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MORFEO Calibration Unit Optomechanical System – OFDR Alignment Plan

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1. Introduction

1.1 Content

This document describes the alignment plan of the MORFEO Calibration Unit, defined for the Optical Final Design Review (OFDR).

1.2 Common definitions, acronyms and abbreviations

AD	Applicable Document
AIV	Assembly, Integration and Verification
AO	Adaptive Optics
ARR	Acceptance Readiness Review
A.U.	Arbitrary Unit
BIH	Bologna Integration Hall
BW	Bandwidth
CMM	Coordinate Measuring Machine
CoG	Center of Gravity
CTE	Coefficient of Thermal Expansion
CU	Calibration Unit
ELT	European Extremely Large Telescope
ESO	European Southern Observatory
DL	Diffraction Limited
DM	Deformable Mirror
FDR	Final Design Review
FoV	Field of View
FWHM	Full Width at Half Maximum
HW	Hardware
ICD	Interface Control Document
ICH	Instrument Control Hardware
ICS	Instrument Control System
INAF	Istituto Nazionale di AstroFisica
INS	Instrumentation Software
INSU	Institut National des Sciences de l'Univers
IORR	Instrument Operations Readiness Review
IPAG	Institut de Planétologie et d'Astrophysique de Grenoble
IRD	Interface Requirement Document
LFP	Laser Focal Plane
LGS	Laser Guide Star
LOR	Low Order and Reference

LT	Laser Tracker
LUT	Look-Up Table
MAIT	Manufacturing Assembly Integration and Test
MAT	Micro-Alignment Telescope
MORFEO	Multiconjugate adaptive Optics Relay For ELT Observations
MCAO	Multi Conjugate Adaptive Optics
MICADO	Multi-AO Imaging Camera for Deep Observations
MMF	Multi-Mode Fiber
MOA	MORFEO Optical Alignment
MPO	Main Path Optics
MS	Main Structure
N/A	Not Applicable
NDF	Neutral Density Filter
NGS	Natural Guide Star
NUIG	School of Physics at the National University of Ireland Galway
OAAb	Osservatorio Astronomico d’Abruzzo
OAS	Osservatorio di Astrofisica e Scienza dello Spazio di Bologna
OD	Optical Density
PAC	Percentage Area Coverage
PAC	Preliminary Acceptance Review in Chile
PAE	Preliminary Acceptance Europe
PPS	Pupil Point Source
PCUP	Paraxial Calibration Unit Prototype
PDR	Preliminary Design Review
PFRO	Post-focal Relay Optics
PI	Principal Investigator
PM	Pupil Mirror
PSF	Point Spread Function
PT	Product Tree
PU0	MORFEO Calibration Unit subsystem/work-package
PUA	MORFEO Calibration Unit Optomechanical System
PV	Peak-to-Valley
QE	Quantum Efficiency
RAMS	Reliability, Availability, Maintainability and Safety
RD	Reference Document
RMS	Root Mean Square
RoC	Radius of Curvature
RON	Read Out Noise
RSS	Root Sum Squared
RTC	Real-Time Computer
SA	Sub-Aperture
SAG	Sagitta
SAT	System Architect Team

SCAO	Single-Conjugate Adaptive Optics
SE	System Engineer
SET	System Engineering Team
SL	Stray Light
SMF	Single-Mode Fiber
SMR	Spherically Mounted Retroreflectors
SNR	Signal to Noise Ratio
SOW	Statement of Work
SR	Strehl Ratio
SRR	System Requirements Review
SW	Software
TAC	Test & Alignment Camera
TBC	To Be Confirmed
TBD	To Be Defined
TBE	To Be Evaluated
TBW	To Be Written
TIS	Total Integrated Scatter
TFP	Telescope Focal Plane
WFE	Wavefront Error
WFS	Wavefront Sensor
WL	Wavelength
WP	Work Package

2. Related documents

2.1 Applicable Documents

The following applicable documents form a part of the present document to the extent specified herein. In the event of conflict between applicable documents and the content of the present document, the content of the present document shall be taken as superseding.

AD1 E-MAO-PU0-INA-DER-002_01 MORFEO Calibration Unit Optomechanical System – OFDR Design and Analysis Report

2.2 Reference Documents

The following documents, of the exact version shown herein, are listed as background references only. They are not to be construed as a binding complement to the present document.

RD1 https://wp.optics.arizona.edu/optomech/wp-content/uploads/sites/53/2016/09/Lab2_Alignment_procedure_V2.doc

3. PUA Internal Optical Alignment

In this section we describe a possible procedure preliminarily identified for the PUA internal optical alignment. The final procedure will be defined by the Contractor in agreement with the CU team.

The optical alignment of the PUA can be performed in two main steps:

a) Alignment of the “Telescope” Optics (TEL), composed of the Window (W) and the Spherical Mirror (SM)

b) Alignment of the Optical Bench (OB), including all the other optical components.

The split is represented in Figure 1. This separation is enabled by the nearly collimated NGS beam at the Pupil Mirror (PM), which provides an easy optical interface between the two blocks, each to be aligned as a functional, optical, standalone system. This is strictly true only for the NGS configuration and the NGS optical components. A different procedure will be applied for the LGS arm optics. However, the LGS optical alignment will benefit from the alignment of the NGS optics.

The split is also functional from the mechanical point of view, because of the different estimated masses of the optical components, reported in Table 1. The two largest components, W and SM, belong to the TEL subsystem, with an overall weight of about 60 kg (glass only), while all the others lie on a common center plane with a total mass of about 42 kg (glass only).

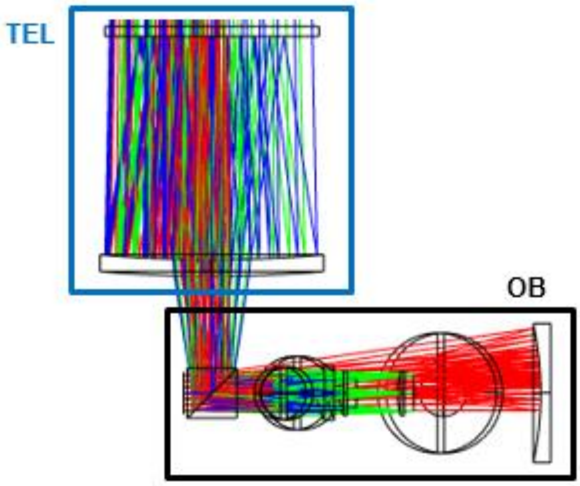

Figure 1. PUA alignment strategy: main alignment blocks.

Table 1. Weight of the PUA optical components (no mounts, CT = center thickness, ET = edge thickness).

Component	Aperture type	Size (mm)	Material	Weight (kg)	
W	Circular	Ø640 x 30 CT	Fused Silica	21.4	~60

SM	Circular	Ø670 x 50 CT	Fused Silica	38.7	
PM	Circular	Ø130 x 20 CT	Zerodur	0.7	~42
CBS	Square	150 x 150 x 150	N-BK7 / Fused Silica	8.5	
BS1	Elliptical	320 x 220 x 30 CT	Fused Silica / N-BK7	3.7	
BS2	Elliptical	480 x 330 x 30 CT	Fused Silica / N-BK7	8.2	
EM	Circular	Ø410 x 55 ET	Zerodur	14.4	
L1	Circular	Ø150 x 22 CT	S-BSL7	0.9	
D1	Circular	Ø160 x 38 CT	S-BSL7 S-NSL36	1.8	
D2	Circular	Ø135 x 33 CT	S-LAL18 S-TIH14	1.5	
LFM	Elliptical	220 x 160 x 25 CT	Zerodur	1.7	
				TOTAL	~102

3.1 Adjustments

<u>Coordinate axes definition</u>

The alignment degrees of freedom (DoF) of each optical component or an optical subsystem are defined with respect to their respective local axes:

- The Z-axis is the optical axis of the element / subsystem
- The Y-axis is defined in the plane of the drawings
- The X-axis completes the coordinate system according to the right-hand convention
- The origin is generally placed at the vertex of the first surface, except the CBS where it is more convenient to place it at its center.

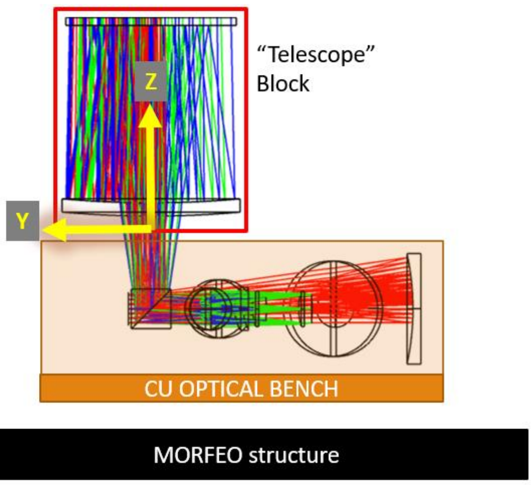

Figure 2. Schematic diagram of the local coordinate axes of the TEL subassembly.

Subassembly adjustments

The Telescope (TEL) will be interfaced to the Optical Bench (OB), as shown in Figure 2. Adjustments will allow to align the TEL with respect to the OB.

Currently, 5 DoF are required:

- 3 lateral displacements (DecX, DecY, DecZ)
- 2 rotations (RotX, RotY)

OB will be interfaced to MORFEO through kinematic supports. The adjustments between PUA and MORFEO are not included here (space has been reserved at system level, it is expected that up to 6 DoF will be required to align the PUA with respect to MORFEO).

Table 2. Adjustments for the TEL sub-assembly over the OB.

DoF	**DecX**	**DecY**	**DecZ**	**RotX**	**RotY**
Units	*mm*	*mm*	*mm*	*Deg*	*deg*
Range	±1	±1	±3	±0.2	±0.2
Resolution	0.05	0.05	0.03	0.003	0.003

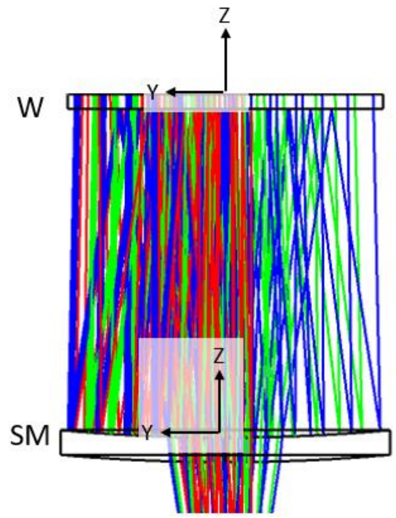

Figure 3. Local coordinate axes of the TEL optics.

Telescope adjustments

The Telescope (TEL) will be integrated and pre-aligned as a functional subassembly with respect to its mechanical interfaces to the PUA main frame. Adjustments such as temporary or permanent alignment screws or calibrated shims, will allow the alignment of W and SM with respect to its mechanical structure. Table 3 and Table 4 provide the range and resolution of the adjustments for W and SM, respectively.

Table 3. Adjustments for the Window (W).

DoF	**DecX**	**DecY**	**DecZ**	**RotX**	**RotY**
Units	*mm*	*mm*	*mm*	*deg*	*deg*
Range	NA	NA	±3	±0.1	±0.1
Resolution	NA	NA	0.03	0.001	0.001

Table 4. Adjustments for the Spherical Mirror (SM).

DoF	**DecX**	**DecY**	**DecZ**	**RotX**	**RotY**
Units	*mm*	*mm*	*mm*	*deg*	*deg*
Range	±2	±2	±3	±0.1	±0.1
Resolution	0.1	0.1	0.03	0.001	0.001

Optical Bench adjustments

All Optical Bench (OB) components will be interfaced to a common optical bench, except the doublet D2 and the LGS mask, both mounted onto a translation stage. The LGS subsystem components (L1, LFM, D1, D2, LGS mask interface, LGS translation stage) are likely to be mounted onto a common structure to facilitate their relative alignment. All other components will have single-component mounts: PM, CBS, BS1, BS2, EM, NGS mask.

The following figures and tables define the local coordinate axes and adjustments are given for each optical component of the OB.

Please note that:

- The fixed PM is a plano, slightly aspherical, mirror. Therefore, its RotZ should be irrelevant. However, in case it will be used to compensate for WFE, this will break its axial symmetry, thus requiring the clocking DoF.
- At the same time, when the PM is exchanged with the deformable mirror DM, it will be important to align its actuator grid with respect to some given orientation, thus requiring a good control of RotZ.
- The CBS is used in double-pass; then it acts both as a 45° mirror and a thick window. Only X-decenter does not introduce any change, apart from vignetting for large values. Y and Z-decenters affect pupil position (in its Z and Y axes). All rotations matter, affecting both the horizontal (TEL) and vertical (OB) optical axes.
- Both beam-splitters BS1 and BS2 work as a mirror and wedged windows (prisms). Due to their wedge, their clocking angle will need to be aligned.
- The EM is an axisymmetric ellipsoidal mirror, so that it is invariant for RotZ. It will be mostly used as final compensator for on-axis (power, 3rd spherical) and off-axis (coma) aberrations in the NGS arm.
- LGS lens L1, 45° folding mirror LFM, and LGS doublet D1 will be assembled to a common structure and optically aligned:
    - Each lens will be mounted in its own lens cell, which will control lens tilt in the arcmin range;
    - Each lens cell will move axially and laterally.
- The LGS mask linear stage will have the following characteristics:
    - Travel range: > 170 mm

- Focusing resolution: < 0.01 mm
- Pitch & Yaw: < 150 urad
- The translation axis must be parallel to the LGS optical axis within 0.1 mm along the whole travel range (=~0.5mrad=~1.5 arcmin)

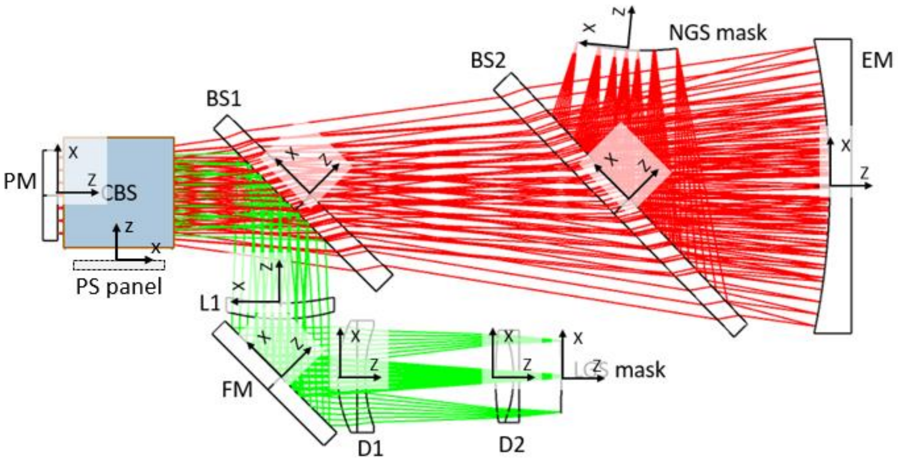

Figure 4. Local Coordinate axes of all OB optical components.

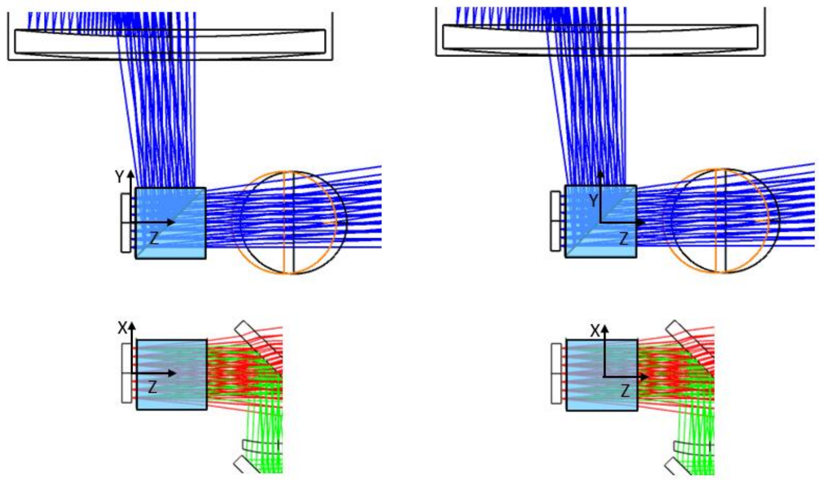

Figure 5. Local coordinate axes of the PM/DM (left) and the CBS (right).

Table 5. Adjustments for the Pupil Mirror (PM).

DoF	DecX	DecY	DecZ	RotX	RotY	RotZ
Units	*mm*	*mm*	*mm*	*deg*	*deg*	*deg*
Range	±2	±2	±2	±0.2	±0.2	±1
Resolution	0.02	0.02	0.05	0.002	0.002	0.05

Table 6. Adjustments for the Cube Beam Splitter (CBS).

DoF	DecX	DecY	DecZ	RotX	RotY	RotZ
Units	*mm*	*mm*	*mm*	*deg*	*deg*	*deg*
Range	±2	±2	±2	±0.2	±0.2	±0.2
Resolution	0.05	0.05	0.05	0.002	0.002	0.002

Table 7. Adjustments for the plano Beam Splitters (BS1, BS2).

DoF	DecX	DecY	DecZ	RotX	RotY	RotZ
Units	*mm*	*mm*	*mm*	*deg*	*deg*	*deg*
Range	NA	NA	±3	±0.3	±0.3	±0.3
Resolution	(*)	(*)	0.03	0.003	0.003	0.003
(*) Working in nearly collimated beams, translations in the plane of the optical component have no (X) or very small effects (Y), that can be compensated during the EM alignment.						

Table 8. Adjustments for the Ellipsoidal Mirror (EM).

DoF	DecX	DecY	DecZ	RotX	RotY	RotZ
Units	*mm*	*mm*	*mm*	*deg*	*deg*	*deg*
Range	±3	±3	±5	±0.2	±0.2	NA
Resolution	0.01	0.01	0.01	0.001	0.001	NA

3.2 Alignment procedures

Telescope

The TEL Assembly consists of two optical elements: one powered optics – SM – and one plano optics – W. Both elements are used in double-pass, being 50:50 beam-splitters. Therefore, they act as four optical elements, if considered as an unfolded system. However, those four elements are fully coupled, reducing the number of degrees of freedom to be controlled.

The spherical mirror has 5 DoF: piston, two lateral decenters, and tip & tilt (Table 4). It must be highlighted that the two lateral decenters affect the SM only when used in transmission (first pass), while have no impact in the second pass, when its concave spherical surface acts just as a spherical mirror, so that any decenter can be compensated by a tilt. Because the two SM tilts have almost zero power in transmission, lateral decenters have almost no impact on the WFE, while influencing the boresight and pupil position.

Only adjustments in lateral decenters are required to mechanically center it on its mount and no fine adjustments are required. The other three remaining fine adjustments (piston, tip, tilt) will be required to perform the optical alignment. The window also has only 3 DoF: piston, tip, tilt (Table 3). Overall, only 6 DoF are actually used to perform the optical alignment of the TEL. The two pistons control the relative distance between the two elements, and the global position of their assembly with respect to the pupil (PM), the former being the most important, because the other is quite insensitive. We conclude that axial positions can be achieved using only mechanical tolerances.

The remaining 4 DoFs are the rotations of the optics. They need to be controlled accurately, thus asking for some optical alignment.

A preliminary alignment procedure is described below.

- Before W and SM are integrated, an alignment telescope (or a pencil laser beam) is placed near the NGS focal plane and it is aligned to two targets, one placed in the center of the NGS focal plane, and the other one in the center of the Pupil. The folding mirror (45° mirror shown in black in Figure 6) is not really required, but it may help in setting up the system onto an optical bench, keeping in mind that SM and W will work with their optical axes aligned with the gravity vector.

- SM is inserted and its tip/tilt angles are adjusted by using the reflected ghosts. The two ghost images may overlap well, unless there is a large uncorrected lateral decenter. If so, the lateral position of SM (with respect to the axis defined by the centers of the NGS focal plane and the Pupil plane) has to be checked.

- W is inserted and its tip/tilt angles are adjusted using the back-reflection with the Micro-Alignment Telescope (MAT) in auto-collimation. The bottom surface of the W is semi-reflective at 50%. The MAT was previously aligned to two targets, one at the NGS output FP (entrance FP of MORFEO) and one at the CU Pupil.

- As a cross-check, an interferometer or SH wavefront sensor (TEL throughput ~12%) can be placed at the center of the NGS focal plane and a custom spherical reference mirror placed at the pupil to check the on-axis wavefront error (expected nominal residual WFE < 7 nm rms). Residual aberrations (defocus, coma) can be compensated by adjusting W axial position and tip/tilt.

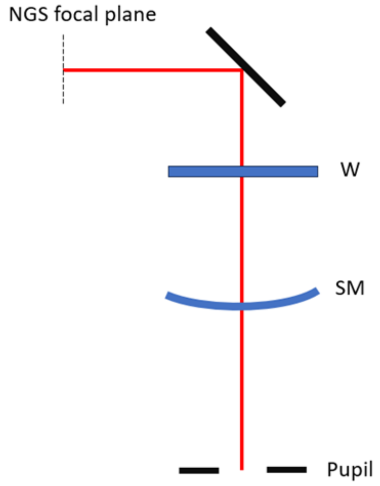

Figure 6. TEL Assembly optical elements and interfaces.

NGS arm optics

The optical elements residing on the optical bench and belonging to the NGS arm are shown in Figure 7. To help the alignment process, some targets are placed at the nominal positions defined by raytracing: one at the entrance port of the LGS arm assembly, one at the center of the NGS mask, and a third one opposite to the NGS mask. It may also help to have a fourth target on the center of EM, to facilitate the initial alignment of the reference beam.

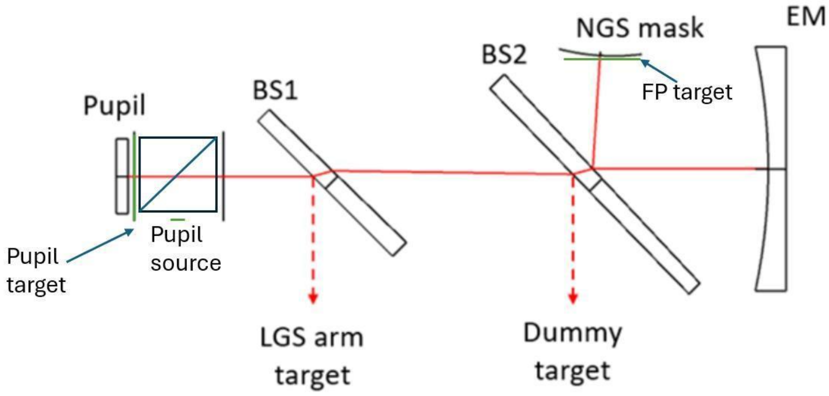

Figure 7. Main OB alignment elements and alignment targets (green).

The optical components that control the NGS arm are BS1, BS2 and EM. Two elements are plano optics (BS1, BS2), while the third is a powered optic (EM), and they have quite different behaviors in controlling the different optical performances. The two wedged plano optics mostly control boresight directions (both image and pupil), astigmatism and lateral color, while the ellipsoidal mirror will control focus and other coma aberrations. Keeping in mind this split between aberrations and related adjustments, it is possible to optically align the NGS arm optics.

Here are the main steps:

- A red pencil laser (e.g., at 633 nm) beam is aligned to the pupil center. The laser is also normal to the mechanical datum of the pupil plane, and can be visualized with an auxiliary flat mirror parallel to the mechanical interface. This laser beam allows control of the angles of the optical path for an initial coarse alignment that will be refined with the MAT.
- Targets are placed at the computed intercept positions on BS1, BS2 and the vertex of EM and they are installed at mechanical accuracy.
- Four additional targets are placed: at the “entrance port” of the LGS arm, on the NGS mask, at the pupil plane (3.5 mm away from the DM/PM) and properly positioned below BS2.
    - *NGS mask:* We conceive the presence of a removable alignment target, reflective surface + crosshair to be mounted on the cover of the NGS mask (item used to baffle the optical fibers), and positioned with a repeatability of ~50 um in

the center of the NGS mask cover, using small pins permanently mounted onto the NGS mask cover. The position of such a target shall be characterized with respect to the NGS mask cover with a CMM. The target is used to fine-tune TT and decenter of the NGS cover mask that is coaxial with the NGS focal plane mask.

- The laser direction is adjusted until the pencil beam hits the EM vertex (imprinted during manufacturing) and it overlaps to the cross-hair target at the pupil plane.
- BS1 and BS2 are adjusted (all rotation angles) until all reflected beams will hit all targets.
- The CBS is integrated in front of the pupil and adjusted in 5 DoF (2 lateral decenters + 3 rotations). Additional laser targets will be installed on the CBS faces and the alignment is performed by looking at them and at the reflected ghosts produced by the different optical surfaces of the CBS. Five out of six CBS DoFs are relevant to the alignment procedure. A black mask is placed between the CBS and the BS1 to avoid additional images. The CBS defines two pupil planes, one in correspondence of the PM/DM and the other one at the bottom of the CBS. The alignment target (green planes in Figure 7) will be installed in the pupil plane in front of the pupil mirror (plus the target at the NGS mask). The pupil source at the bottom of the CBS can also be used as a reference point during the alignment of the CBS to the NGS arm. The alignment is achieved focusing the MAT (placed upstream the CBS) on the three targets alternately and setting the CBS position until their images overlap on the axis. Once the horizontal branch of the PUA optics is fully aligned (NGS+CBS), these three targets guide the mutual alignment between the TEL and the NGS optical path with a comparable procedure having the MAT upstream of W.

It must be emphasized that the two beam-splitters, due to their wedge, will send the pencil beam out of plane (the same plane of the figure), when their RotZ is wrong. This is why targets along the nominal path will help to control this DoF on them. Moreover, if the laser beam is bright enough, secondary reflected ghosts will be generated, which will help to further control this angle. Ray-tracing will help to compute the sensitivity of the position of those secondary spots with respect to the RotZ angle. The required accuracy in spot position has been estimated to be a fraction of a millimeter, easily visible by eye. Once this is achieved on all targets, the position of all optical elements in rotation is good enough.

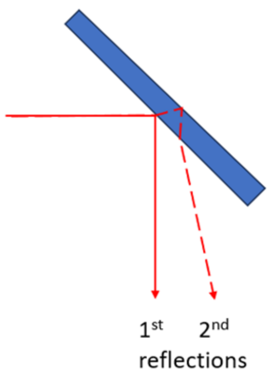

Figure 8. Secondary ghost on BS1 and BS2.

As in the case of the TEL Assembly, an interferometer or Shack-Hartmann (SH) wavefront sensor can be placed at the center of the NGS focal plane and a custom spherical mirror placed at the pupil to check the on-axis WFE. Nominal aberrations are mainly primary spherical, that can be easily measured and compared with its nominal value used as reference. The main aberrations are expected to be defocus and coma. Then, by using the adjustments in piston, it is possible to remove the defocus. Any residual coma will be controlled by the lateral decenter of EM. By doing so, a small boresight error is introduced between the pupil center and the NGS mask center, thus requiring small tip/tilt adjustments of the EM. This is automatically accomplished using an interferometric setup, by keeping the number of fringes small, because any boresight error will translate into tip/tilt of the WFE.

<u>LGS assembly</u>

The LGS Assembly contains the LGS optics, the LGS mask and its linear stage to switch between the conjugated altitudes. This linear mechanism is also very useful to adjust for any differential focus between the NGS and LGS arms which may arise during the operational life of the PUA, and also as refocusing mechanisms for the LGS beams, to offload, for example, any excess of focus term measured by the LGS WFSs.

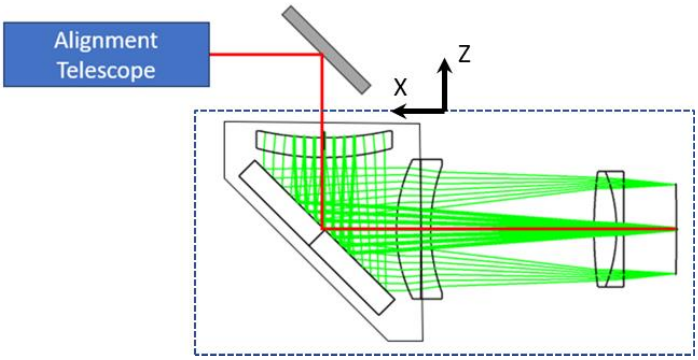

Figure 9. LGS assembly alignment setup.

During the alignment process, the main goal is to align the optical components with respect to the linear mechanism axis, selected as the reference axis.

Here are the main steps.

- The LGS Assembly is mounted onto an optical bench, together with an alignment telescope and an auxiliary folding mirror in front of the LGS entrance port, corresponding to the center of the first lens (see Figure 9). The alignment telescope is equipped with a point-source generator (also known as “PIP” [RD1]), aligned with the telescope axis. This auxiliary source provides a bright spot object that can be reflected by optical surfaces, even when they are anti-reflection coated, because the source intensity can compensate for the low reflectivity of the optical surfaces.

- With no lenses in place and just the LGS folding mirror (LFM) installed, the axis of the alignment telescope is centered on the LGS arm entrance port, where a dummy target is placed, and to the LGS mask center, placed in the closest position.
- The LGS mask is then positioned at its furthest position by moving the linear stage, and the center of the LGS mask is measured again. If the image is decentered, then the axis of the alignment telescope does not match the axis of the stage. Then, by acting on the two folding mirrors (LFM and the auxiliary one), it is possible to overlap the two axes. This is an iterative process. To converge, one folding mirror is used to control the centering of the LGS mask in one position, and the other folding mirror in the other one. Because the two folding mirrors will change both images, being coupled, the convergence is slow, and some overshoot may help.
- Once the alignment telescope is aligned, the LGS lenses can be installed, one at a time, starting from the one close to the LGS mask, and looking at reflected ghosts from both external surfaces (the internal surface of the doublet D1, being made with two materials with the same refractive index, produces no reflection). All lenses need to be aligned in 5 DoF using their decenter and tip/tilt adjustment mechanisms. Given the limited amount of space in the LGS optical assembly the use a PIP generator mounted in front of the MAT. This item generates a point source in front of the LGS optics, and the ghosts produced by the two surfaces of the LGS lenses materialize the optical axis of each lens that can be with opto-mechanical axis identified at step 2 and 3. This procedure allows us to get rid of the opto-mechanical targets whose placement and referencing with respect to the LGS optics is not trivial.
- The sensitivity of the LGS lenses to their axial position is 5 nm WFE / 0.2 mm of piston (with re-focusing performed by the stage). Considering 3 fixed lenses, the rms WFE can develop up to 8.7 nm assuming the contribution from each lens (5 nm rms) is combined in quadrature with the others. The focus term of the LGS objective will be fine-tuned during the LGS assembly and alignment using, for example, a WFS.

<u>PUA Assembly</u>

To align the overall PUA, three main subassemblies need to be put together: TEL, OB, LGS arm. We may start by aligning the LGS arm with OB:

- The alignment telescope will be realigned at the PUA pupil interface.
- The LGS arm is installed and adjusted until both the LGS mask center and the LGS arm entrance port center are aligned to the optical axis of the alignment telescope.
- There is no need to control the axial position of the LGS arm, because any small displacement will be easily accommodated by the LGS linear stage.
- There is no need to control the rotation along the axis, because the LGS mask can rotate, too.
- The TEL is installed and adjusted only in lateral position, while the other DoFs will be defined by mechanical tolerances.

Once TEL is centered, the Pupil Mirror (PM) alignment procedure starts:

- The alignment telescope is centered at the center of the NGS mask or at the NGS focal plane, whichever is more convenient. The alignment telescope is well aligned when both the center of the pupil, visualized by a dummy target at the pupil position, and the center of the NGS conjugated plane lie on the telescope axis.
- The dummy target at the pupil plane is removed and the PM is installed.
- The PM is adjusted in lateral decenter by looking at a centering mask in front of the PM itself, while its tip/tilt is controlled by looking at the centering of the conjugated image.

Once these main alignments are done, it is still possible to measure some residual aberrations by placing a SH WFS, given the low PUA throughput, at the center of the NGS mask and a point source at the center of the NGS focal plane. It is quite useful to check WFE both on-axis and off-axis, within a grid of points spread of the full technical FoV of the PUA.

Any focusing error can be easily adjusted by moving EM in its axial position, while any residual lateral coma can be removed by tip/tilt fine adjustments of the PM.

If after that there are still some residual aberrations above the requirements, it is likely that they will come from the CBS. In this case, it is possible to apply the compensation strategy described in AD1.

4. PUA External Optical Alignment

The alignment of the PUA to the MORFEO Main Path Optics (MPO) is achieved in three steps:

1. An initial alignment of the PUA and the Calibration Unit Folding Mirror (CUFM) to MORFEO driven by the Laser Tracker (LT) feedback;
2. A fine optical alignment optimizing the image quality at the MORFEO output focal plane using the TAC imaging channel;
3. The PUA pupil registration onto the MORFEO NGS and LGS WFSs.

4.1 Initial alignment with laser tracker

The PUA shall be equipped with at least six Spherically Mounted Retroreflectors (SMRs) placed around the W holder and in proximity of the PUA support points. PUA is brought in its nominal position within the MORFEO bench using the LT feedback. In this alignment step two people shall adjust the kinematic supports at the base of the PUA until the PUA position meets the nominal one (cad position within the MORFEO Main Supporting Structure [MSS]). The same procedure is followed to bring the CUFM in its nominal at LT accuracy.

4.2 Fine optical alignment - image quality optimization

Once the PUA is placed at LT accuracy in its nominal position, its alignment is optimized using the optical feedback from the TAC at the output focal plane of MORFEO. The CU NGS-LO sources (diffraction-limited, H-band) are re-imaged at the MORFEO Test-Alignment Camera (TAC) focal plane.

The best focus position can be achieved in two ways: repositioning the PUA in height by acting simultaneously on the three kinematic supports; by refocusing the NGS mask with a motorized NGS mask.

The lateral registration of the PUA focal plane to the MORFEO focal plane is achieved by adjusting the kinematic supports to reposition the PUA in its plane. The observable at the focal plane is the centroid of the on-axis PSF of the PUA+MORFEO system as observed with the TAC.

4.3 Fine optical alignment - exit pupil registration

The lateral position of the PUA exit pupil is efficiently controlled by the tip-tilt of the CUFM which is close to the MORFEO entrance focal plane and takes advantage of a high optical leverage. Two techniques can be deployed:

1. Minimizing the pupil wobble observed during a rotation of the TAC bearing, by looking at the image of the PUA pupil sources re-imaged by the TAC pupil imaging arm; the accuracy achievable with this procedure is of the order of 10 um (size of 1 TAC camera pixel). The bearing runout is estimated at 60 um;

2. Minimizing the image spot wobble at different defocus configurations during a rotation of the TAC with the bearing. This latter technique takes a longer time, but it can be a valuable sanity check of the first technique.

5. PUA and CUFM repeatability

Table 9. Relevant requirements for PUA and CUFM repeatability.

MAO-PU0-1.2.7.22 **Pupil mask alignment**	Pupil shift smaller than 1% of pupil diameter with respect to the average telescope pupil image position
MAO-PU0-1.2.7.23 **Reproducibility of sources position**	Relative (distances between each other) and absolute (position of the assembly w.r.t. the optical axis) stability of the sources smaller than 1” on sky (in all operational conditions)
MAO-PU0-1.2.7.26 **Sources alignment**	The whole grid of sources shall be aligned with a minimum accuracy of 2” on sky (between CU and MORFEO optical axes)

Table 10. Relevant numbers summary.

1” on-sky	centroid shift of 3.7879 mm at MICADO FP, MICADO LRI PS = 0.264 asec/mm
WFE allocated budget for CU-MORFEO interface	15 nm RMS
Pupil shift at the cold stop of MICADO	< 1%
CUMB feet separation	670 mm in X, 1519 mm in Y
CUMB feet minimum gear	(5deg rotation) step 0.017 microns along X, 0.02 microns along Y

Table 11. Repeatability requirements for the CU selector mechanism and the CUMB interface points

CUFM (selector mechanism)			
Degree of Freedom	**-Tol**	**+Tol**	**Comment**
Piston CUFM	-0.1 mm	+0.1 mm	Worst offender
Dec X CUFM	-0.1 mm	+0.1 mm	
Dec Y CUFM	-0.1 mm	+0.1 mm	
Tip X CUFM	-0.01°	+0.01°	
Tilt Y CUFM	-0.01°	+0.01°	
Rot Z CUFM	-0.25°	+0.25°	
Total mean ΔWFE	**13 nm**		
Focal plane shift at MICADO LRI	**(0.011”, 0.012”)**		
Pupil shift at cold stop	**(0.54%, 0.57%)**		
Pupil shift at MORFEO exit pupil	**(0.49%, 0.52%)**		
PUA (support points)			
Degree of Freedom	**-Tol**	**+Tol**	**Comment**
Piston PUA	-0.1 mm	+0.1 mm	Worst offender
Dec X PUA	-0.1 mm	+0.1 mm	
Dec Y PUA	-0.1 mm	+0.1 mm	
Tip X PUA	-0.025°	+0.025°	
Tilt Y PUA	-0.025°	+0.025°	
Rot Z PUA	-0.05°	+0.05°	
Total mean ΔWFE	**6.9 nm**		
Focal plane shift at MICADO LRI	**(0.045”, 0.055”)**		
Pupil shift at cold stop	**(0.81%, 0.74%)**		
Pupil shift at MORFEO exit pupil	**(0.37%, 0.67%)**		
CUMULATIVE (RSS)			
Total mean ΔWFE	**14.72 nm < 15 nm**		
Focal plane shift at MICADO LRI	**(0.046”, 0.056”) < (1”,1”)**		
Pupil shift at MICADO cold stop	**(0.97%, 0.93%) < (1%, 1%)**		
Pupil shift at MORFEO exit pupil	**(0.62%, 0.85%) < (1%, 1%)**		

In Figure 10 we report the CUFM degrees of freedom in Zemax world to be translated into the MORFEO selector mechanism (carrying the MCA and CUFM) reference frame.

In Figure 11 we report the PUA degrees of freedom in the Zemax world to be translated into the MORFEO MSS reference frame.

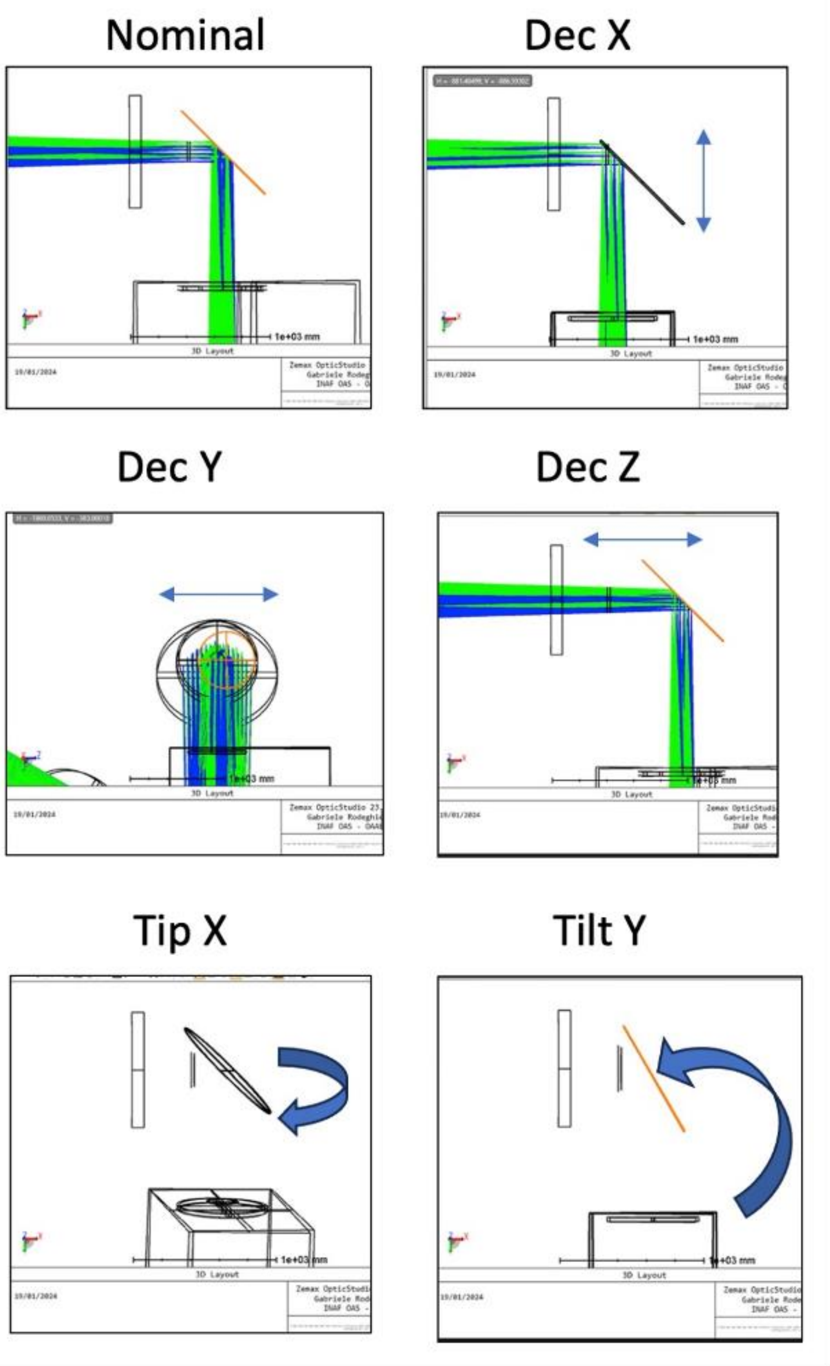

Figure 10. CUFM degrees of freedom in Zemax to be translated into the MORFEO selector mechanism (carrying the MCA and CUFM) reference frame.

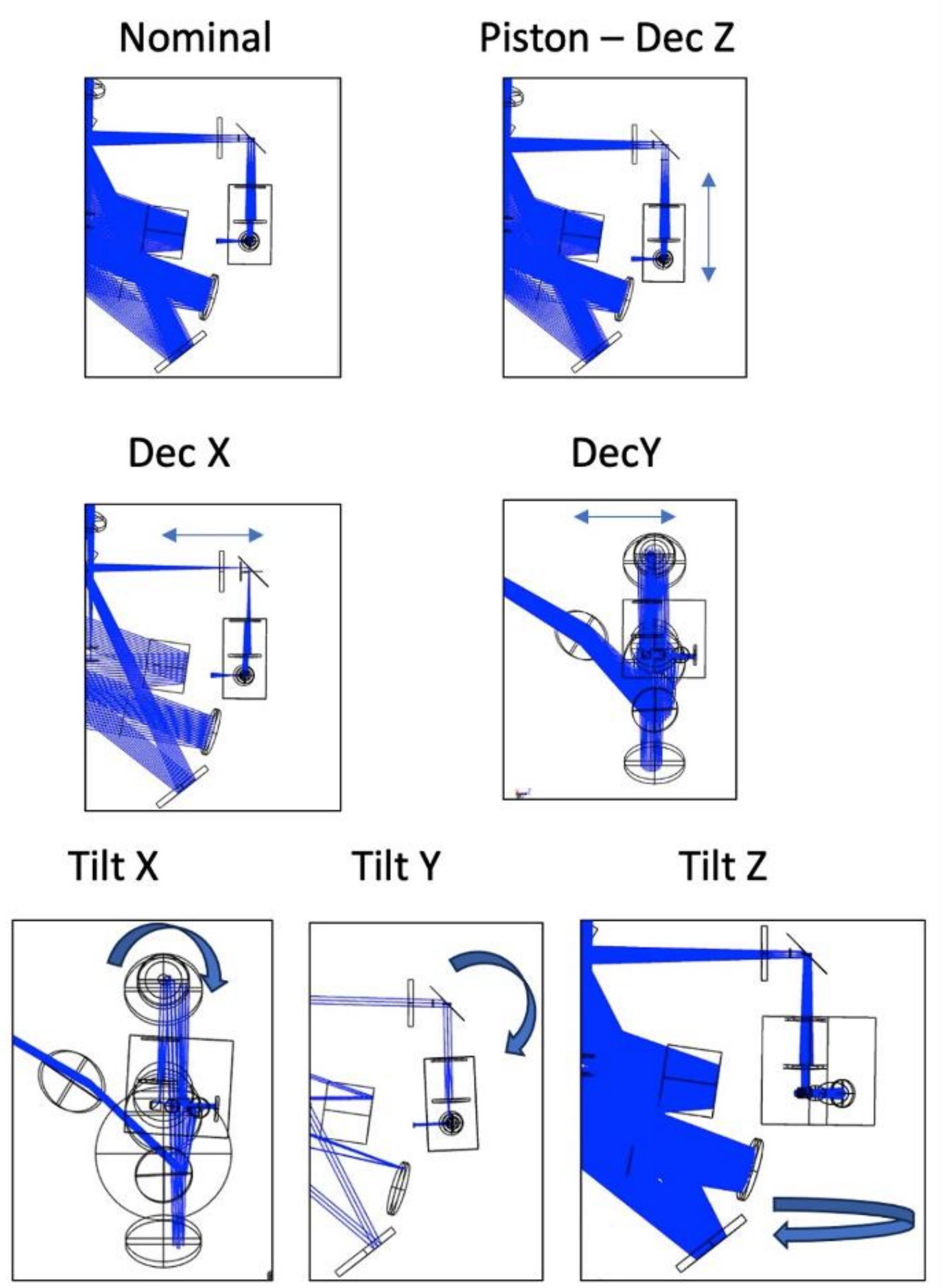

Figure 11. CUMB degrees of freedom in Zemax to be translated into the MORFEO MS reference frame.

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