



Publication Year	2022
Acceptance in OA	2025-03-07T14:34:22Z
Title	MORFEO optical design and performances: status at preliminary design review
Authors	PARIANI, Giorgio, MAGRIN, DEMETRIO, MUNARI, MATTEO, Rakich, A., Delabre, B., Kosmalski, J., Rabou, P., BIANCO, Andrea, BERGOMI, Maria, REDAELLI, Edoardo Maria Alberto, ALIVERTI, Matteo, OGGIONI, Luca, FARINATO, JACOPO, RODEGHIERO, Gabriele, GREGGIO, Davide, CIANNIELLO, Vincenzo, DE CAPRIO, VINCENZO, BUSONI, Lorenzo, FOPPIANI, Italo, RIVA, Marco, DI GIAMMATTEO, Ugo, CILIEGI, Paolo
Publisher's version (DOI)	10.1117/12.2629415
Handle	http://hdl.handle.net/20.500.12386/36527
Serie	PROCEEDINGS OF SPIE
Volume	12185

MORFEO optical design and performances: status at preliminary design review

G. Pariani^{a*}, D. Magrin^b, M. Munari^c, A. Rakich^d, B. Delabre^e, J. Kosmalski^e, P. Rabou^f, A. Bianco^a, M. Bergomi^b, E. Redaelli^a, M. Aliverti^a, L. Oggioni^a, J. Farinato^b, G. Rodeghiero^{g,h}, D. Greggio^b, V. Cianielloⁱ, V. De Caprioⁱ, L. Busoni^l, I. Foppiani^g, M. Riva^a, U. Di Giammatteo^g, P. Ciliegi^g

^aINAF – Osservatorio Astronomico di Brera, via E. Bianche 46, 23807 Merate, Italy;

^bINAF – Osservatorio Astronomico di Padova, Vicolo dell’Osservatorio 5, 35122 Padova, Italy;

^cINAF – Osservatorio Astrofisico di Catania, Via S. Sofia 78, 95123 Catania, Italy;

^dMersenne Optical Consulting, 41 Rimu Rd., Raumati Beach, Paraparaumu 5032, New Zealand;

^eESO, Karl-Schwarzschild-Strasse 2, D-85748 Garching bei München, Germany

^fIPAG – Institut de Planétologie et d’Astrophysique de Grenoble, 414, Rue de la Piscine, Domaine Universitaire, 38400 St-Martin d’Hères, France;

^gINAF – Osservatorio di Astrofisica e Scienza dello spazio, Via Piero Gobetti 93/3, 40129 Bologna, Italy;

^hINAF – Osservatorio Astronomico d’Abruzzo, Via M. Maggini s.n.c., 64100 Teramo, Italy;

ⁱINAF – Osservatorio Astronomico di Capodimonte, Salita Moiariello 16, 80131 Napoli, Italy;

^lINAF – Osservatorio Astronomico di Arcetri, Largo Enrico Fermi 5, 50125 Firenze, Italy.

ABSTRACT

MORFEO, formerly known with the acronym MAORY, is the Multi-Conjugated Adaptive Optics (MCAO) module for the European Extremely Large Telescope (ELT). MORFEO is designed to feed the Near Infrared (NIR) camera MICADO with both MCAO and Single-Conjugated AO (SCAO) operation modes. The optical configuration provides a one to one imaging of the telescope focal surface on two ports (one feeding MICADO and the other dedicated to a future instrument) and it is equipped with two post-focal deformable mirrors together with the Laser Guide Star (LGS) and Natural Guide Star (NGS) channels for wavefront sensing and tomographic reconstruction.

In this paper, we present the status of the optical configuration at the completion of the Preliminary Design Review (PDR). We will focus our attention on the tolerance analysis of the elements, consisting in both manufacturing and alignment, to provide the expected performances of the instrument after initial integration. We will also present the outcomes of the stability analysis of the instrument, consisting in rigid-body motions and thermoelastic deformations of the structure and optomechanics, used to define the procedures and benchmark to maintain the instrument performances during operation. Details on the integrated modelling, specifically developed for this purpose, will be provided.

Keywords: MORFEO, ELT, Adaptive Optics, high frequency errors, stability

1. INTRODUCTION

The main function of MORFEO is to relay the light beam from the ELT focal plane to the client instruments, while compensating the effects of the atmospheric turbulence and of the other disturbances of the wavefront. The MORFEO main path optics (MPO) [1][2] provides a one-to-one image of the ELT focal surface to MICADO focal entrance focal plane [3] and to a second instrument port focal plane. The optical system splits, near the pupil, the light of infinitely distant sources from the light of 6 Laser Guide Stars (LGS), generated at the atmosphere sodium layer, by means of a dichroic filter. The LGS light is then focused on the entrance focal plane of the LGS WFS module by an objective. The optical system accommodates up to two post focal Deformable Mirrors (DMs), conjugated at altitudes of 17.5 km and 6.5 km, and, together with the ELT M4, provide the AO correction.

*giorgio.pariani@inaf.it

After the study of several optical solutions, during the last project phase the design of the MPO converged to a solution composed by a correcting plate positioned close to the module entrance focal plane, two aspherical and two spherical powered mirrors, plus a series of flats to accommodate the instrument on the Nasmyth platform and properly feed MICADO.

We previously described in details the optical design of MORFEO [4], which passed the preliminary design phase with ESO in 2021. In this paper, after a brief recap of the instrument optical design, we will focus our attention on the tolerance analysis of the elements, consisting in both alignment and manufacturing tolerances, talking specifically on the effects of the mid-high spatial frequency polishing errors.

We will also show the outcomes of the stability analysis of the instrument, consisting in rigid-body motions and thermoelastic deformations of the structure and optomechanics, used to define the procedures and benchmark to maintain the instrument performances during operation.

2. PDR DESIGN

The present configuration has been initially proposed by Bernard Delabre, and, in a similar arrangement, by Johan Kosmalski. It is based on four powered mirrors (two aspherical and two spherical) able to deliver high quality in terms of WFE and field distortion. It is tolerant to defocus and astigmatism that can be compensated by acting on the last mirror with power. This configuration implements the concept, firstly introduced by Andrew Rakich, of using an aspherical plate near the telescope focal surface to correct multiple object conjugate distances [5][6][7]. The correcting plate greatly improves the quality of the exit pupil image, of the DMs meta-pupil images and of the LGS images at different conjugation altitudes, without degrading the quality for the infinite conjugated surface.

We have adapted and re-optimized the general optical solution to the MORFEO specific requirements and constraints, namely the available volume on the Nasmyth platform and the position of the MICADO entrance surface. Folding mirrors were added to place the instrument in a vertical layout and to provide the switching between MICADO and the second instrument. A scheme is shown in Figure 1.

2.1 MPO description

The F/17.75 beam coming from the ELT focal surface initially passes through the correcting plate (CPM). It is a window that thermally separates the external and internal environments. The CPM second surface is aspherical and allows increasing the quality of multiple object conjugated distances. Following the path, there is a first flat mirror, M6M, folding the beam down to the first aspherical concave mirror M7M. The beam is reflected up to the second aspherical concave mirror M8M, and then down again towards the first DM, M9M, having a spherical surface. This mirror is the only convex surface of the main path. After that, the beam is reflected by the second DM, M10M, which is concave and spherical. For the time being, the decision to install or not the second DM has not been already taken. However, the optical configuration has been designed to accommodate both DMs.

After M10M, the image of the pupil is formed, and just after this image, the science and NGS light is separated from the LGS light by means of a dichroic filter. The LGS light (589 nm) is transmitted, while science and NGS light (600 nm - 2400 nm) is reflected. The reflected light then reaches M11M, a flat flip mirror that allows the selection of the MICADO path or of the second instrument path through a rotational axis. Finally, the light is reflected by a flat mirror, M12M (or M12M bis), installed over MICADO (or, as previously mentioned, some future second instrument) and comes to a focus at the gravity invariant entrance focal surface of the instruments.

2.2 LGSO description

The LGS Objective (LGSO) reduces the LGS beam F/# at wavelength 589 nm to F/5 at the LGS WFS module entrance focal surface. It is composed by four silica spherical lenses and three fold mirrors (see Figure 2). The first two mirrors have been introduced in order to maintain the objective within the available envelope, while the third mirror allows to feed the LGS module with a gravity invariant and telecentric focus. The LGS asterism required by MORFEO is fixed to field angle 45 arcsec with a FoV of ± 15 arcsec (LGS elongation). As the ELT declination angle varies (Zenith angle 0-60 degrees), the LGS launchers will maintain the LGS sources on the sodium layer at the fixed angle of 45 arcsec. Thanks to the telecentric beam delivered by the LGSO, the radial coordinate of the LGS images on the LGSO focal surface will not change as the apparent altitude (84-180 km) of the sodium layer varies. In this way, the LGS module just needs to rotate around its central axis and to move up and down in order to follow the declination variation effect.

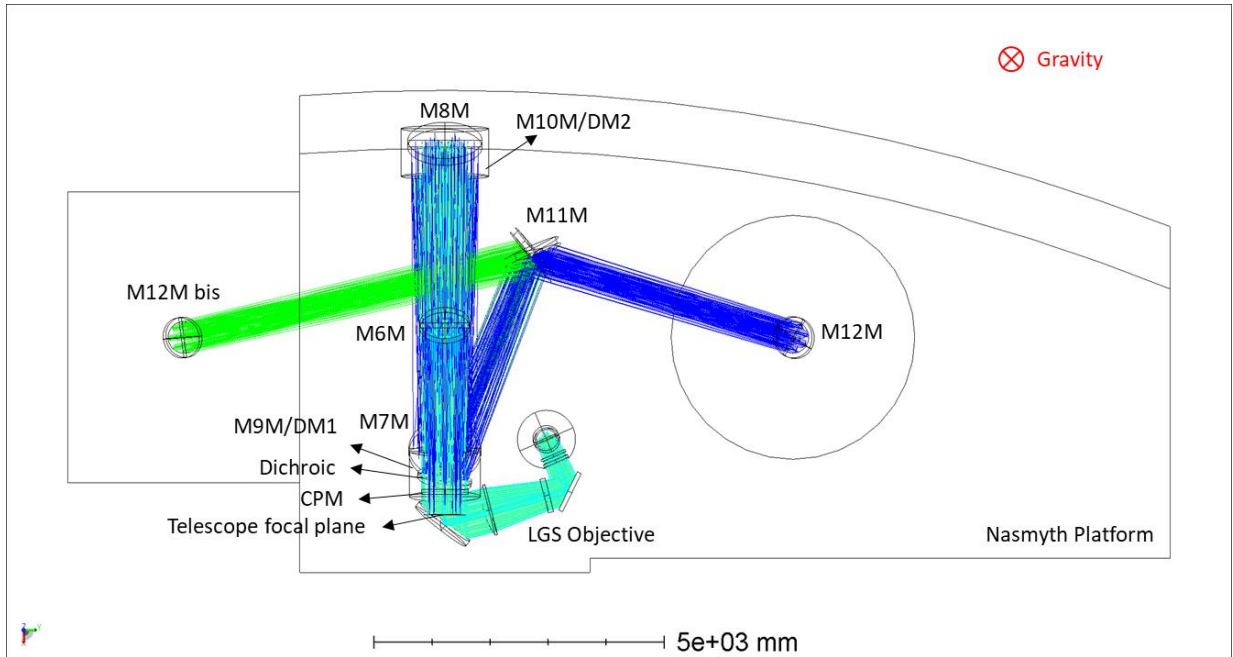
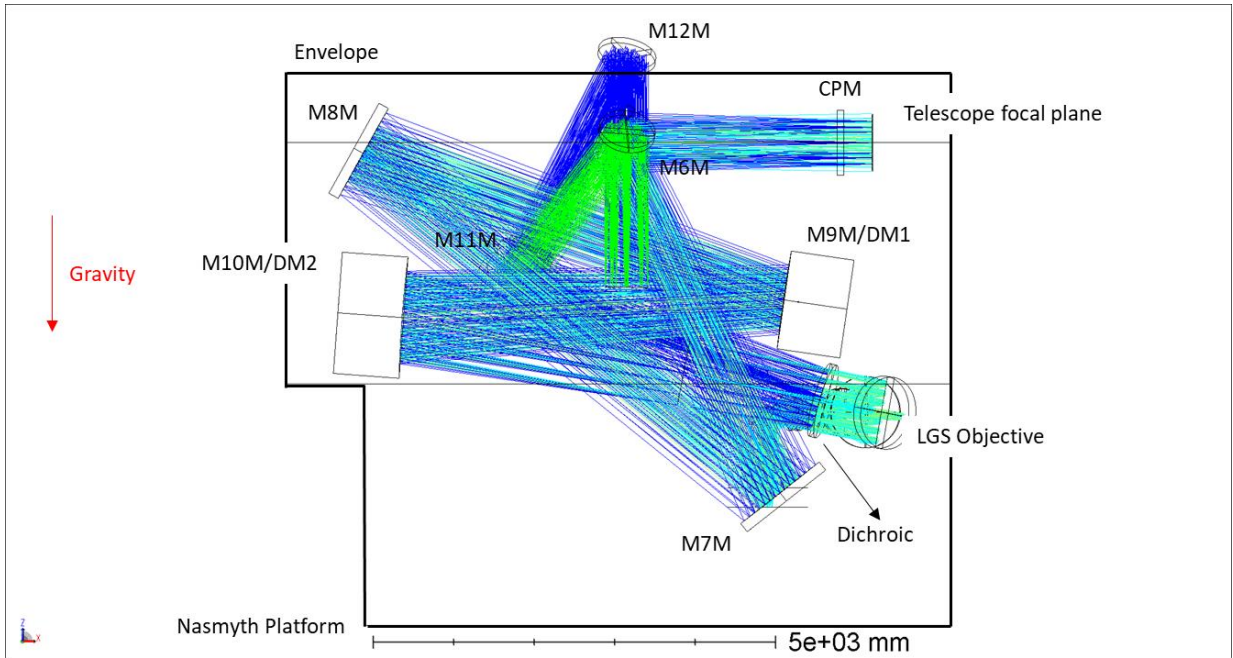


Figure 1. Side view layout (top) and top view layout (bottom). Blue rays represent the science and NGS path to MICADO, green rays represent the science and NGS path to second instrument, Cyan rays represent the LGS path.

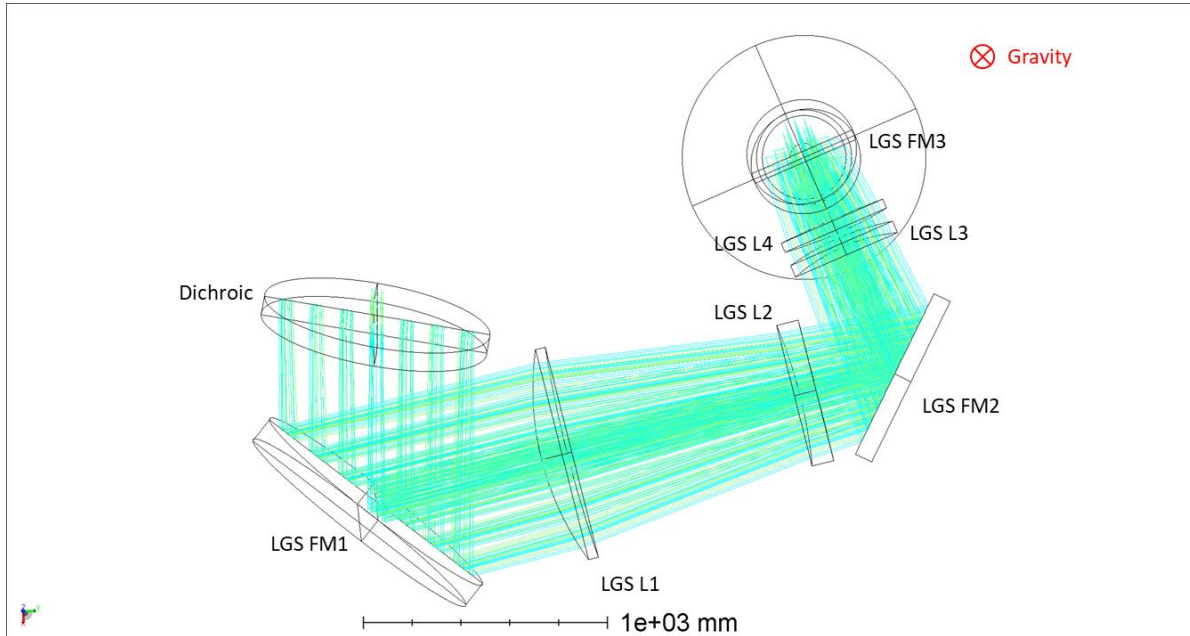


Figure 2. LGSO top view layout. The two colors represent rays incoming from two different LGS apparent conjugation altitudes.

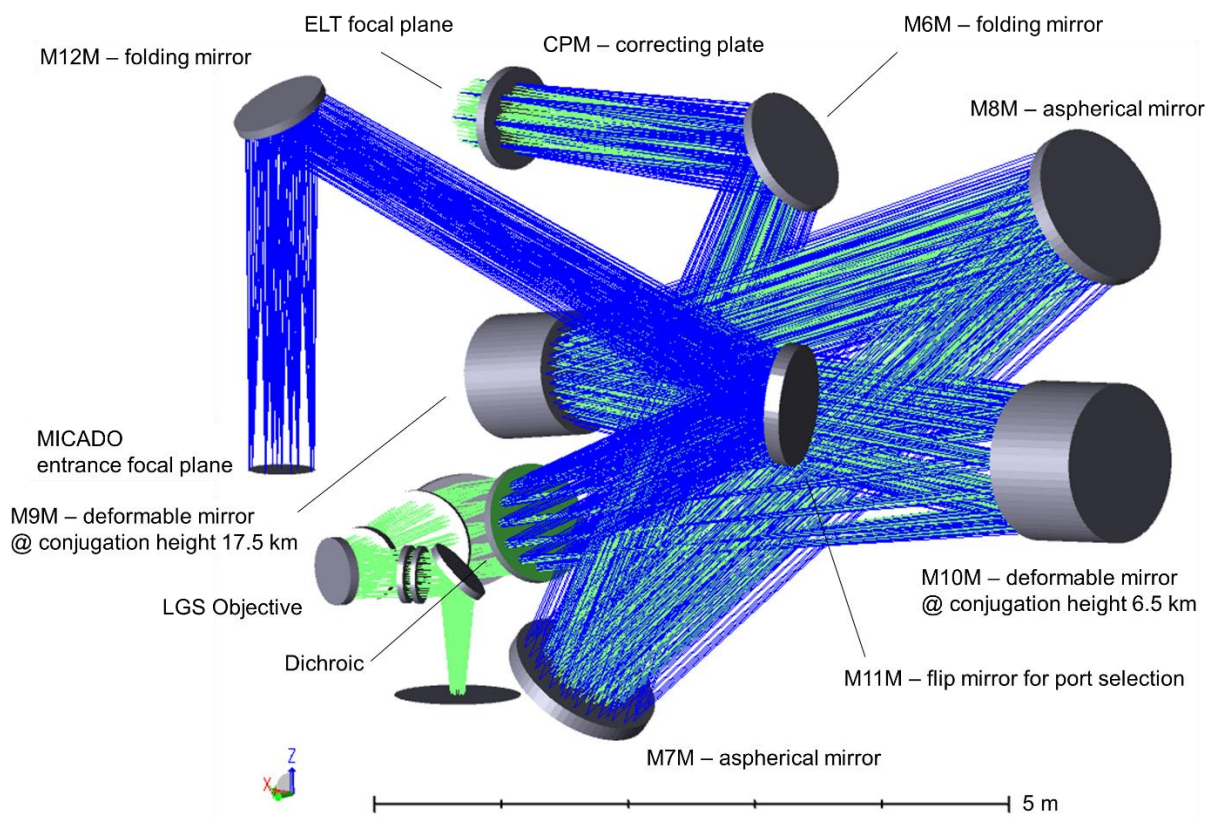


Figure 3. 3D view of the MORFEO optical configuration. Blue rays represent the science and NGS path to MICADO, Cyan rays represent the LGS path.

3. TOLERANCE ANALYSIS

We present hereafter a summary of the tolerance analysis we performed on the MPO, consisting mainly in:

- alignment errors
- optics manufacturing errors, here intended as:
 - o optics geometrical parameters
 - o low spatial frequency surface errors (Z4-Z36 of the Noll notation)
 - o mid spatial frequency surface errors (Z37-Z231 of the Noll notation)
 - o high spatial frequency surface errors (from 5 to 250 mm of spatial scale)
- stability errors, as the ensemble of all the dynamical contributors. At this working level, we have considered:
 - o the rigid body motion between MORFEO and ELT, i.e., the mechanical flexures of the instrument structure due to the Nasmyth platform motion during operation
 - o MORFEO and Nasmyth-induced thermo-elastic deformations, i.e., the displacements of the optical elements as rigid bodies due to temperature changes (seasonal or nightly based). Deformations of the optical surfaces due to thermal effects are currently included in the manufacturing budget.

As a general approach, we consider that:

- in order to relax the optics manufacturing specifications, we consider both the accuracy and the precision of the optical parameters, i.e., as built parameters may be out of nominal, but with a very good knowledge. Given the very long radii of curvature of the optics, this will allow for reduced correction ranges in the positioning of the optics in the instrument.
- the integration and preliminary alignment procedure is based on the positioning the opto-mechanics, equipped with retroreflectors (SMRs), using a laser tracker [8]. We assume that the producer references the optical surfaces to mechanical fiducials.
- after the initial positioning, the fine alignment is performed using the piston and tip/tilt of M10M as degrees of freedom to minimize defocus and astigmatism over the MICADO FoV, and tip/tilt of M11M and M12M to realign the focal surface and the exit pupil to MICADO. This operation is considered as baseline to recover long term image motions and degradation.

To follow these assumptions, the main tolerance evaluation was implemented in three steps, considering a Monte Carlo (MC) approach implemented on the Amazon HTC cloud platform. In each step, we performed 3000 simulations and we selected a 98-percentile worst occurrence in terms of WFE to pass to the next step. We also evaluated in each step the 98-percentile in terms of astrometric performance, since it is not correlated with the WFE.

Astrometry refers to the capability to perform relative astrometric measurement between a pair of stars observed at different epochs. Such technique assumes, as part of the reduction process, the application of an astrometric polynomial fit correction between the two images taken at different epochs [9]. For a regular grid of points in the entrance field we calculate the centroid map on the exit focal plane; we assume this map as reference. We then apply a field rotation to the centroid map and we compute the residuals between the corresponding centroids grid and the reference centroids grid. We estimate the astrometric error as the point to point distance variation among sources having relative on sky distance by subtracting their residuals both in x and y directions. On the centroid maps we apply, sequentially, the astrometric correction by mean of the first, third and fifth order polynomials fit.

This is the procedure we follow to estimate alignment errors, low and mid spatial frequency manufacturing errors (up to Z231):

1. we applied optics geometrical parameters errors, and low-order manufacturing errors (radii of curvatures, defocus, astigmatism); we assumed to reposition the opto-mechanical subsystems after the as-built measurements are provided by the manufacturers; manufacturing errors and characterization with respect to SMRs are considered with infinite precision at this stage; the optimization is done by redefining the tip-tilt and piston of M7M, M8M and the tip-tilt, piston and decenter of M9M and M10M.

2. we applied accuracy of the other low and mid spatial frequency manufacturing errors; no compensation was applied in this step.
3. we introduced the precision errors on the low spatial frequency surface errors (radii of curvatures, defocus, astigmatisms) and on the surface referencing and we applied the fine alignment procedure.

Details of this procedure are reported in [4]. The main result is that the WFE RMS in the MICADO FoV has an average value of 75 nm and a maximum value of 100 nm, while in the technical FoV about 100 nm in average and 150 nm at maximum. Concerning the astrometry, the tolerance has essentially no effects. After the 5th order polynomial fit correction, the residuals are below 5 μas on average and below 50 μas at maximum for any field rotation angle. The effect of the high spatial frequency errors and the stability will be described hereafter.

4. HIGH SPATIAL FREQUENCY SURFACE ERRORS

It is a common way to specify the high spatial frequency errors using the PSD. In particular, we considered the 1-D PSD, calculated from the azimuthal average of the 2D FFT of the surface map [10]. We set a requirement on the high frequency errors (above Z36 in the Noll notation) using the following equation (Figure 4, left):

$$PSD = \frac{A}{f^B}, \text{ for } 4 \text{ m}^{-1} < f < 200 \text{ m}^{-1}$$

where PSD [m^3], f [$1/\text{m}$], A [$\text{m}^2 \text{m}^{1-B}$]. We considered a constant PSD below 4 m^{-1} .

The effects of high spatial frequency surface errors are difficult to be simulated, due to the large computational efforts required by ray trace software. We followed this approach:

- we described each optical surface in Zemax as a Grid Sag surface, with a grid frequency corresponding to twice the maximum frequency of the PSD ($400 \text{ m}^{-1} = 2.5 \text{ mm}$).
- with a Matlab code, we generated for each surface a map from the specified PSD , assigning at each spatial frequency a random phase (Figure 4, right); considering the size of MORFEO elements, we end up with map of 500x500 pixels
- we automatically load the map to each surface of the Zemax file, with a dedicated Matlab routine, and we run the analysis.

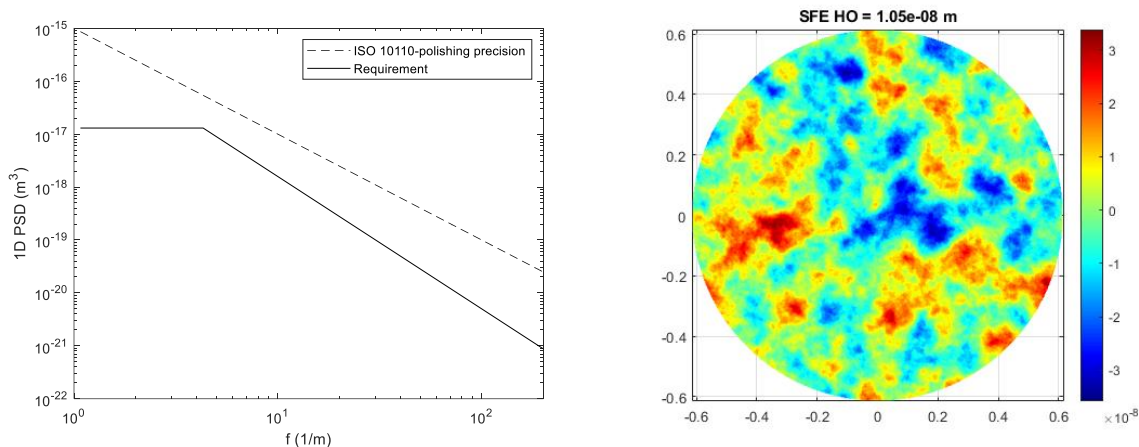


Figure 4: PSD requirements for the simulation of the high spatial frequency errors (left) and example of a generated surface (right)

Before evaluating the performances of the instrument, we verified the accuracy of the analysis and the calculation time as function of the simulations parameters, namely the surface grid spacing, the pupil sampling and the field sampling, especially in the evaluation of the distortion maps, which determine the astrometric accuracy.

For reduced pupil samplings, the centroid calculation shows artefacts that are amplified by the operations of field rotation and differentiation used to calculate the point to point distance error. Above pupil sampling 61 the results are consistent, but the computation time is of several hours, on a i7-8550U CPU @ 1.80 GHz, 32 GB RAM machine (Figure 5, left).

As shown in Figure 5 on the right, the residuals of the distortion maps cannot be reduced increasing the order of the polynomial fitting, being of very high spatial frequency, and their behaviour is not linear as function of the point to point separation, reaching a plateau after approximately 10 arcsec of separation. In the direction of reducing the calculation time, we note that at lower separations (2 to 6 arcsec) the trend is almost linear, allowing to extrapolate the behaviour at 1 arcsec (where the performance is specified) from the data calculated at 2 arcsec.

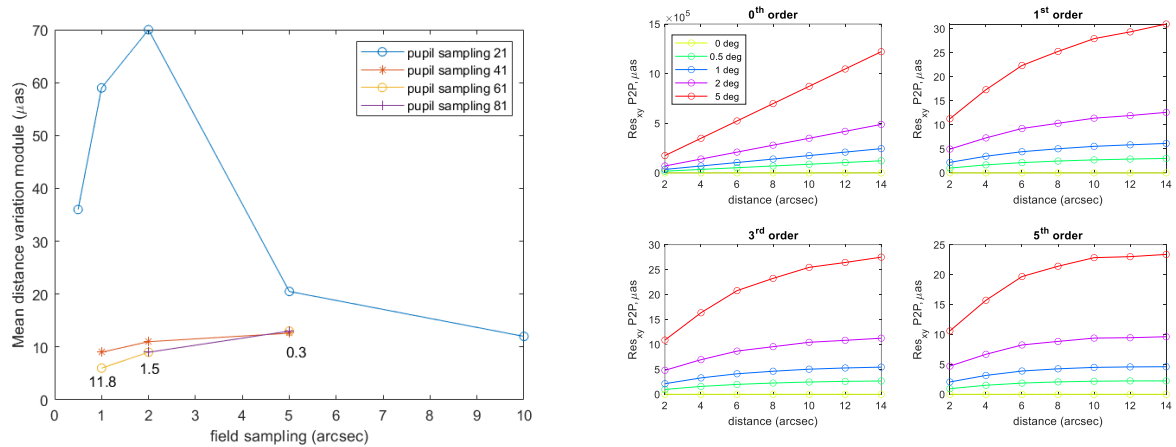


Figure 5: mean point to point distance variation module (residual after 5th order polynomial fitting) after 5 deg field rotation for different pupil and field samplings (left); numbers in the plot shows the computation time in hours for the pupil sampling of 61, on a i7-8550U CPU @ 1.80 GHz, 32 GB RAM; mean point to point distance variation module, calculated from a pupil sampling of 81 and a field sampling of 2 arcsec, as function of the point separation, after polynomial fitting (right)

We evaluated the sensitivity of the system applying a map to a single surface or subsystem (LGSO), with a grid sag spacing of 2.5 mm. The map was composed by low spatial frequency errors, between Z4 and Z36 as in the previous paragraph, and high spatial frequency errors derived by the PSD, set to zero above 200 m⁻¹. We consider that the high spatial frequency errors defined by the PSD replace and complement the mid spatial frequency errors defined with the Zernike polynomials (Z37-Z231). We calculated the WFE and the point to point distance errors (approximately 4 hours/file), as shown in Figure 6 and Figure 7.

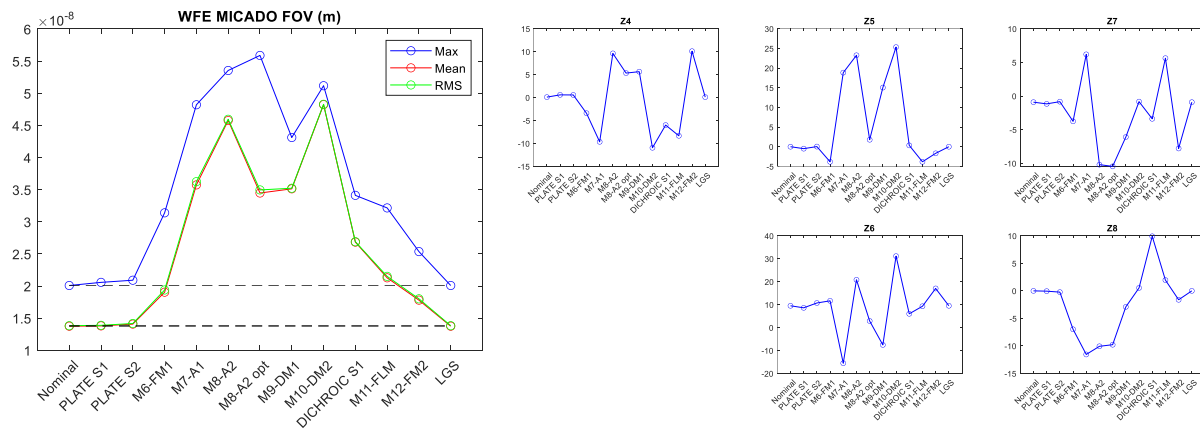


Figure 6: WFE on the MICADO field of view (left) and Zernike coefficients (Z4-Z8) of the on-axis field (right).

The surfaces contributing to the WFE are the ones closer to the pupil, and their contribution is mainly given by low order terms (focus, astigmatism and coma). In fact, by optimizing the fine alignment as previously described, the global WFE is reduced, since focus and astigmatism are minimized. On the contrary, the surfaces contributing to the point to point distance astrometric errors are the ones closer to the focal planes, especially the CPM, M6M and M12M. As before, the residuals are not reduced if we increase the order of the polynomial fitting, being the errors of very high spatial frequency.

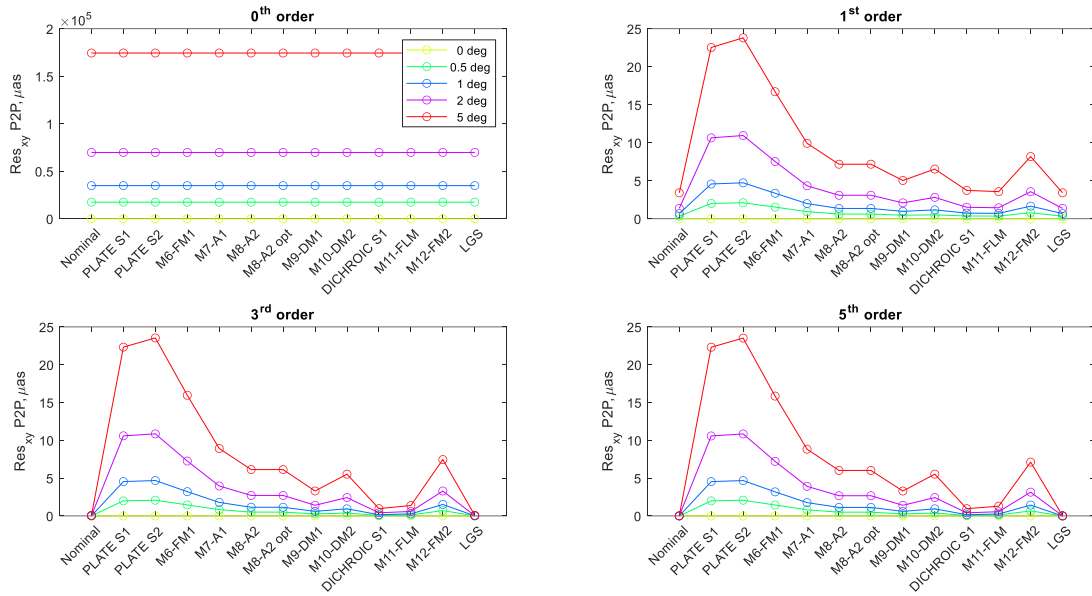


Figure 7: mean point to point distance variation module as function of the field rotation angle when the high frequency errors are applied to the single surface.

We also performed a Monte Carlo analysis with a small statistics (a dozen cases), where we applied surface errors to all surfaces (MPO and LGSO). The computation time was approximately 15 hours/file. The results as reported in Figure 8. The WFE, which is mainly driven by low spatial frequency errors, is spread between 60 and 110 nm RMS on average and between 120 and 150 nm at maximum in the MICADO FoV, and from 80 to 120 nm RMS in average, 100 to 160 nm RMS at maximum on the technical FoV. On the contrary, the point to point distance error is essentially constant in the different cases, being around 40 μas in all cases. This suggests that only one case is sufficient to evaluate the effects of the high spatial frequency errors.

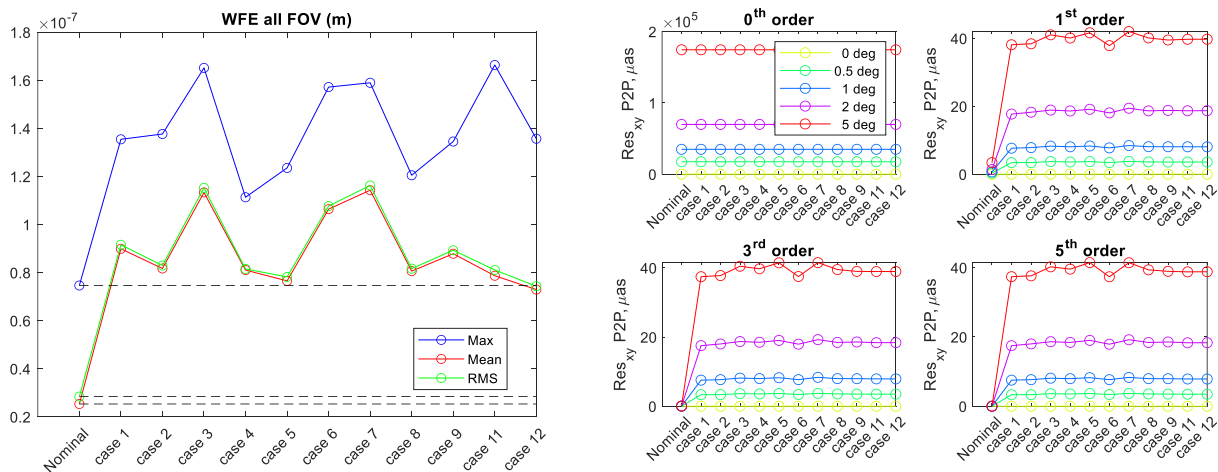


Figure 8: WFE (left) and mean point to point distance variation module as function of the field rotation angle (right) for different MC cases.

5. STABILITY

For each stability case, we evaluated the impacts on the MORFEO performance on the output focal plane and the capability to recover the variation through the instrument fine alignment (i.e., acting on M10M, M11M and M12M). To do so, we developed a combined Ansys-Matlab-Zemax model [11]. The displacements and rotations of the optical elements were calculated with Ansys, applying the load cases to the MORFEO structure. We used the local reference system, considering the deformations of the connection points of the optics mounts with the structure. The obtained values were processed with a Matlab script and automatically inserted into the Zemax model to perform the optical analysis, including optimizations.

5.1 Rigid body motion between MORFEO and ELT

The rigid body motion between MORFEO and ELT is given by the relative movement between the instrument attachment points on the Nasmyth platform and the telescope exit focal plane. The simulations were performed on the nominal optical configuration, imposing the displacement of each degrees of freedom to the whole instrument mounted on the bench, i.e., from the entrance plate to M11M (M12M and MICADO has been considered fixed). The movement of the central field position (i.e., pointing) in the local reference system and the pupil position variation are shown in Figure 9.

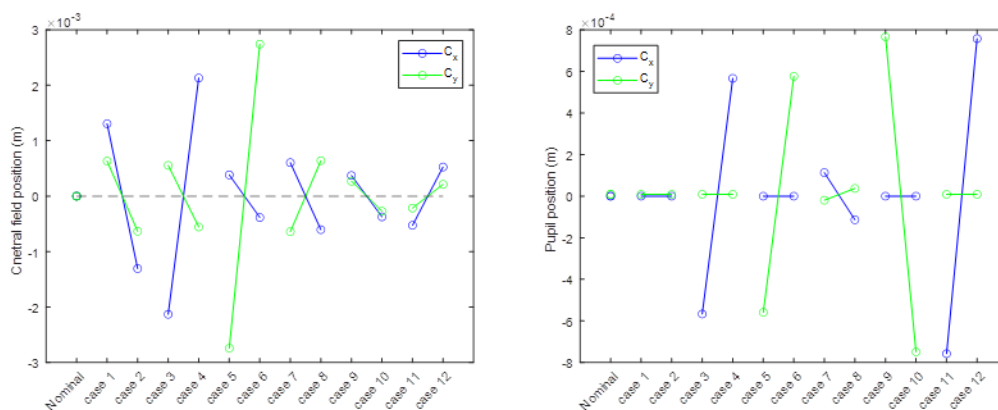


Figure 9. Position of the central field on the exit focal plane, in the local coordinate system (left) and pupil position (right) in the different cases.

The impact on the WFE is due only to defocus, in the range of ± 230 nm RMS. The higher order Zernike polynomials are negligible with respect to the nominal value. All the performances are completely recovered after the MORFEO fine alignment, with a millimeter motion of M10M in focus to recover the WFE, and of few tens of millidegrees for M11M and M12M to recover the pointing on the exit focal plane and the exit pupil position.

5.2 MORFEO and Nasmyth-induced thermo-elastic deformation

To have a first-order estimate of the thermoelastic effects inside MORFEO and the ones induced by the platform, we initially performed a sensitivity analysis on the MPO, considering:

- uniform temperature variations inside MORFEO
- temperature gradients inside MORFEO
- temperature variations between the Nasmyth platform and MORFEO

Such components are responsible for local movements of the optical elements, modifying the optical path. The thermoelastic analysis were propaedeutic for the design of the thermal cover, and the residual WFE after correction is part of the instrument stability budget.

To verify the system performances with the baseline design, we performed a three days long analysis considering a time-varying environment. We produced a tentative but very conservative temperature profile (operational) inside the telescope during the night-time, starting from expected night trends (0.5 K/h) and night-to-night variations (4 K). The MORFEO structure has been kinematically connected to the Nasmyth platform through three legs, so that the Nasmyth

effects have been not accounted for. The deformations on the steel structure have been calculated applying the temperature distributions in a static structural analysis, and the obtained deformation imported in the Zemax model as displacement and tilt of the I/F points with the opto-mechanical assemblies. Also for this simulation, M12M has been considered fixed over MICADO. We have computed the effects of the thermo-elastic deformation as function of time on WFE, central field centroid position (pointing), and exit pupil displacement. The results are shown in Figure 10.

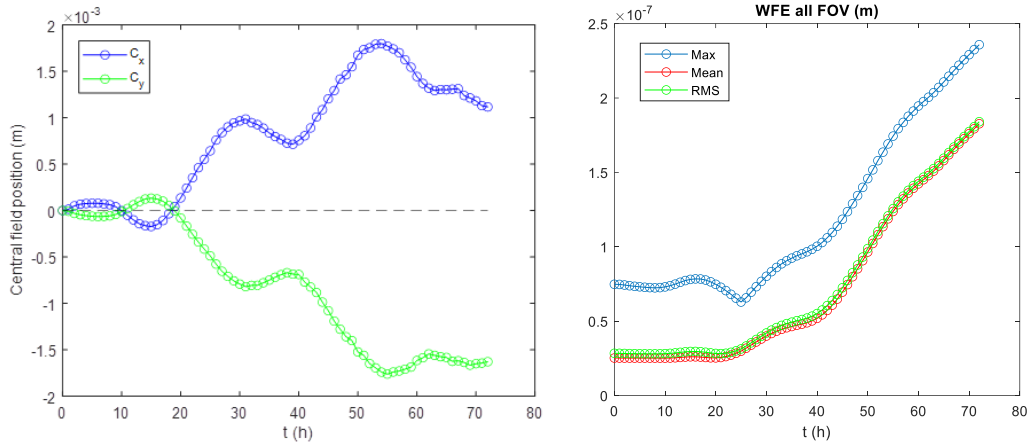


Figure 10. Central field position on the MORFEO exit focal plane (left) and WFE on the technical FoV (right) as function of time considering the operational temperature profile.

The main effects after the three days are pointing (few mm on the exit focal plane), exit pupil displacement (few mm) and WFE (degradation up to a maximum of 250 nm RMS on the technical FoV, due mainly to defocus and astigmatism). Also in this case we verified the capability of the system to recover the full performance, applying the MORFEO fine alignment procedure during the third day every four hours. Tilts of few arcsec and a displacement in z of few hundred microns for M10M were sufficient to recover the nominal performances. Results are given in Figure 11. Distortion residuals are negligible after the subtraction of the third order polynomial, even if the calibration is performed only at the beginning of each night.

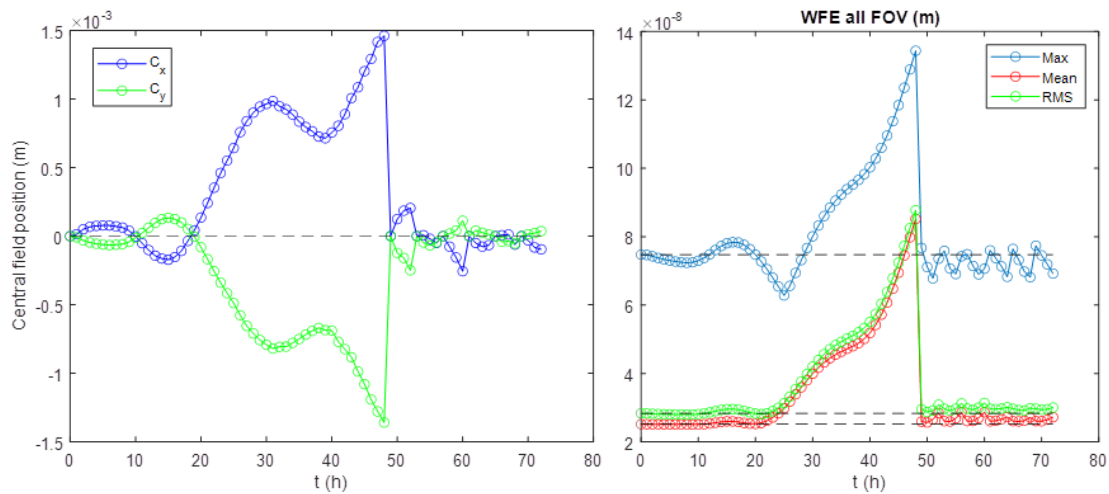


Figure 11. Position of the central field on the exit focal plane (left) and WFE on the full FOV (right) after MORFEO collimation every 4 hours during third day. Dash lines refer to nominal value.

Those simulations showed that, from the thermoelastic point of view, MORFEO could withstand an operative night and a night-to-night variation of 4 K with a fine alignment procedure and an astrometric calibration at the beginning of the night. When the temperature difference between MORFEO and the telescope environment increases, other actions may be required.

6. CONCLUSIONS

We described the tolerance analysis process we performed to specify alignment and manufacturing tolerances of the MORFEO optics.

Concerning the WFE performances, given by alignment and mid-low spatial frequency surface errors, we obtained a WFE RMS in the MICADO FoV of 75 nm in average and 100 nm at maximum, while in the technical FoV about 100 nm in average and 150 nm at maximum.

High spatial frequency errors bring the WFE to 110 nm RMS in average and 150 nm at maximum in the MICADO FoV, and to 120 nm RMS in average, 160 nm RMS at maximum on the technical FoV, which is still within the requirements (150 nm RMS in average on the scientific field of view at the reference wavelength of 1 μm and 200 nm RMS in average on the technical field of view at the reference wavelength of 1 μm). Stability is not influencing the WFE performances, if the proper realignment is performed at the beginning of the each observation. If realignment is performed at the beginning of the night only, a slight degradation of the WFE is expected due to thermoelastic fluctuations of the bench. Accordingly, the level of residual WFE is will drive the frequency at which the fine alignment procedure will be performed.

To be noted that all this analysis is not considering the correction loop, including sensing errors and non-common path aberrations between the MPO and the LGSO. However, to some extent, the system is capable of self-adjustment given the two deformable mirrors.

Astrometric performances have been evaluated and are mainly related to the high spatial frequency errors on the optics surface. At this design level, we cannot commit on the final instrument performances, but set a limit in the field rotation angle that is tolerated between epochs to be within the 50 μas astrometric specification.

REFERENCES

- [1] P. Ciliegi, et al. "MAORY: the adaptive optics module for the Extremely Large Telescope (ELT)", Proc.SPIE 11448 (2020)
- [2] P. Ciliegi, et al. "MAORY: a multi-conjugate adaptive optics relay for E-ELT", ESO Messenger, No.182 (2021).
- [3] R. Davies, J. Alves, Y. Clenet, et al., "The MICADO first light imager for the ELT: overview, operation, simulation", Proc. SPIE 10702 (2018)
- [4] D. Magrin, G. Pariani, M. Munari, et al. "MAORY: optical configuration and expected optical performances", Proc. of SPIE 11448 (2020)
- [5] A. Rakich, J.R. Rogers, "A Maxwellian "Ideal Imager" optical relay suitable for AO applications", Proc. SPIE, 11451 (2020)
- [6] A. Rakich, J.R. Rogers, "Aberration theory-based approaches to optical design", Proc. SPIE 11548 (2020)
- [7] A. Rakich, Absolute Instruments as Laser Guide Star Adaptive Optics relays, Proc. of SPIE (2022)
- [8] G. Rodeghiero, C. Arcidiacono, J.U. Pott, et al. "Performance and limitations of using ELT and MCAO for 50 μas astrometry", JATIS, 7, 3 (2021)
- [9] G. Rodeghiero, J. Farinato, D. Magrin, et al. "The MAORY/MORFEO fine optical alignment and recollimation strategies, preliminary simulations from 'out of focus' PSF images", Proc. of SPIE (2022)
- [10] E. Sidick, "Power spectral density specification and analysis of large optical surfaces", Proc. SPIE. 7390 (2009)
- [11] M. Aliverti, G. Pariani, D. Magrin, et al. "MAORY thermal behaviour", Proc. of SPIE 11450 (2020)