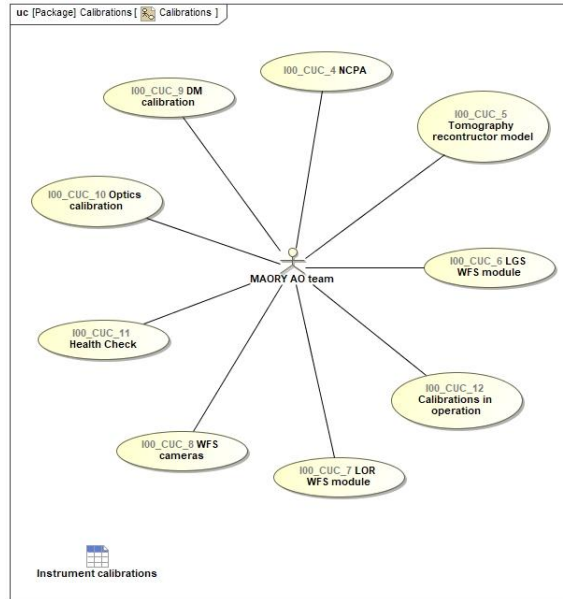


Figure 11 Calibration use cases as example of the case modeling

<b>NCPA3:</b>	MICADO NCPA calibration Primary calibration result: DMs shapes
<b>Prerequisites</b>	MICADO is online and can be used in fast imaging mode The MAORY RTC has been setup to be able to close the loop between the NGS reference WFS and the PFDM(s)
<b>Description</b>	This calibration step consists in mapping the NGS WFS focal plane with the MICADO focal plane. For each MICADO wavelength filter, calibrate the NCPA from the MICADO optical path
<b>Responsible</b>	Calibration WP
<b>Duration (days)</b>	2 hours per filter
<b>Tools needed</b>	
<b>Manpower required</b>	1 man to record the data 1 man to post-process the data and generate the optimal DM shape
<b>Tools required / HW devices</b>	MAORY focal plane calibration unit or MICADO calibration unit MICADO detector in fast imaging mode NGS WFS pupil centering, focusing stage, camera and stage RTC MAORY ICS MICADO ICS and sequencer
<b>Success Criteria</b>	Low order aberrations can be identified with sufficient SNR
<b>Frequency</b>	Once in Chile
<b>Input</b>	0 reference slopes on NGS reference WFS
<b>Output</b>	Delta aberration maximizing performance in each calibrated point of FoV. Reconstruction of field aberrations in terms of DM shape
<b>Procedure</b>	1. For each point in FoV measure LO aberration map, by phase diversity or by DM harmonic modulation 2. Inverse problem N PSFs aberrations x 3 DMs (N>4) Determine shape of 3 DMs for a given orientation of the FoV

<b>NCPA3:</b>	MICADO NCPA calibration Primary calibration result: DMs shapes
<b>HW requirements</b>	<b>Requirements:</b> - CU with 9 light sources (number of points in the FoV to interpolate aberration maps to be determined after optical design is frozen. Baseline is 9) simulating stars in the MICADO focal plane + 3 NGS feeding the reference WFS. One possibility is to use the MICADO calibration unit if it can be modified to incorporate 3 NGS sources - MICADO filter motion driven by the template - Access to MICADO frames in fast imaging mode This calibration can also be performed on sky with the loop closed by the NGS reference WFS
<b>SW/ICS requirements</b>	1. Control focal plane calibration unit light source 2. Control LOR arms position to center then on focal plane calibration source 3. Configure the RTC to be able to close the loop between the NGS reference WFS and the PFDM(s) 4. Request MICADO filter motion

Figure 12 grab screen of an example of the document generation content

In order to define proper procedures and keep control of the relevant activities to be done on MORFEO, four main families of use cases have been defined.

- AIV
- Calibrations
- Operations

- Maintenance

This organization is applied to the instrument and in the same way to the subsystems.

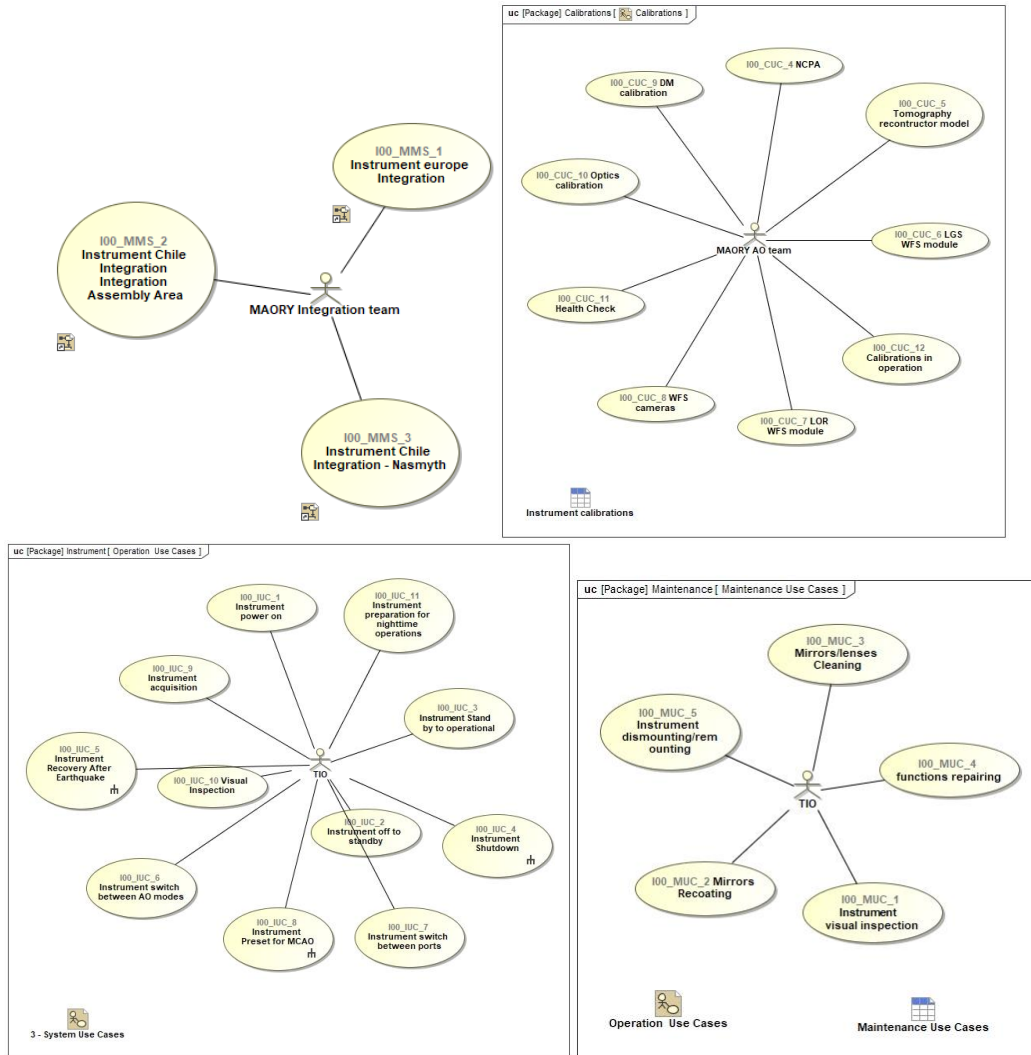


Figure 13 MORFEO use case diagrams: AIV (top left), Calibration (top right), Operation (Bottom left), Maintenance (bottom right)

## 6. BUDGET MANAGEMENT

When The requirement analysis described in previous section defined the need of sharing values among subsystem, budget tracking has been deployed in the model through properties roll up in the flow down process.

The budgets have been maintained under table form with links to the proper generated requirements, as shown in Figure 14 where the cooling budget is spelled out as an example.

Unit	Power (W)	Flow [l/min]
cabinets	4102	7,79
Enclosure	2811	13,30
Panels	1440	2,73
<b>MAORY Sub-Total</b>	<b>8353</b>	<b>23,82</b>
<b>With Cont. 20%</b>	<b>10024</b>	<b>28.58</b>
<b>MAORY Tech Specs</b>	<b>14800</b>	<b>30</b>



Figure 14 Cooling budget management (summary table up) (requirement flow down bottom)

Below is spelled out the list of all system level budgets.

- Mass budgets
- Volume budget
- Power Budget
- Cooling power
- Heat Dissipation
- Alignment/Error budget
- Pointing Error Budget
- Time budget allocation
- Time to deliver performances
- Time to switch SCAO-MCAO
- Time to switch from off to stand-by and back
- Time to switch from stand-by to operational and back
- Time needed for preparation of nigh time operation
- First integration personnel allocation
- Dismounting personnel allocation
- RAMS budget allocation
- MTBF definition
- Unavailability limit in stable operation
- Availability limit during burn-in
- MCMT requirement
- preventive/predictive maintenance personnel allocation
- Overhaul plan

## 7. INTERFACE MANAGEMENT

In Figure 15 are schematized all the external interfaces of Morfeo. Morfeo receives light, mechanical support, coolant, electrical supply and network from Nasmyth platform.

Instrument and WFS cameras Workstations and RTC interfaces with Computer rooms, in terms of network, power supply and Mechanical support (inside cabinets).

Two optical interfaces are identified with Micado, input from Micado calibration Unit and output to Micado scientific instrument itself. In terms of Mechanical interfaces Micado provide support to the Micado Thermal cover, to M12 and to the LOR, while it supports the Micado Calibration Unit. Still under discussion (not baseline at the moment) the possibility to get coolant and power supply to the LOR electronics from the Micado SCP.

It also provides light to the second instrument.

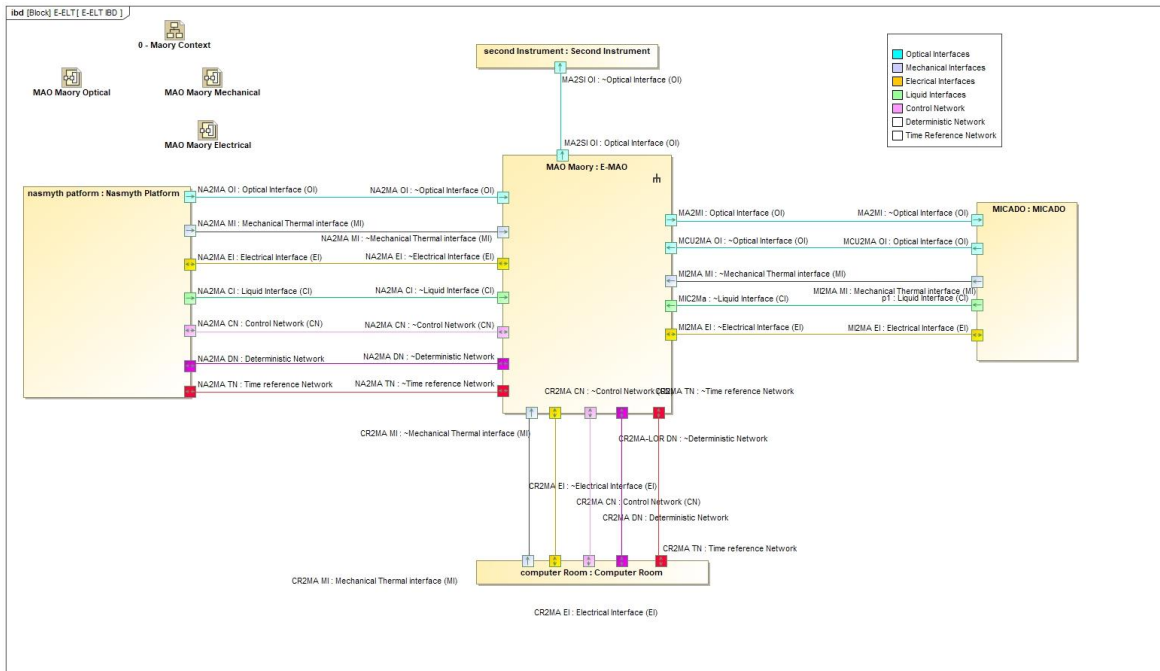


Figure 15 Morfeo External Interfaces

The internal interfaces have been modeled considering all the internal relationship and have been organized per topics. Five types of interfaces has been considered:

- Optical
- Mechanical Thermal
- Fluid
- Electrical Software

Whenever there is a relation between two subsystems, an Interface is identified. Each Interface is handled with proper documentations, according to the architecture shown below.

All the 29 relations between subsystems are summarized in the following N-squared diagram:

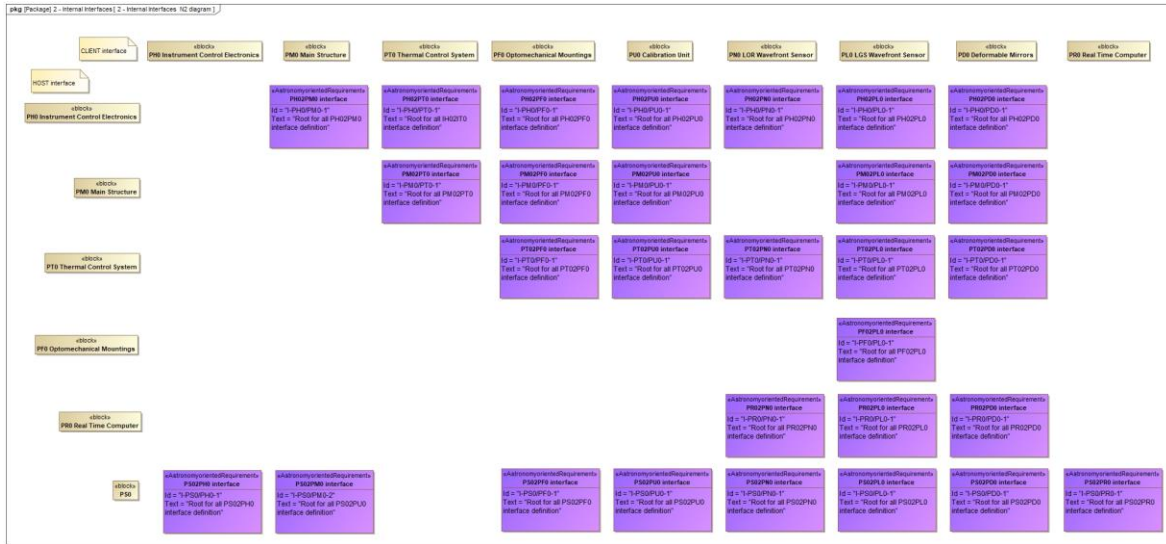


Figure 16 N 2 diagram of Morfeo internal interfaces.

Any of the violet blocks of Figure 16 represent an interface between two subsystems. Depending on the case, the interface can be of a single or multiple types. The carrier of interface is on the rows, while the passenger is on the columns.

The control of each interface is handled at different level as shown in Figure 17. At system level, it is created one Interface requirement document for Each of the 29 interfaces (brown block of Figure 17). In this document are listed all the agreed Interface related requirements. It will define then all the numbers and the duties of each side of the interface. It is handled by The SE and require the approval of both Interface sides. For completeness there will be also a short description of the interface.

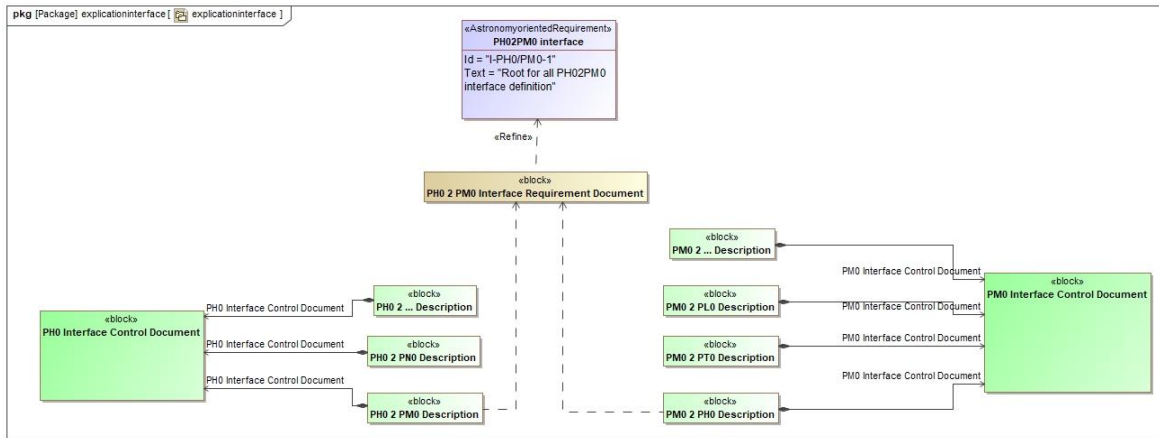


Figure 17 Scheme of the Interface Management (PM0 2 PH0) as an example.

Each Subsystem will have then a dedicated Interface Control Document (green Blocks) which will collect all the interfaces of this subsystem with any of the other subsystems. Each chapter of those documents (light green blocks) will describe, the subsystem's side of the interface (Carrier or passenger) and will show the compliances w.r.t. the related IRDs. In summary there will be 29 Interface Requirement Documents (brown blocks), 10 Interface control documents (green blocks) and in each Interface Control Document  $n$ -chapters, where  $n$  is the number of violet blocks of Figure 16 that belongs to the related work packages. This document is the Interface Requirement Document (brown block) between Instrument Control Hardware and LOR unit.

## 8. CONCLUSIONS

Significant role of the system engineering activity towards the successful PDR, has been the team motivation and smoothing of relationship. Each team member plays a special role and its contribution is crucial for the accomplishment of the mission. Proper motivation and engagement is determining technical success. COVID infection was a difficult obstacle to overcome, but the team spirit was so efficient and devoted that lead to a successful review despite of all the difficulties.

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