The MAORY/MORFEO MAIT strategy in Europe

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ABSTRACT

MAORY stands for Multi-conjugate Adaptive Optics RelaY (the name has been recently changed to MORFEO, which stands for Multiconjugate adaptive Optics For ELT Observations, thus in this article we will use MORFEO), and it is one of the instruments of the European Extremely Large Telescope (ELT). The main function of MORFEO is to relay the light beam from the ELT focal plane to the client instrument (initially MICADO) while compensating, through a multi-conjugate adaptive optics system, the effects of the atmospheric turbulence and other disturbances affecting the wavefronts coming from the scientific sources of interest.

The MORFEO instrument is designed and developed by a European consortium composed of INAF (Istituto Nazionale di AstroFisica, Italy), CNRS/INSU (Centre National de la Recherche Scientifique/ Institut National des Sciences de l'Univers, France), NUIG (National University of Ireland Galway, Ireland) and ESO (European Southern Observatory, Europe).

The opto-mechanical design of MORFEO has been developed in 3 dimensions, using the volume between the ELT output focal plane and the Nasmyth floor. The design uses the available volume in a very efficient way, but this poses constraints on the orientation of the optical elements and adds complexity to the AIT operations.

In this paper we describe the strategy of the AIT process which will be performed at INAF-OAS Bologna (Italy), which is conceived to maximize knowledge of the instrument and thereby optimize (and, possibly, minimize) the time requested at Armazones for the AIV operations.

Keywords: ELT, MCAO, MICADO, MAIT, Handling Tools, Support Equipment

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Adaptive Optics Systems VIII, edited by Laura Schreiber, Dirk Schmidt, Elise Vernet,
Proc. of SPIE Vol. 12185, 1218571 · © 2022 SPIE
0277-786X · doi: 10.1117/12.2629537

1. INTRODUCTION

MORFEO (previously MAORY[1][2]) is a wide field adaptive optics system, that will serve the MICADO[3] camera and a second instrument TBD of the ELT[4],[5]. MORFEO will take advantage of the ELT M4[6][7] adaptive mirror, which will deliver a partially corrected wavefront to the instrument.
MORFEO has to provide two adaptive optics modes to support MICADO (and, later on, the 2nd instrument):

- MCAO mode, in which at least two deformable mirrors are conjugated to different altitudes in the atmosphere; one of these deformable mirrors being the telescope M4. In MCAO mode; wavefront sensing is performed by up to six LGS and three NGS. The NGS are used for both Low-Order and Reference (LOR) sensing; wavefront compensation is performed by means of the telescope's M4/M5 mirrors and by one or two (TBC) post-focal DMs inside MORFEO. The choices to implement the MCAO technique and to use LGS for wavefront sensing have been taken to improve the uniformity of the correction over the field of view and the sky coverage. The MCAO technique[8] has already been demonstrated on sky by MAD on VLT[9][10] and, together with multiple LGS, by GeMS on the Gemini Telescope[11].
- SCAO mode, in which wavefront compensation is performed using M4 only. In SCAO mode; wavefront sensing is performed by a single NGS as close as possible to the direction of the scientific target in the sky; wavefront compensation is performed in this mode by means of the telescope's M4/M5 mirrors only

The MCAO mode has to be available at first light with at least one deformable mirror in MORFEO, with provision for a second deformable mirror as an upgrade, implying that MORFEO has to be designed for two deformable mirrors from the beginning, with one deformable mirror being possibly replaced by a rigid mirror.

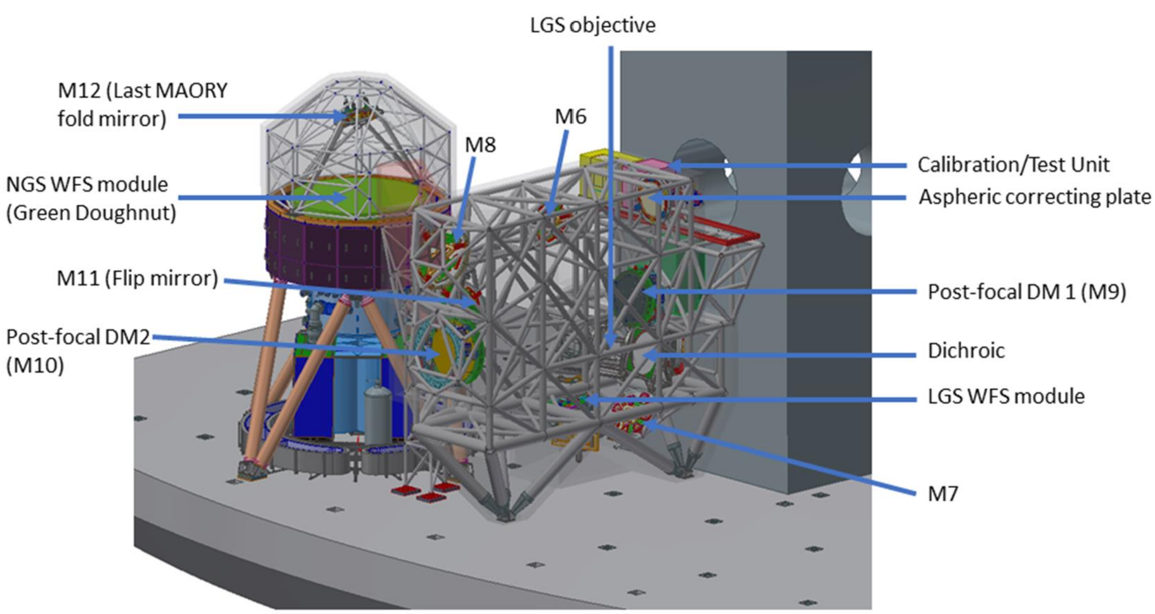


Figure 1: a 3-D view of the MORFEO instrument (the thermal cover is shown in transparency) installed on the Nasmyth platform with MICADO

The NGS wavefront sensor and the last MORFEO folding mirror (M12) are hosted in the same structure, the so-called Green Doughnut (GD), located above the MICADO instrument.
The MORFEO main structure, holding all the opto-mechanics of the bench and the main sub-systems, is a tubular structure which is connected to the Nasmith floor with 3 legs. A thermal cover will maintain the instrument temperature stable within a certain range.
In Figure 1 there is a view of the MORFEO instrument on the ELT Nasmyth platform, with the main sub-systems highlighted, which will be briefly described in the following.

In Figure 2 we report in fact the instrument product tree, which identifies the main MORFEO sub-systems, that we list in the following, together with the institute responsible of its design and MAIT:

- Main structure (main optical bench and supporting structure, including all the nessary HTs at sub-system level); INAF-OACN (Osservatorio Astrofisico di Capodimonte Napoli) is the responsible of this sub-system.
- Opto-mechanics (all the opto-mechanical components of the main train optical path, which is including all the optical components and their mounts and adjusting mechanism and all the HTs at sub-system level); INAF-OAB is the responsible of the opto-mechanics.
- Deformable Mirrors (two post focal DMs providing the correction of the upper part of the atmosphere, M9/DM1 convex with 1026 actuators, M10/DM2 concave with 1147 actuators); INAF-OAA is responsible of this sub-system.
- The Low Order and Reference (LOR) Module (which implements the Natural Guide Star Wavefront sensing functionalities needed by MORFEO in the MCAO mode); INAF-OAA is responsible of this sub-system.
- The LGS WFS module (dedicated to the measurements of the high order wavefront aberrations using as references the laser beams provided by the telescope). IPAG is responsible of this sub-system.
- The Calibration Unit (which is a system dedicated to the MORFEO calibration, equipped with light sources simulating the NGSs and LGSs); INAF OAAB ir responsible of this sub-system.
- Instrument Control SW (the SW controlling all the functions of the MORFEO instrument and providing interfaces toward ELT and MICADO); INAF OAPD is responsible of such a system.
- E2E Simulation Code (a simulation tool dedicated to estimate the performance of the MCAO system); INAF OAA is responsible of such a system.
- RTC (HW and SW controlling the AO real time MORFEO functions); INAF OAPD is responsible of this system.
- Instrument Control Hardware (controllers, power supplies, harnesses and other electronics components to control the MORFEO instrument at system level); INAF OACN is responsible of this system.
- Thermal Control System (which provides a passive shielding of the MORFEO instrument to maintain the instrument temperature stable within a certain range); INAF OAB is responsible of such a sub-system.
- Test Unit (a support equipment be used at PAE to verify the MORFEO AO performances); NUIG is responsible of this sub-system.
- ESO deliverables (WFSs detectors)

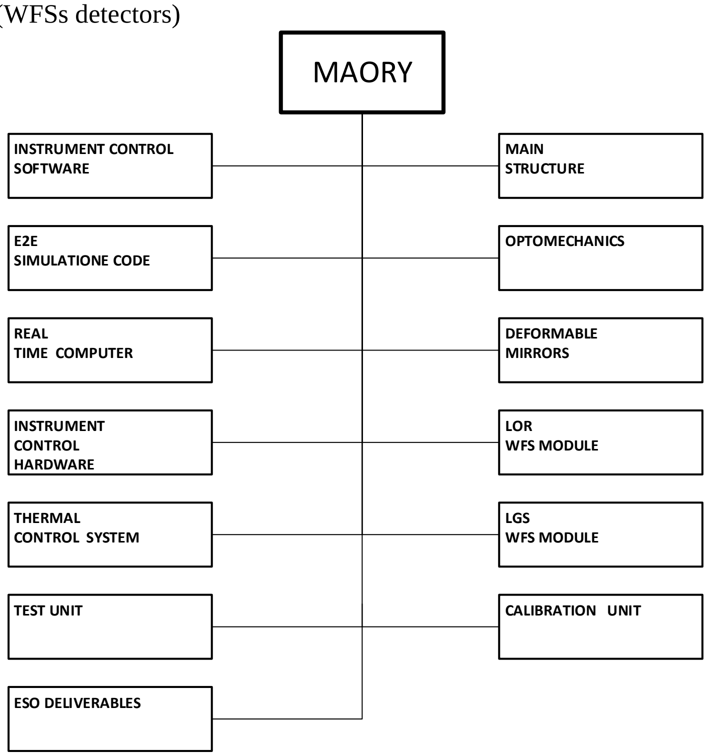


Figure 2: the MORFEO instrument product tree

2. MORFEO MAIT OVERVIEW

According to the current schedules, MICADO will be most probably installed at the ELT before MORFEO will be ready. For this reason, and for the difficulties to mimic the telescope behaviour, the final instrument performance of MORFEO + MICADO can only be assessed at ELT level. Furthermore, all the final interfaces and the "instrument to telescope alignment" can be only performed at ELT level too.

Therefore, a test/verification strategy has been developed based on:

- partial performance and functional test at MORFEO sub-systems level
- even though the MICADO camera will not be available, the alignment procedure will be performed considering the instrument performance throughout the whole FoV, to minimize the risk of more conventional on-axis alignment strategy. MICADO will be simulated by using a test camera moving over the full FoV.
- overall instrument test to characterize the instrument performance on and off-axis in a wide variety of situations
- an "instrument to telescope" alignment procedure defined accordingly the guidelines, defined by ESO, concerning the way to align to the ELT Nasmyth Pre Focal Station (PFS), which will be partially reproduced and tested also in the Bologna Integration Hall (BIH), by checking the capability to adjust the MORFEO MSS within the expected range and accuracy

We also recall the baseline assembly and alignment strategy, which has been presented at the trade-off review, consisting in the following main steps:

1. Main Support Structure (MSS) population with all the opto-mechanics and reference (Input Focal Plane (IFP) SMRs) for the Laser Tracker alignment, within a reasonable accuracy (see Table 1)
2. Fine tuning of the WFE acting on M10/DM2 tip/tilt and focus
3. Fine tuning of pupil and exit focal plane position by tip-tilting the last two flat mirrors, M11 and M12. If necessary, iterate with the previous step, since the alignment of DM2 will affect the position of the pupil and of the exit focal plane. No active corrections are necessary to the optics up to M10/DM2, simplifying the AIV procedure.
4. Alignment of the LGS Objective, using a laser materializing the main optical train chief ray
5. Alignment of the Calibration Unit (CU) to the output focal plane and pupil, already defined at step 3
6. Pupil and focal plane alignment within the LGS WFS, using the CU references
7. MORFEO to ELT Pre Focal Station (PFS) alignment test
8. MORFEO testing phase

Alignment Tolerances

	dx [mm]	dy [mm]	dz [mm]	tx [deg]	ty [deg]	tz [deg]
Plate	1,000	1,000	1,000	0,0083	0,0083	0,1666
M6	1,000	1,000	0,300	0,0083	0,0083	0,0000
M7	2,000	2,000	0,000	0,0083	0,0083	0,0833
M8	2,000	2,000	0,000	0,0083	0,0083	0,0833
M9	2,000	2,000	0,000	0,0083	0,0083	0,0000
M10	2,000	2,000	DoF	DoF	DoF	0,0000
Dichroic	1,000	1,000	0,300	0,0083	0,0083	0,0000
M11	1,000	1,000	0,300	DoF	DoF	0,0000
M12	1,000	1,000	0,300	DoF	DoF	0,0000

Table 1: the loose alignment tolerances of the various sub-systems, to be intended +/-

Concerning the alignment strategy just presented, it has to be emphasized that the MORFEO optical design allows for loose alignment tolerances of all the optics but M10/DM2 (see Table 1), the focus and TT of which are the only compensators permitting to fine tune the final optical quality of the wavefront delivered by the system (see Sec. 2.2). More information concerning what reported in the following sections can be found in [12][13][14][15][16][17][18][19].

2.1 Assembly and internal alignment

The opto-mechanical components assembly will require several dedicated Handling Tools (HTs) and the usage of Support Equipment (Seq), such as internal and external ladders, platforms and scissor lift to reach the various installation locations (see Figure 3).

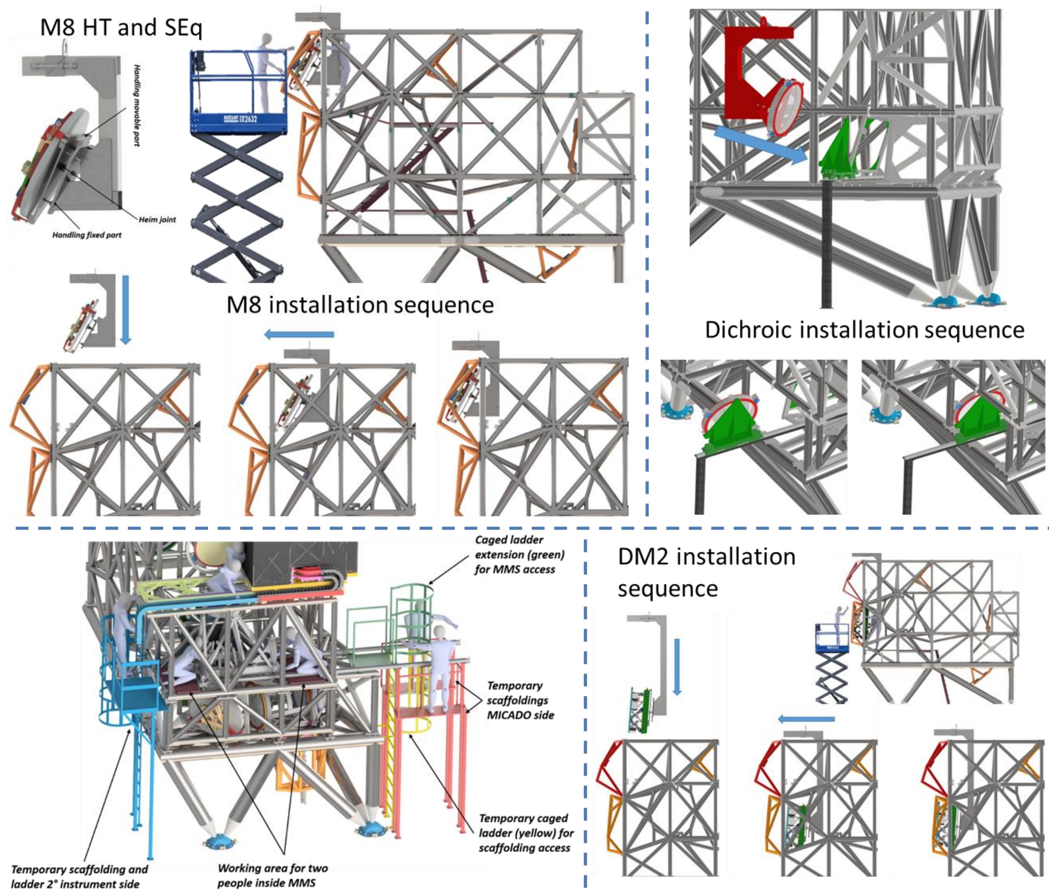


Figure 3: Some examples of Handling Tools and Support Equipments needed for the sub-systems assembly

For the alignment, with just 3 Laser Trackers (see Figure 4) all the opto-mechanics (but M10, which is the compensator) can be positioned within the required accuracy, which is very loose (as already shown in Table 1). All the optomechanical sub-systems need to have references (Retro Reflectors) chracterized wrt the optics.

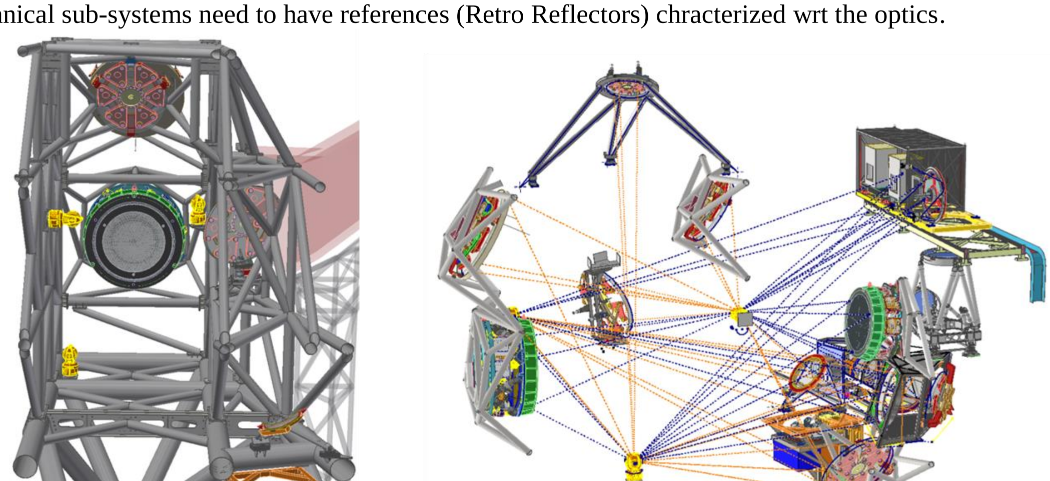


Figure 4: the positions of the 3 LTs allowing to spot the retro reflectors on each opto-mechanical component

The alignment of all the bench sub-systems/components is carried on wrt the Input Focal Pplane (IFP), which will be materialized through a flange that will be connected to the same interface of the MORFEO entrance window (the

Corrective Plate CP). Such a flange has 3 SMRs, positioned at the edge of the IFP on a circle, representing the IFP plane (see Figure 5).

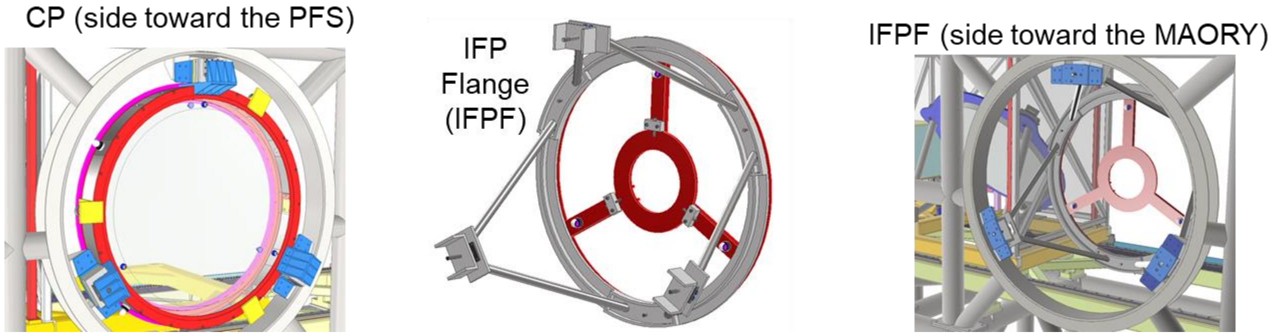


Figure 5: On the left side the Corrective Plate (CP), on the center and right side the IFP Flange that can be **installed** instead of the CP

The mechanical positioning error between the IFP flange on the MSS and the IFP nominal position has mainly this effect: a shift/TT of the focal plane would translate in an shift/TT of all the opto-mechanics, which can be compensated with an overall shift/TT of the MORFEO bench during the alignment of the MORFEO bench to the PFS, provided that we are within the MSS alignment range.

2.2 Wavefront Error fine tuning

The fine tuning of the WFE is performed acting on M10/DM2 tip/tilt and focus, retrieving the correction from the signal coming from a few references (Calibration Unit Fibres) distributed over the FoV; as already mentioned, the MORFEO optical design permits loose positioning tolerances on all the optical elements but M10, which is the only compensator needed allowing to recover the final optical quality delivered to MICADO, by moving in TT and focus (actuated with motors remotely controlled).
Simulations are showing that 5 positions in the field (one in the centre and four on a cross, almost at the edge of the diagonal field of MICADO) are enough to recover the necessary information (see Figure 6 left side), and the wavefront analysis on such positions has to be limited on to very low orders (defocus and astigmatism). Wavefront sensing in Europe will be thus performed on 5 sources of the Calibration Unit, positioning a technical camera (Test & Alignment Camera – TAC - spanning the overall MICADO FoV) on them (see Figure 6 right side), and the wavefront sensing method is partially inspired to the so-called Donut technique proposed in [20], that measures the optical aberrations from a single extrafocal image. This technique has been successfully implemented with LBC@LBT, SOAR and at the Blanco 4m telescope and it has the advantage of not requiring additional hardware other than a Test and Alignment Camera (TAC) for the first alignment (without MICADO) and the MICADO instrument in imaging mode for the final (re-)alignment at the Nasmyth platform.

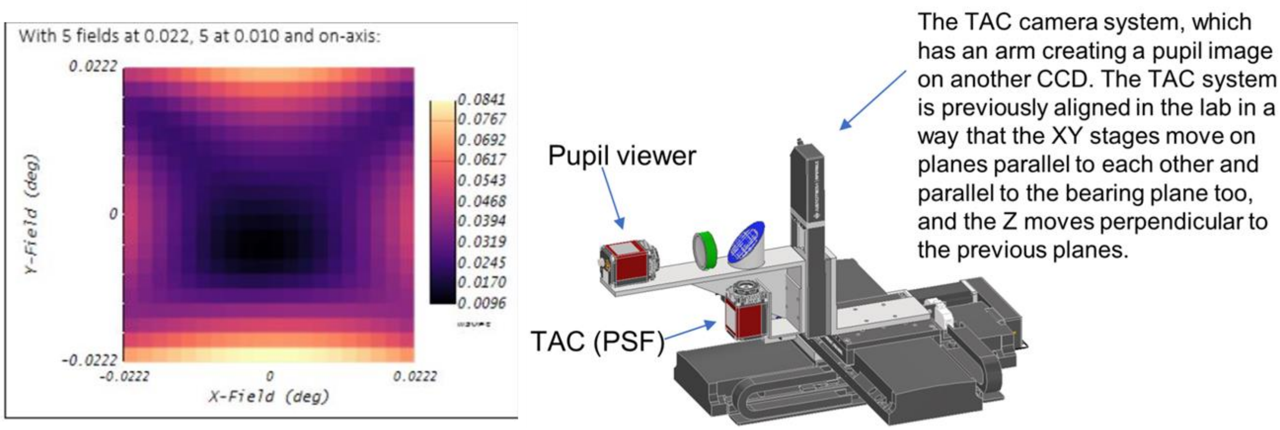


Figure 6: on the left side, the residual WF (nm) obtained tuning the optical quality with 5 references; on the right side, the TAC system

2.3 Pupil and Focal Plane alignment

In Europe we will use a system simulating the MICADO instrument, called MES (Micado Emulating Structure, shown in Figure 7), to which the MORFEO bench has to be aligned (mimicking the situation at the ELT, where MICADO will be positioned on the Nasmyth within the accuracy ±5mm in XYZ and ±0.58mrad in TT, and MORFEO has to be aligned to MICADO through M11 and M12, plus M10 for the focus). The MES (see next Figure) is essentially a structure which is holding:

- a bearing, simulating the one that will be used at the telescope by MICADO and by the LOR WFS
- a test camera (the TAC, working in J and H bands), connected to the bearing, and spanning the whole MICADO FoV on a XYZ motorized system
- the LOR WFS, also connected to the bearing
- the M12 sub-system and the cover

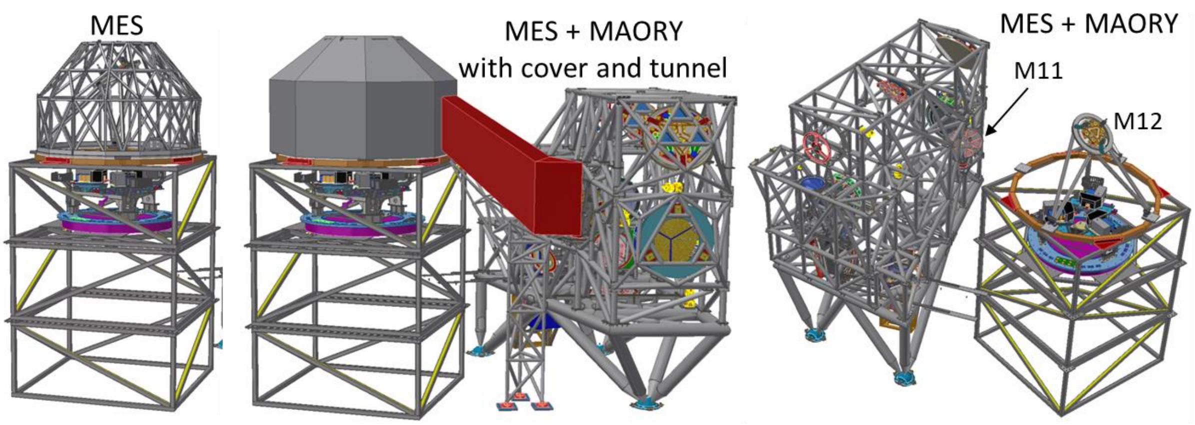


Figure 7: the MES (Micado Emulating Structure)

The fine tuning of pupil and exit focal plane position is performed by tip-tilting the last two flat mirrors, M11 and M12. M11 will move mostly the focal plane but also slightly the pupil plane and vice versa M12 will move mostly the pupil plane but also slightly the focal plane, and thus it will be an iterative process. Here below (Figure 8) you can see the results (100 montecarlo simulations) concerning the centroids of on-axis (top) and off-axis (bottom) PSFs at the interface focal plane between MORFEO and MICADO before (green) and after (blue) alignment (left side) and Pupil scollimation between the MORFEO pupil and the MICADO cold stop before (green) and after (blue) alignment (right side, the data are given in percentage of the pupil diameter.

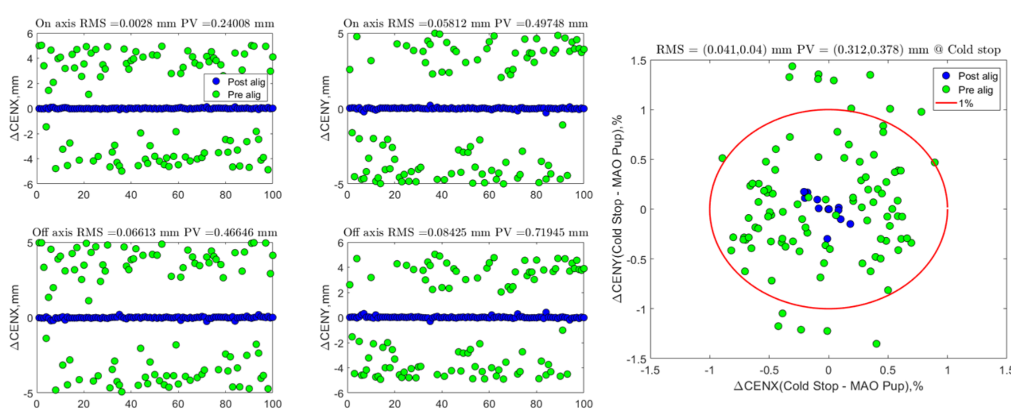


Figure 8: The results of the focal and pupil plane after fine tuning their alignment using M11 and M12 tip-tilt

2.4 LGS Objective Alignment

The procedure for the alignment of the LGSO (supposed to be integrated previously fully aligned) to the Main path foresees the usage of a laser, installed in the Input Focal Plane (IFP) Flange (IFPF) in its alignment configuration. The IFPF (introduced in Sec. 2.1 and shown in Figure 9) can in fact accommodate a laser, co-aligned with the IFP flange mechanical axis, which materializes the optical beam chief ray. The laser (mounted on a bearing and with centring and TT adjustment) is previously co-aligned with the centre of the IFP flange and with the beam perpendicular to the IFP. The laser flange is pinned, to allow precise repositioning if needed. The IFPF in its alignment configuration

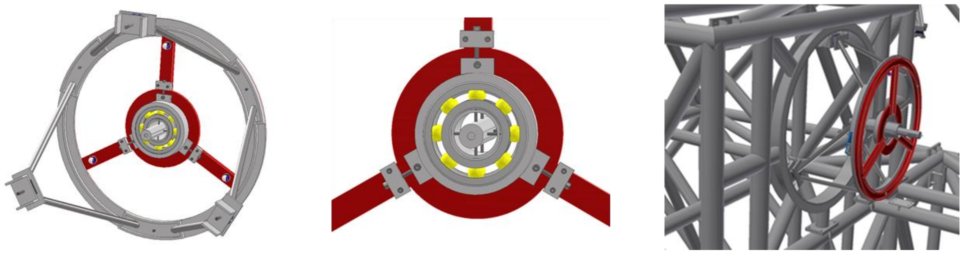


Figure 9: The IFPF in its alignment configuration

Given that the laser has to be transmitted by the dichroic, its wavelength has to be close to 589 nm. Refinement of the LGS-O alignment tolerances is ongoing, and depending on the precision required to the alignment, we are evaluating 3 ways:

- Pure mechanical alignment using LTs and RRs on the LGS-O characterized wrt optical parameters
- Mixed optical/mechanical alignment, based on 2 targets to be positioned with mechanical accuracy before L1 and after L4, using the target on L1 to centre the LGSO with the laser beam and the target on L4 to for the tilt FM1. In such way, the optical axis of the LGSO is aligned to the laser, i.e. to the chief ray of the central field.
- Optical alignment, using the transmitted and back-reflected spots to be superimposed to the laser beam.

2.5 Calibration Unit Alignment

The procedure for the alignment of the CU (supposed to be integrated fully aligned) to the Main path foresees to align it in TT, centering and focus by looking at the pupil and focal plane images seen the TAC system (described in Sec. 2.2), which is the lab camera simulating MICADO. M10, M11 and M12, already tuned to align MORFEO to MICADO (the TAC system in Europe) will not be touched.

The procedure is the following:

- We insert the CU folding mirror in front of the Corrective Plate and switch on the CU fibres which are diffraction limit
- By looking at the central fibre spot created in the TAC, we align the CU in focus (by acting on acting on the XYZ adjustments foreseen) till having a focussed image on the TAC.
- We align the CU in centring (acting on the XYZ adjustments foreseen) till having the spot in the field centre of the TAC (defined in step 8.4.42).
- We align the CU in TT (by acting on the TT of the CU folding mirror, see next figure) by minimizing the pupil wobble observed by rotating the bearing, by looking at a pupil image created using an additional arm on the TAC system (see Figure 10)

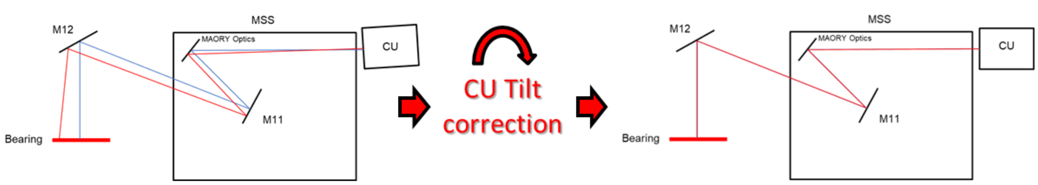


Figure 10: the CU Tilt correction looking at the pupil wobble on the bearing

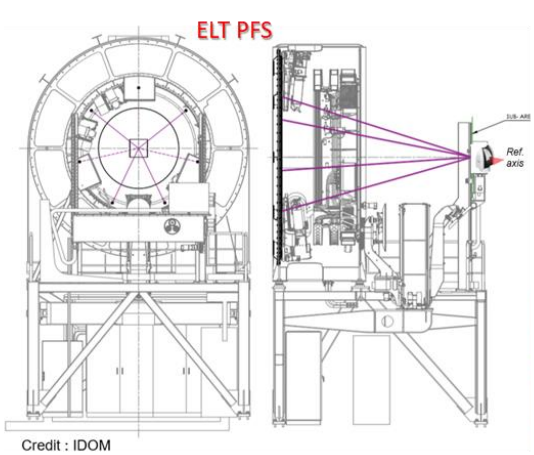
2.6 LGS WFS Alignment

The procedure for the alignment of the LGS WFS (supposed to be integrated fully aligned) is the following:

- Insert the CU and switch on the LGS fibres, in a way that each probes is looking at one fibre
- TT of the LGS WFS should be corrected (by acting on the 3rd LGSO folding mirror TT) by minimizing the differential defocus on the probes. Alternatively, the TT of the LGS WFS should cause a shift of all the pupils on the pupil probes, that should be visible by checking illumination of the SHs sub-apertures, that at the edge should be different (and equal for every probe) depending on the shift direction; TT of the LGS WFS should be tune to have all the sub-apertures at the edge radially equally illuminated.
- Decentre of the LGS WFS should be corrected by minimizing the common TT on the probes (by moving the whole LGS WFS)
- Adjust the F# by observing the illumination of the sub-apertures at the edge of the SH; if there is a radial variation of the light (meaning magnification of the pupil), move L4 along the optical axis to minimize the radial illumination variation
- Defocus of the LGS WFS should be corrected by minimizing the common defocus on the probes (by moving along the optical axis the whole LGS WFS)

2.7 MORFEO to Pre Focal Station (PFS) Alignment test

The plan for the alignment of MORFEO to the PFS at Armazones is to use the LTs provided by ESO inside the PFS (materializing the Nasmyth Output focal Plane) to measure the MORFEO Input Focal Plane, materialized through 3 SMRs on the outer part of the Corrective Plate (CP, which is also the MORFEO input window), which are the same used as reference for the MORFEO internal bench alignment, as explained in Sec 1. Once the MORFEO bench will be internally aligned, and before aligning it to MICADO (the MES in Europe, see Sec. 2.3), the overall bench will be aligned to the PFS acting on the legs adjusting systems (shown in Figure 11), which can provide the overall adjustment range described in the table here below. In Europe/Bologna, we will simulate a simplified version of the PFS, and test the capability to align the overall bench to it.



DoF	Value	Unit
Decenter z	+/- 2	mm
Decenter (x,y)	+/- 4.5	mm
Tip	+/- 0.67	mrad
Tilt	+/- 0.4	mrad
Rotation	+/- 0.1	mrad

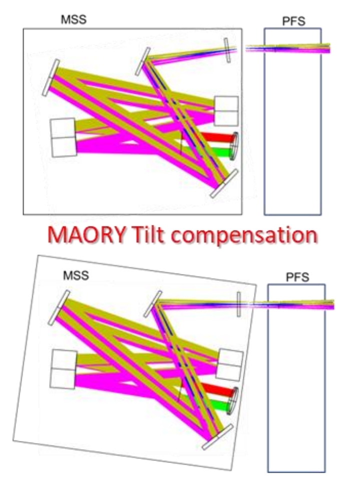


Figure 11: on the left the PFS with the LT used to materialize the ELT output focal plane, on the center the MORFEO legs adjusting system and its travel range, on the right a schematic of the overall instrument tilt adjustment

2.8 The MORFEO testing phase

Two main Support Equipment (Seq) are foreseen in Bologna to allow the instrument to be extensively tested:

- the MES has been already presented in Sec. 2.3, and has the purpose to emulate the MICADO system
- the Test Unit (TU) has the purpose to provide references to simulate both NGS and LGS, and to introduce turbulence allowing performance testing

Considering the similarities with what required to the Calibration Unit, it has been decided as baseline for the PDR to go for a common optical design, in which a flat mirror present on a pupil plane, in the optical path of the CU, can be exchanged with a DM.

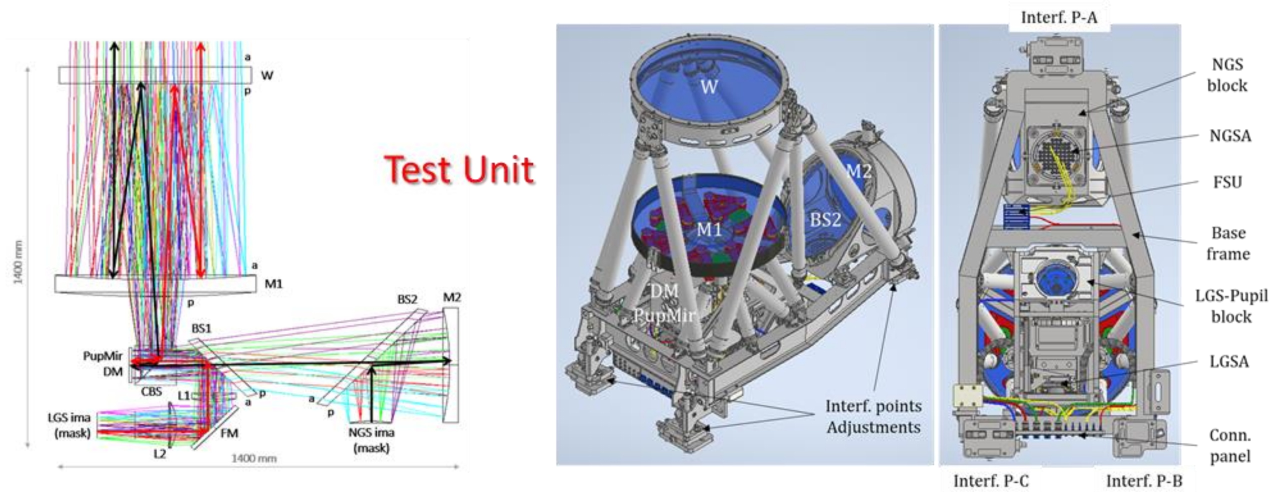


Figure 12: the MORFEO test unit

The TU will provide optical beams to MORFEO which are optically the same as the beams from the ELT i.e. the same f-number, focus position and field aberrations. These beams will emulate the beams coming from both Laser and Natural Guide Stars within a certain accuracy.

Turbulence will be injected into MORFEO software-wise, by applying it directly on the DM.

The TU will thus allow, *before* MORFEO is shipped to the ELT, to:

- perform the necessary optimizations and tuning at system level
- perform the overall system functional verification, including the verification of the main steps of acquisition sequence
- verify the technical calibration templates
- test the system performances

3. CONCLUSION

Instrumentations for the ELT have dimensions and complexity level which are comparable to the one of 4-8m class telescopes. This fact poses new challenges to the teams which have been designated to design and build them, mostly related to the increased importance of the assembly phase, which need to be properly addressed and assisted with several handling tools and support equipment, also keeping in mind the needs of the unavoidable maintenance that such complicated instrument will need. The integration phase has to be properly addressed too, since the accessibility to the opto-mechanical sub-systems is often complicated and requiring additional support equipment to reach them. Eventually, also the time needed to perform some critical operations is very important, above all for instruments that will have to be

Assembled/Integrated (AI) when the telescope will be already operative, meaning that the daytime for the AI operations will be limited to a few hours due to the necessary preparatory operations for the night observations.

In MORFEO, a number of handling devices/support equipment have been designed to allow the instrument assembly and the sub-systems installation. Maintenance operations requiring sub-system removal/re-installation have been thought to last a few hours, allowing to free as soon as possible the Nasmyth platform for the night operations.

The instrument integration is particularly "simple", since the optical design has been developed to have very loos tolerances for all the opto-mechanical components but a single compensator, which for MORFEO is M10/DM2, which allows to recover a very good optical quality by acting on its tip-tilt and defocus, which are motorized and remotely controllable. This fact allows to position all the opto-mechanics using laser trackers, targeting to retro-reflectors positioned on the optics previously characterized wrt the optical parameters, within accuracies which are achievable by the optics manufacturers (looking at the tolerances reported in Table 1 and considering the preliminary studies performed by possible providers).

The alignment of MORFEO to the ELT Pre Focal Station has been developed following the guidelines given by ESO, and will make use of the LTs present in the PFS, which materialize the ELT Output Focal Plane. Using the same PFS LT, we will materialize the position of the Input Focal Plane of MORFEO, by targeting the retro-reflectors which are installed on the corrective plate, which is also the instrument input window, perfectly visible from the PFS LT. The overall bench will then be moved accordingly to this measurements, till having the ELT OFP superimposed with the MORFEO IFP. We also recall that the same retro-reflectors installed on the corrective plate are used for the MORFEO internal opto-mechanics positioning/alignment, thus minimizing the error propagation.

Finally, the alignment of MORFEO to MICADO is performed to match the latter installation position on the Nasmyth platform (which has to be within a certain mechanical accuracy, as reported in Sec. 2.3), by using the tip-tilt of the last 2 MORFEO flat folding mirrors (M11 and M12, both motorized and remotely controllable) to align the focal and the pupil plane, and using the piston of M10 for the defocus.

All the mentioned operations will be tested in the BIH in Europe, using some additional dedicated support equipment to emulate MICADO and the PFS, in order to properly test all the procedures and the necessary handling tools, and the overall AI procedure, to possibly spot in advance all the possible problems and implement the necessary corrective actions, wishing to minimize the (unavoidable, but hopefully not serious) problems that will be encountered at Armazones.

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