Optical tolerance studies for the MICADO's Relay Optics

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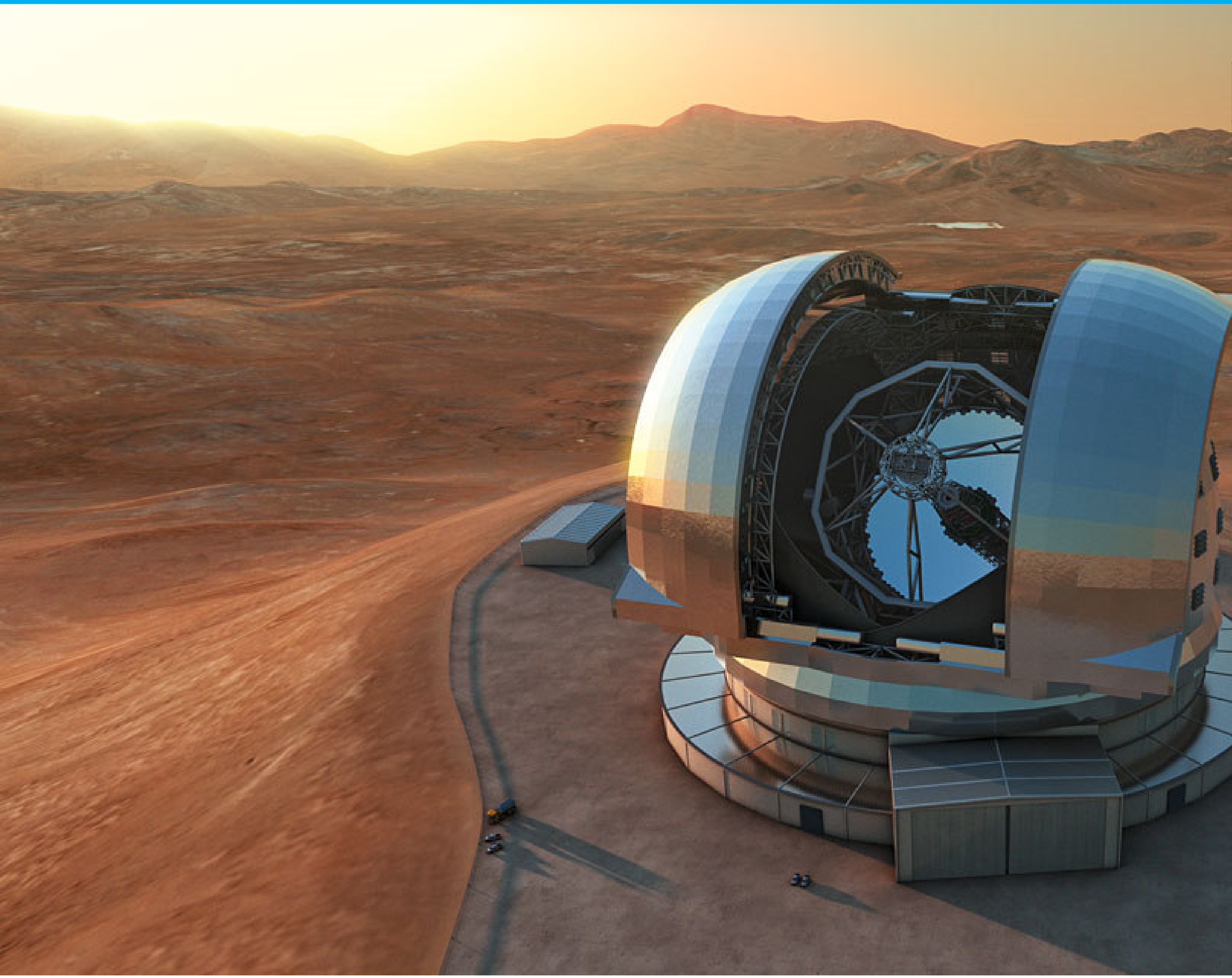
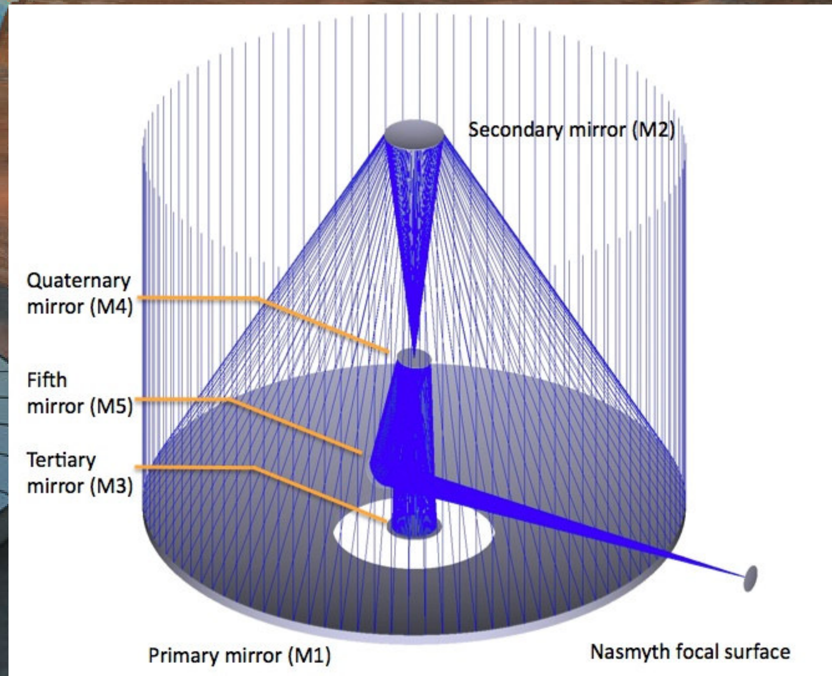
April 26, 2022

1. ESO's Extremely Large Telescope



ELT

- Largest Optical/NIR telescope in the world;
- First light scheduled for 2027.
- 39 m main mirror;



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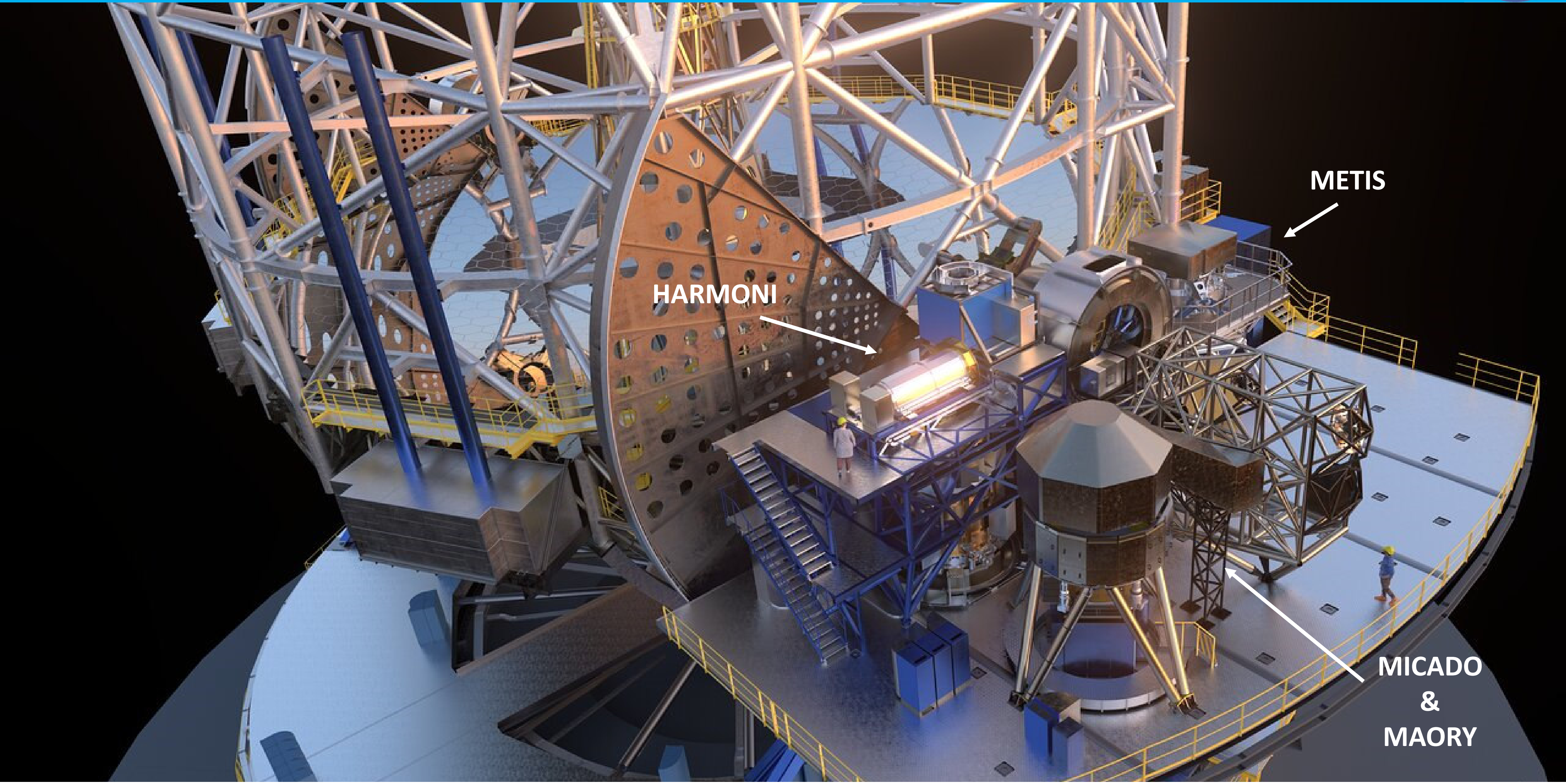


MICADO – Multi-AO Imaging Camera for Deep Observations

MICADO for astronomers

- Will cover near-infrared wavelengths (0.8 – 2.4 μm);
- Field-of-view up to 50.5” x 50.5”;
- Will allow the discovery and characterization exoplanets;
- Will provide astrometric measures;
- Will be able to resolve single stars in nearby galaxies;
- Will provide high-contrast imaging and single-slit spectroscopy;

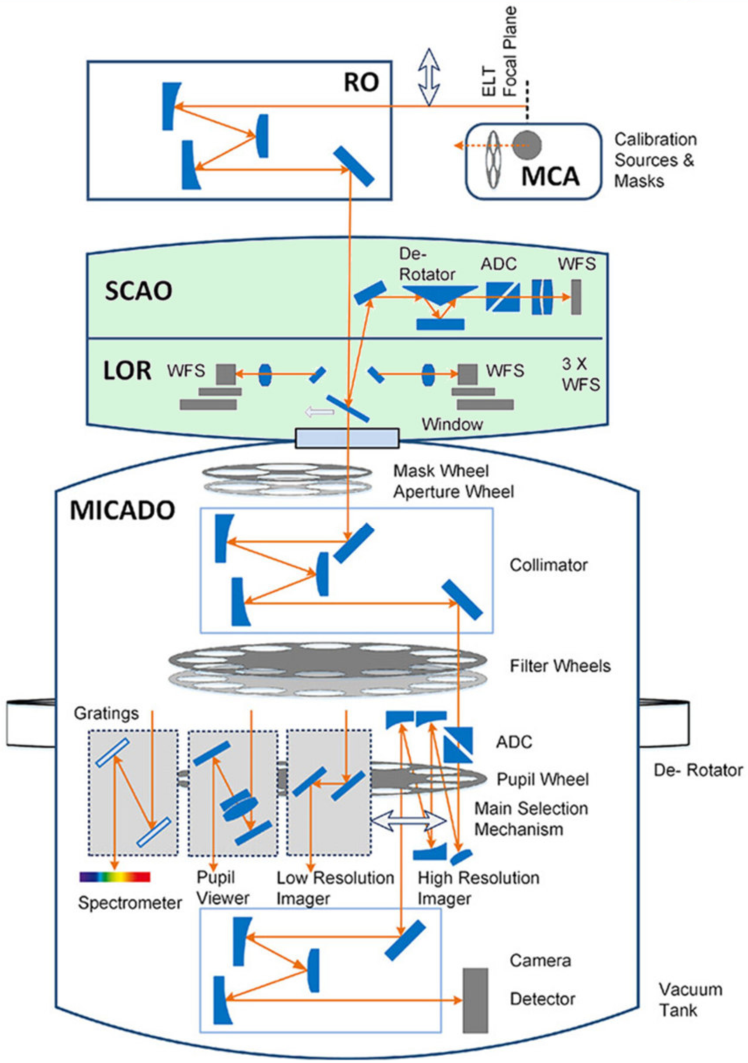
MICADO – Multi-AO Imaging Camera for Deep Observations

Two working modes

- MAORY (Multi-conjugate Adaptive Optics RelaY) will provide compensation for the distortions caused by the atmosphere's turbulence;
- Before MAORY's deployment, MICADO will work in the stand-alone mode, with only SCAO to compensate for the atmosphere's turbulence.

MICADO instrument overview

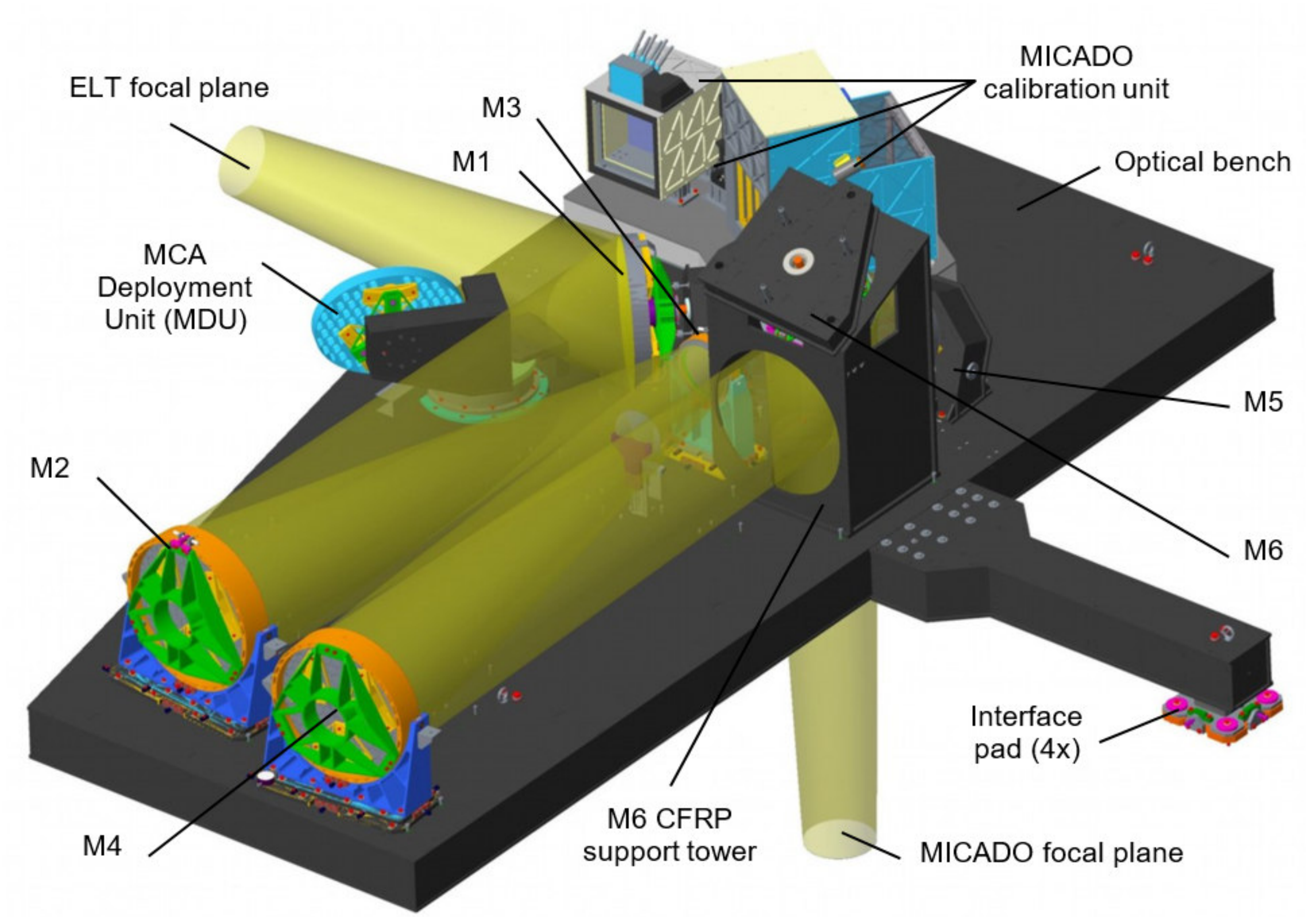
- The cryostat contains the cold optics and is mounted on the de-rotator;
- The SCAO subsystem is mounted in the green donut on top of the cryostat - also rotating;
- The non-rotating Relay Optics (RO) above the cryostat and the green donut;
- The MICADO calibration assembly (MCA) which is integrated in the pre-optics (available both for stand-alone and MAORY mode).

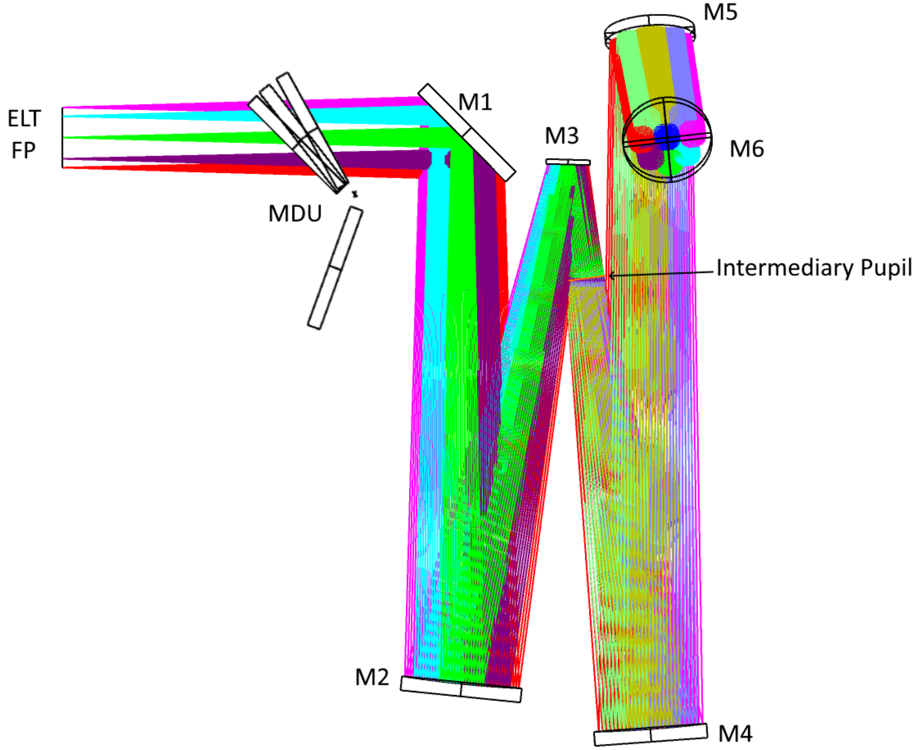


The Relay Optics

The RO bench

- The RO and the MCA are accommodated on a dedicated optical bench which also carries the deployment mechanism for the MCA.





Element	Sag	Motorized DoF
M2 concave	Zernike FF up to 12th term	-
M3 convex	Zernike FF up to 12th term	-
M4 concave	Spherical	-
M1	Flat	Piston, Tip, and Tilt
M5	Flat	Piston, Tip, and Tilt
M6	Flat	Piston, Tip, and Tilt
MDU	Flat	Rotation DoF

The Relay Optics – Main requirements

Wavefront Error (WFE)

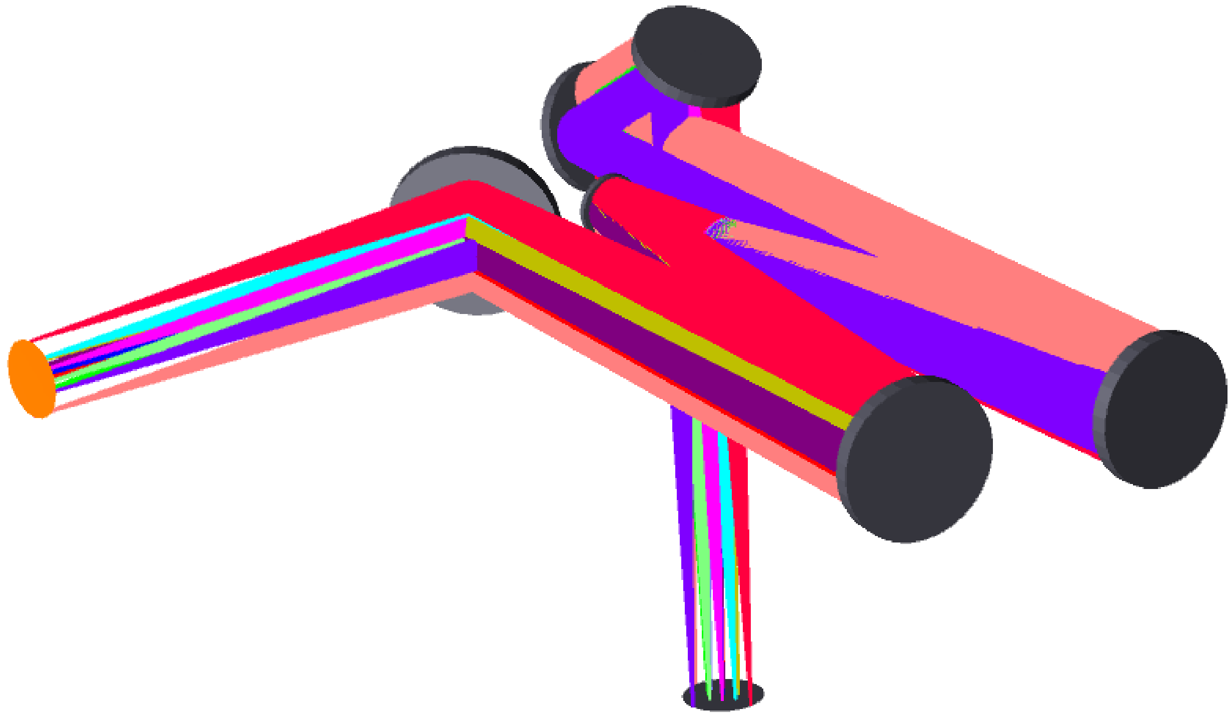
- 100 nm_{RMS} for fields < 10”;
- WFE gradient lower than 10nm $_{RMS}$/arcsec;

Exit Pupil Quality

- Must not drift by more than 0.2%;
- Vignetting should be less than 5%;
- Blur should be less than 0.12%;
- Elongation should be less than 0.12%;
- Magnification should be less than 0.12%
- Should be located 14362 mm ± 400 mm above the Focal Plane.

Distortion

- < 0.1 % for fields < 27”;



The Relay Optics - Tolerances

Internal Alignment

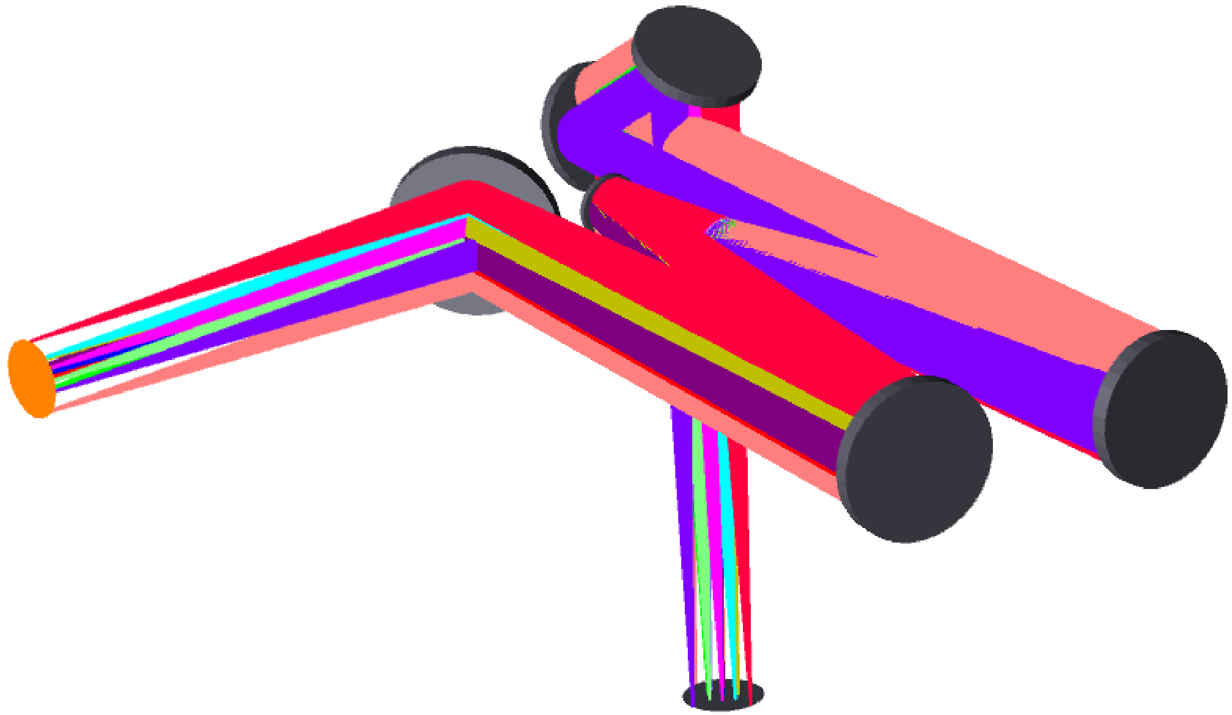
- Post-AIV position and orientation tolerances;
- Thermal expansion of the bench;
- Bench deformation caused by the Namsyth mechanical attachments;

External Alignment

- Alignment tolerances with the ELT;
- Alignment tolerances with MICADO;

Shape of Surfaces

- Mechanical support induced aberrations;
- Thermal expansion of the mirrors and mechanical support;
- Manufacturing tolerances.



Diagnostics - tools

Zemax OpticStudio

- Optical design;
- Diagnostics Tools;

Python script

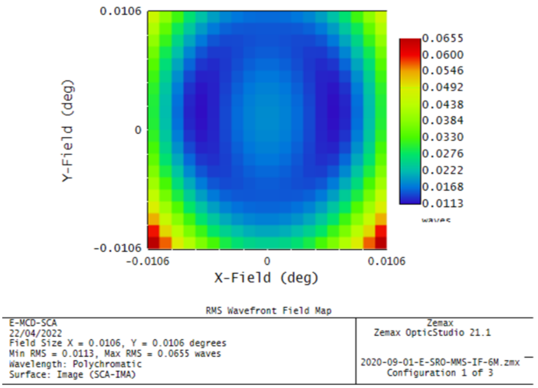
- Set up Monte Carlo simulations:
  - Apply tolerances;
  - Apply compensation;
  - Apply corrections;
- Data Analysis

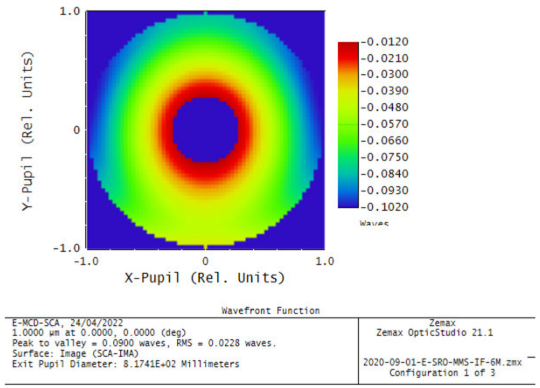
OpticStudio®

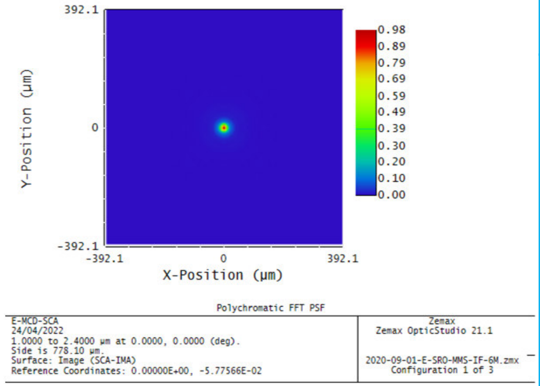
ZOS-API
interface

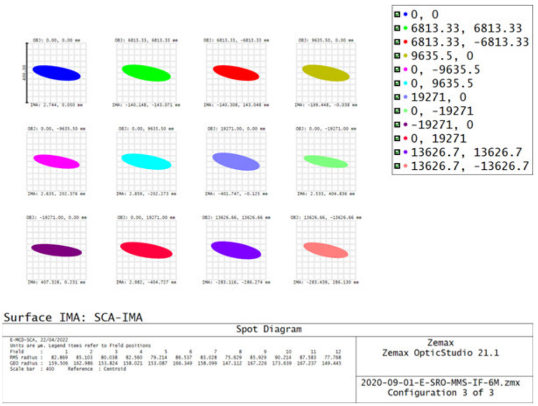
python™

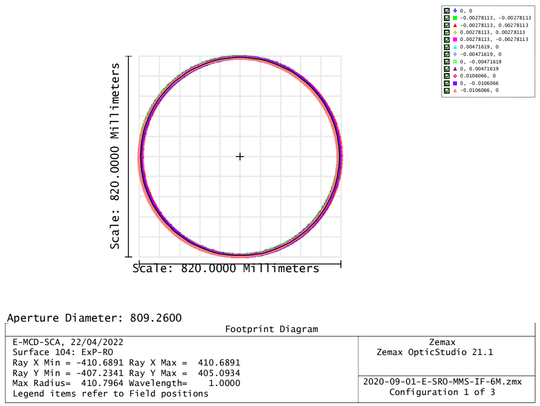
Diagnostic tools

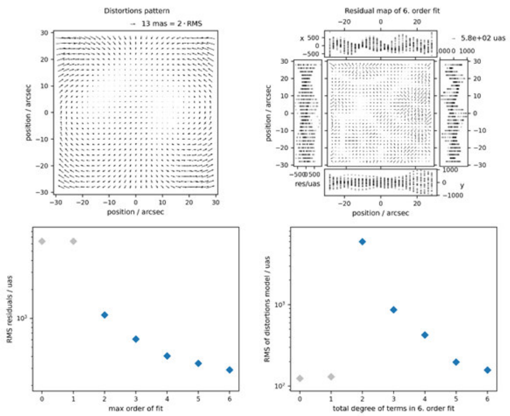












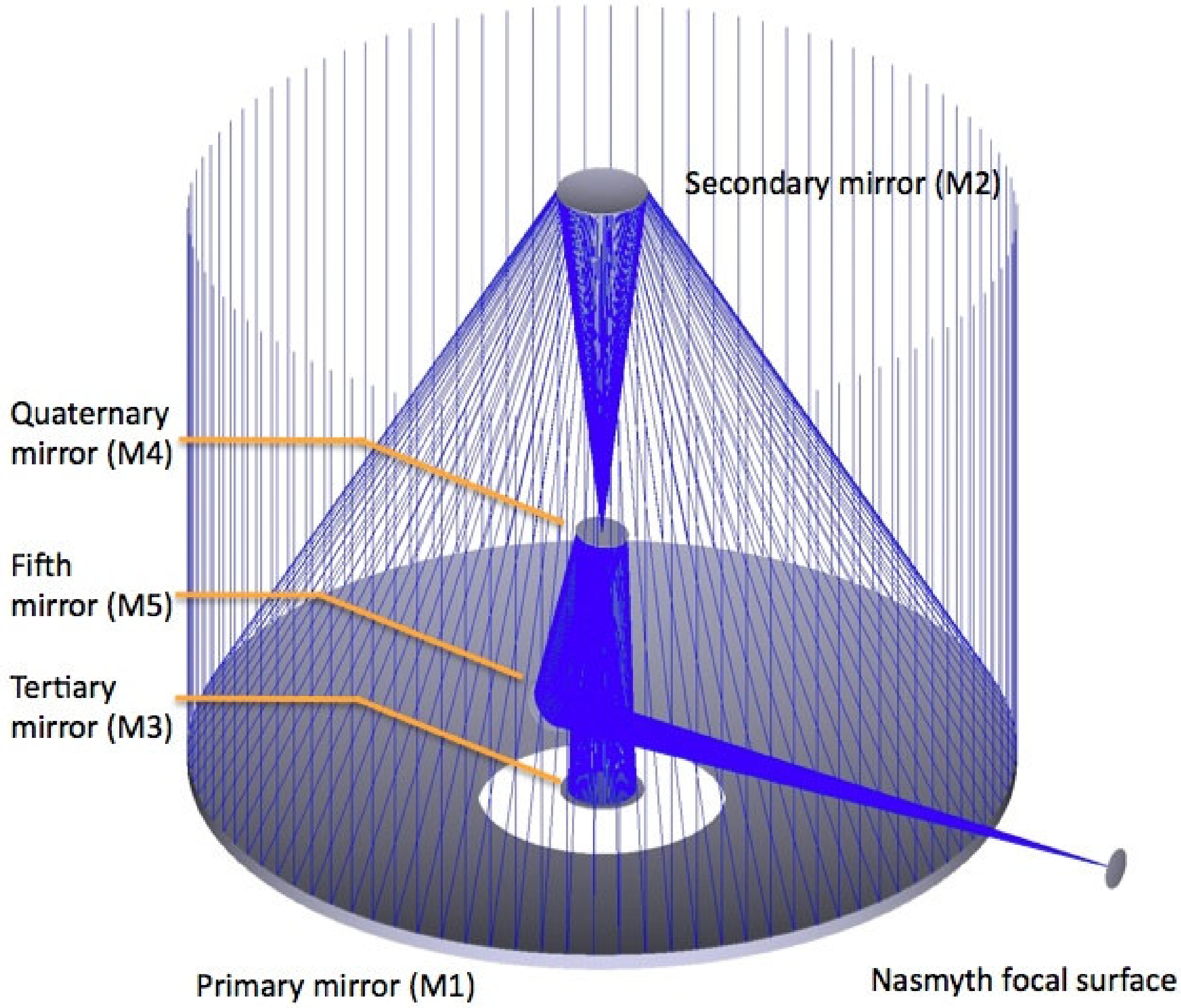
Tools

- RMS field map:
  - WFE analysis, including gradient;
- Wavefront map:
  - WFE spatial frequency analysis;
- FFT PSF:
  - PSF analysis;
- Spot Diagram:
  - Pupil blur analysis;
- Footprint diagram:
  - Other pupil analyses, like drift, elongation, and magnification;
- Single Ray Trace:
  - Geometrical distortion;

External Alignment – The Telescope

Contributors for misalignemnt

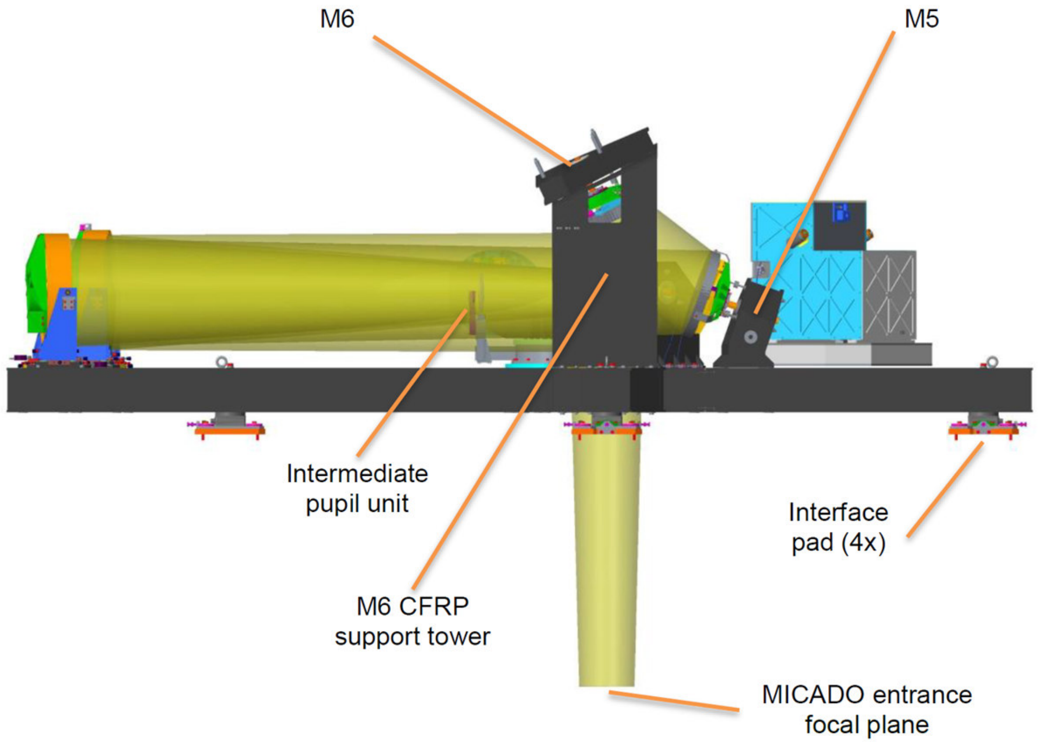
- ELT pupil wander;
- RBM between instrument attachments and ELT focal plane;
- F-number variations
- Initial assembly misalignment;



External Alignment – MICADO interface

Contributors for misalignemnt

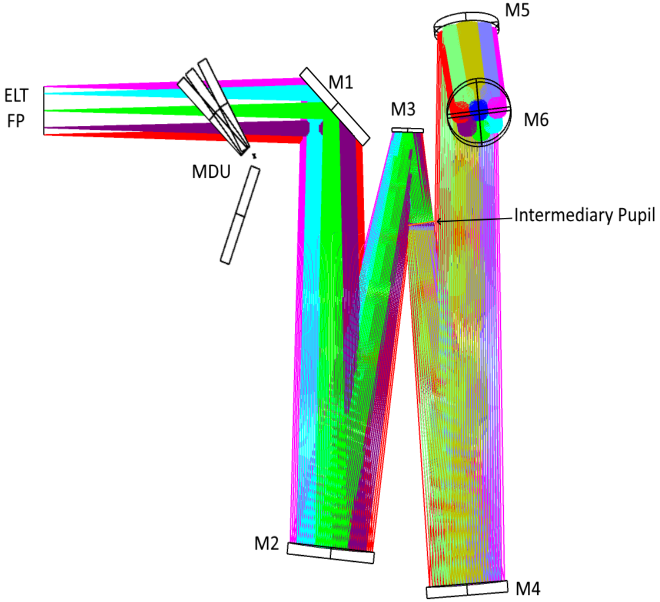
- ~~RO pupil and focal plane drift;~~
- Initial assembly misalignment;

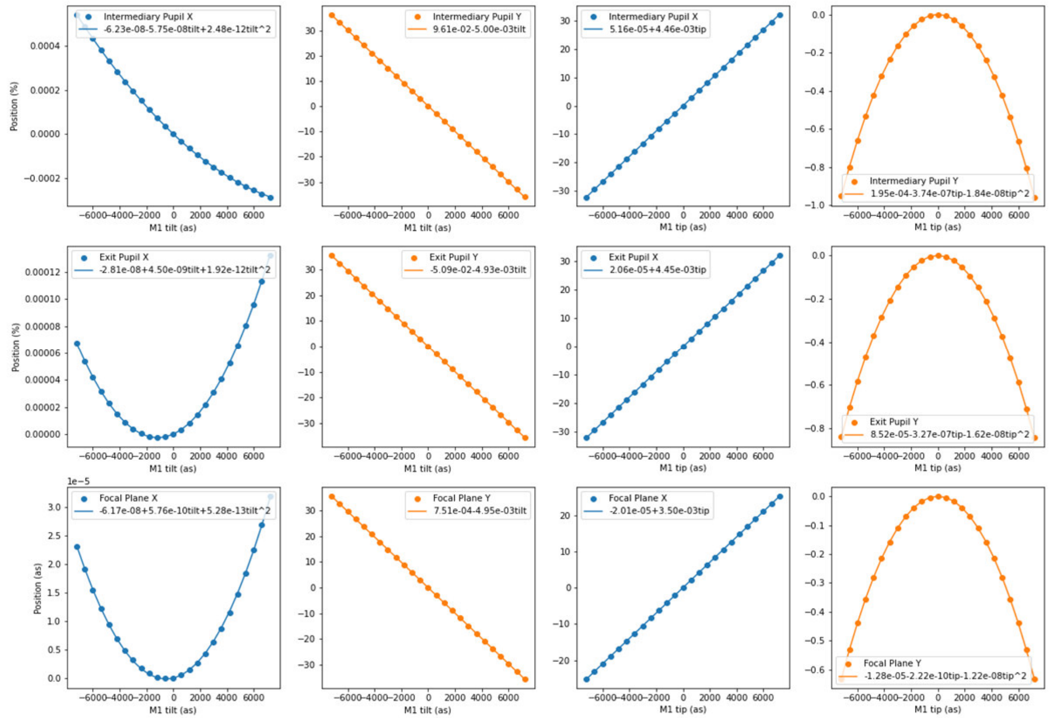


External Alignment– RO-M1

RO-M1

- Used to align the input beam to the intermediary pupil;
- It also affects the exit pupil and focal planes;

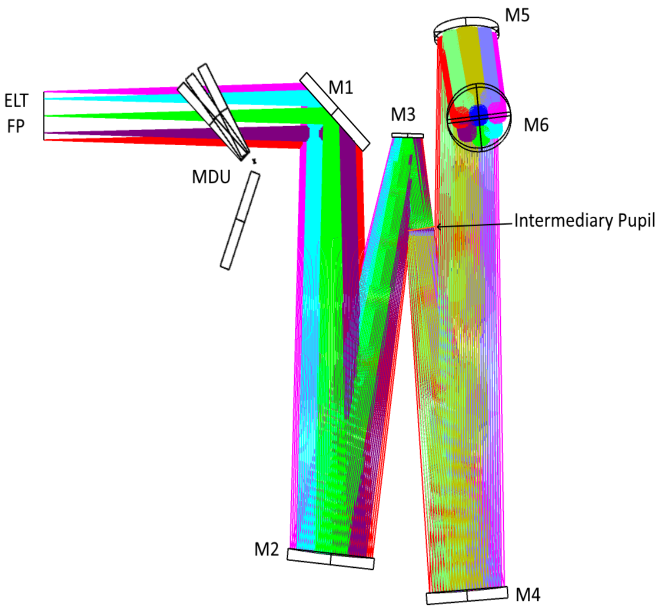


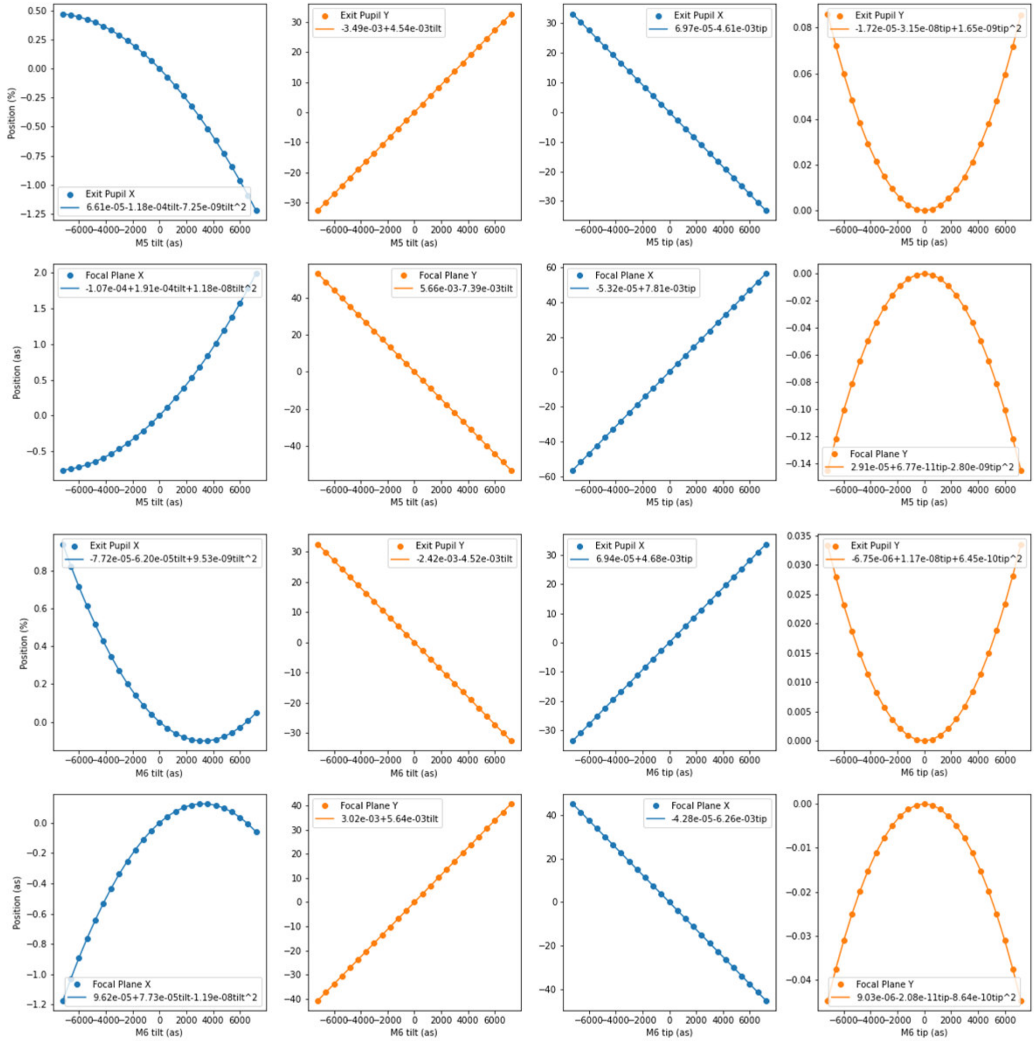


External Alignment – RO-M5 and RO-M6

RO-M5 and RO-M6

- Used to align the exit pupil and focal planes;
- They are downstream the internal pupil.





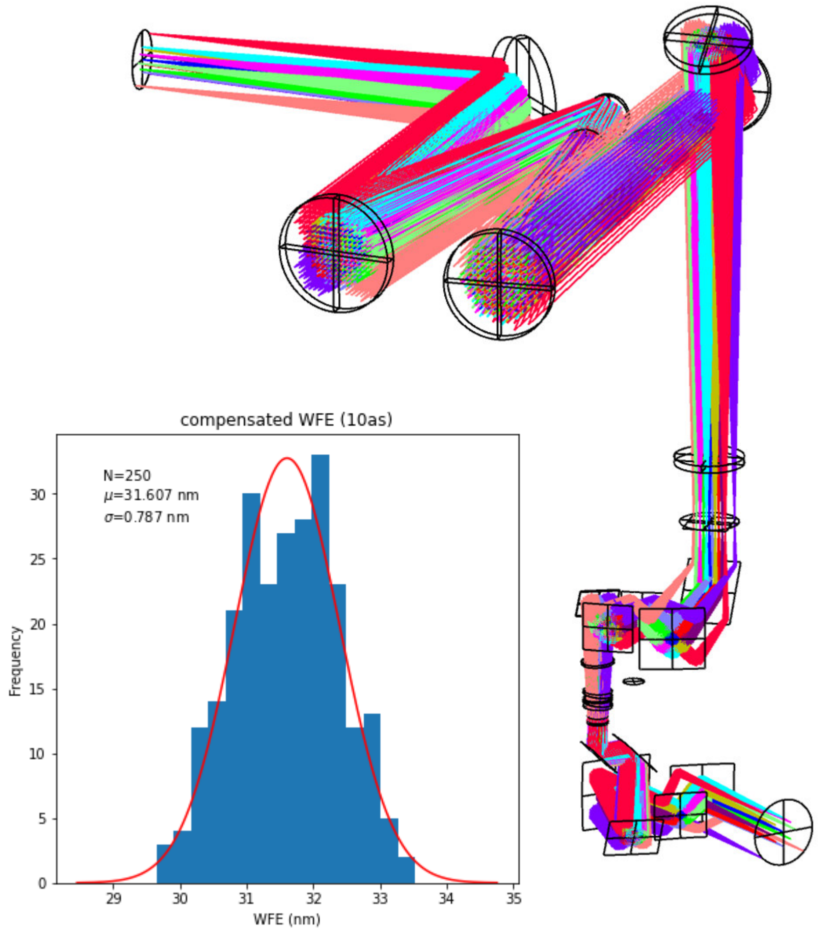
WFE analysis for the external alignment

Preparation

- Apply initial random misalignment on both interfaces:
  - ±1.5 mm in X, Y, Z;
  - 0.05 mrad around X, Y, Z;
- Apply transversal displacement for the ELT pupil:
  - Random ±0.45 mrad tip tilt error at the ELT-RO interface;
- Apply f-number variations:
  - Random re-sizing of the ELT aperture.
- Align Exit Pupil and Focal planes using the RO flat mirrors;

Diagnostic

- Read WFE at MICADO Low Resolution Imaging mode, without any misalignment;
- Read WFE at the same MICADO's mode, with misalignment;
- Compare both.



Shape of Surfaces – Mechanical support induced aberrations

How to calculate them?

- The deformations on each mirror are calculated through mechanical FE simulations for different temperatures;

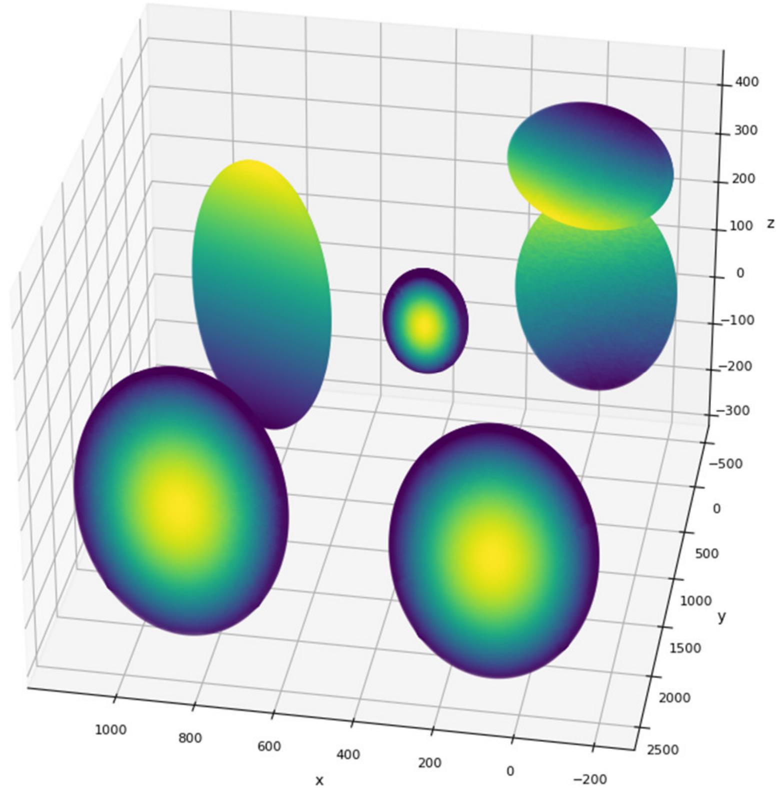
Ansys

How to determine the optical quality

- Numerical scripts can fit the data to Zernike polynomials;

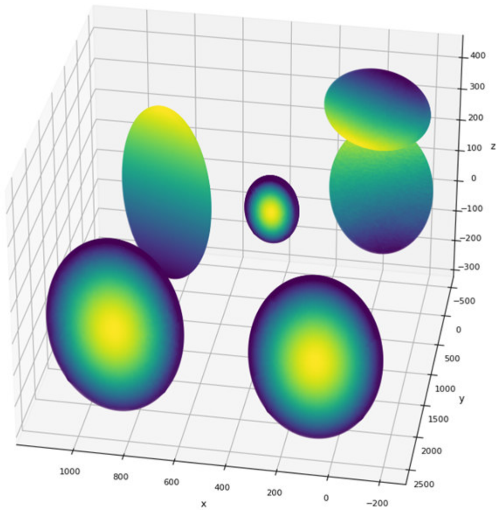
MATLAB® python™

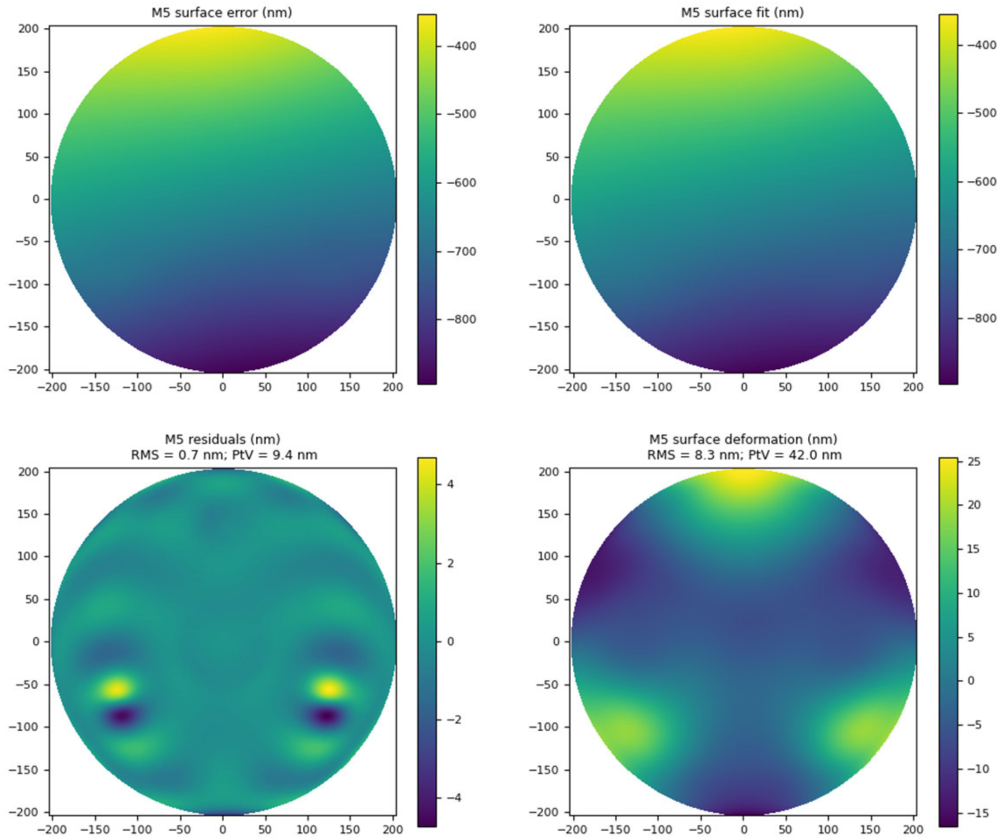
- Zemax can import Zernike polynomials into surface sags;



Static deformations at 20ºC

- The deformations on each mirror are calculated through mechanical FE simulations for the mounting temperature;
- A numerical script loads the data for each mirror:
  - Finds the normal plane and de-projects the surface;
  - Looks at the deformations in the normal direction;
  - Fits the data into Zernike polynomials;
  - Eliminates the first three Zernike terms (tip, tilt, piston);





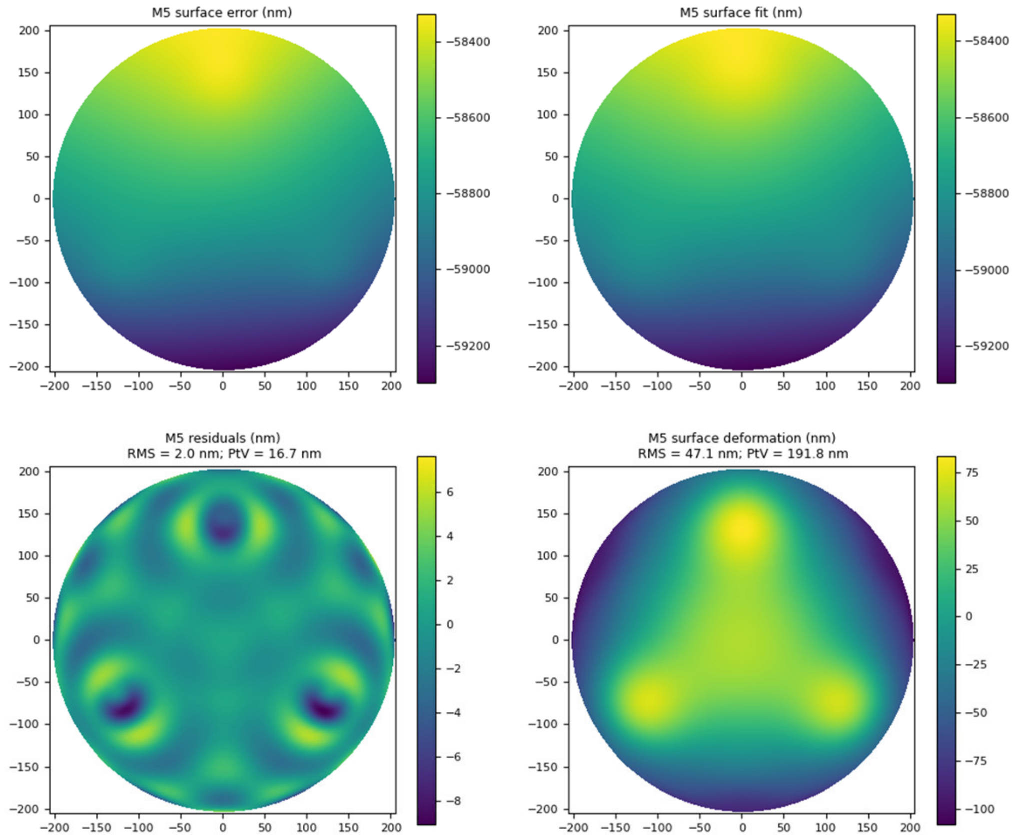
Shape of Surfaces – Mechanical support induced aberrations

Thermal deformations

- The deformations on each mirror are calculated through mechanical FE simulations for 15ºC, 10ºC, 5ºC, 0ºC;
- The numerical script loads the data for each mirror:
  - Applies the same process as before;
  - It only removes the TTP values calculated in the static case;

Iterative process

- The script allows mechanical engineers to quickly evaluate the impact of the mounts on the mirrors;
- A more complete WFE simulation can show where to focus the optimization efforts:
  - In case of the RO, the RO-M5 deformations are the worst offenders.



Shape of Surfaces – Manufacturing Tolerances

Breackdown of irregularities

- The radius of curvature tolerances:
  - 0.1% for powered mirrors;
  - 1 fringe for flat mirrors (at λ=1 μm);
- Very low frequency irregularities: Z5-Z15;
- Low frequency irregularities: Z16-Z36;
- Mid frequency irregularities: Z37-Z55;
- High frequency irregularities: Z56-Z231;

Simulation

- A list of random Zernike terms is normalized according to the requirements;
- Iterative trial and error process to find good conjugation of tolerances:
  - More relaxed for lower frequencies, and FF mirrors;
  - Stricter for flat mirrors;

Frequency	Flat mirrors (M1,5,6) [nm_{RMS}]	FF mirrors (M2,3) [nm_{RMS}]	M4 [nm_{RMS}]
Very low	13.5	23.5	20
Low	9	10	10
Mid	6	7	7
High	4	4	4
Total	17.8	26.8	23.8

Internal Alignment

Post-AIV tolerances

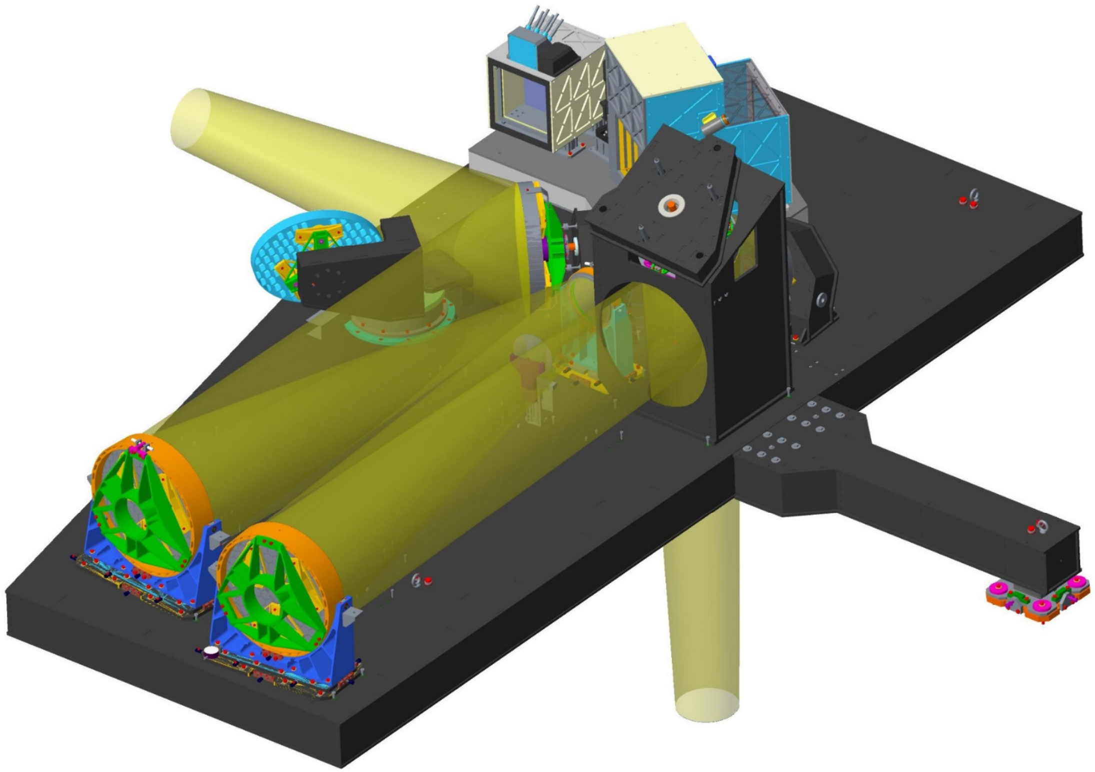
- Apply random position and orientation variations to the mirrors, within the values derived through the alignment protocol;

Thermal expansion of the bench

- The mirror displacement and orientation caused by thermal effects was calculated through mechanical FEA;
- That displacement is applied as function of the temperature;

Nasmyth platform deformation

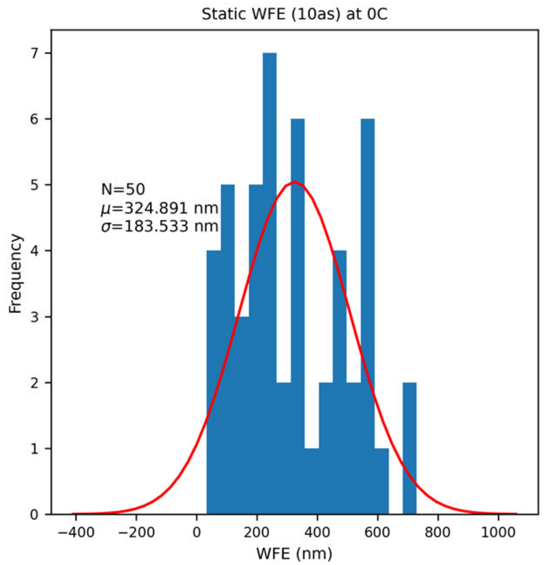
- Occurs overnight – Nasmyth attachments change separately;
- Six most relevant cases are analysed via FEA, from the attachments, up to the RO bench deformation;



Compensation needed...

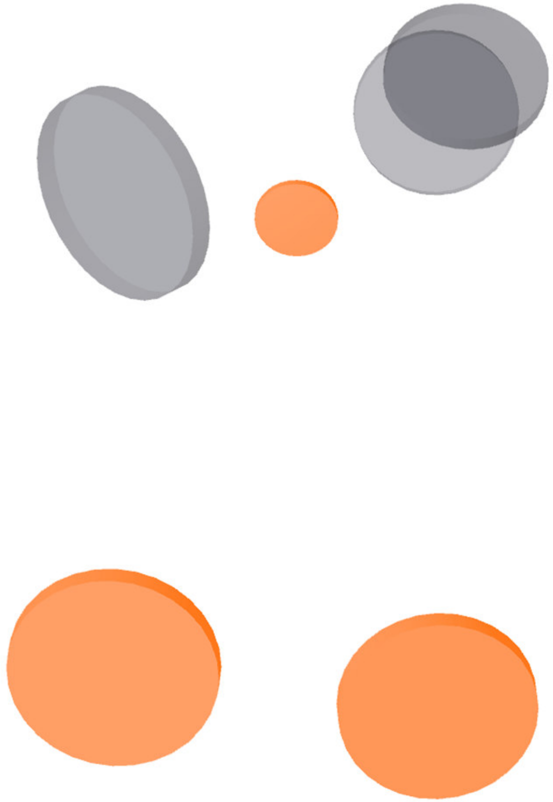
WFE values

- We are clearly non-compliant (requirement of < 100 nm_{RMS})



Finding the best solution

- Simplify: only adjust one mirror;
- Powered mirrors are worse offenders, therefore better compensators;
- Simulations show that RO-M4 is the worst offender, and a very good compensator;



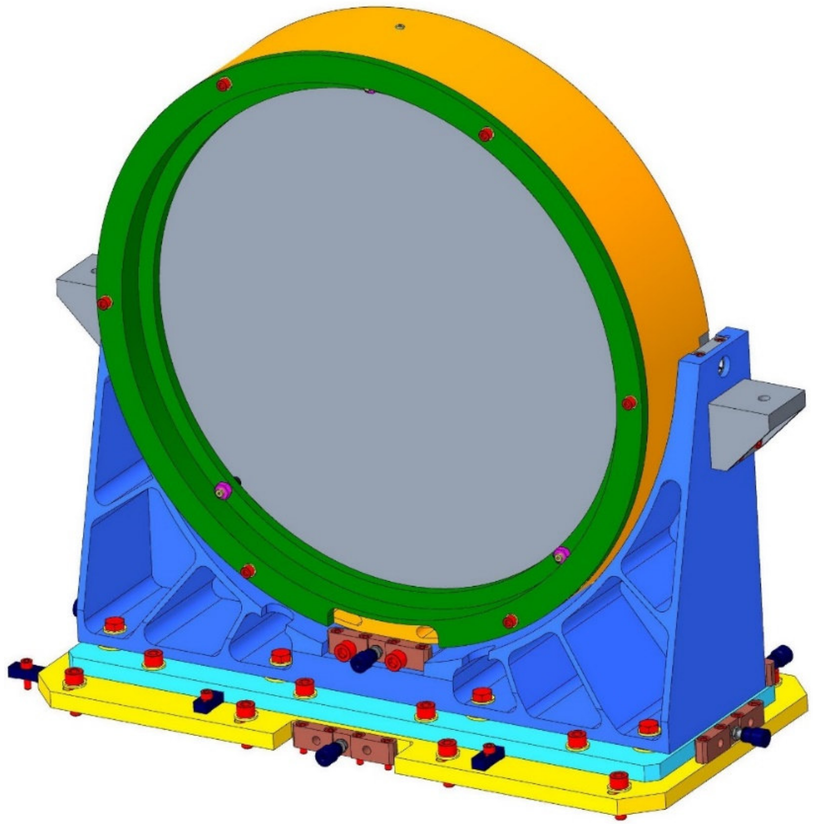
RO-M4 as a compensator

RO-M4 works great as a compensator,

- Is able to correct for misalignment:
  - Static;
  - Thermal;
  - Bench deformation;
- Is able to correct for mirror shapes:
  - Manufacturing tolerances;
  - Mechanical mounts;
  - Thermal effects;

but...

- To correct for variable changes (thermal effects, bench deformation), we need an active solution.



Solutions for M4

Motorized M4

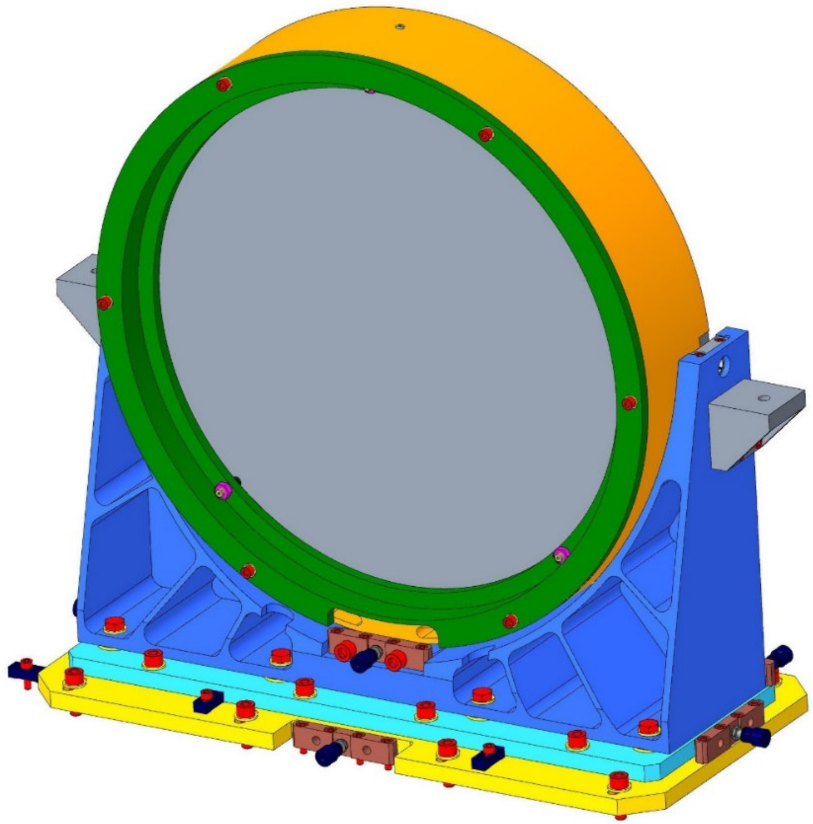
- Provides the best optical quality;
- Requires a slightly larger bench;
- It requires a control loop integrated in SCAO;

Intermediate fixed solution

- Provides compliant WFE for the whole range of operational temperatures;
- It is not compliant when introducing the bench deformation;

Passive solution

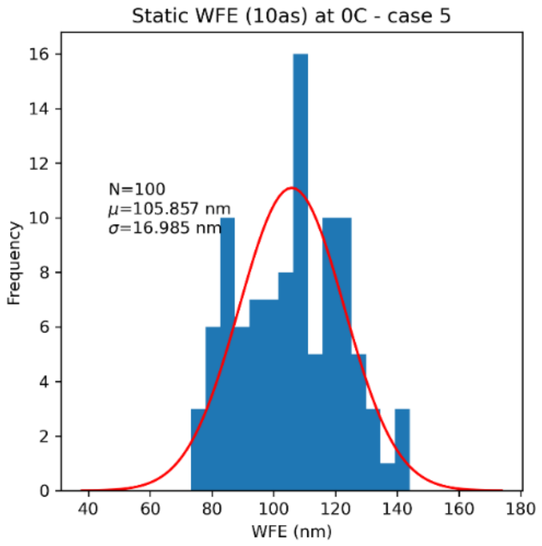
- Adjusting the piston of RO-M4 piston with linear thermal effects corrects the WFE for the full range of operational temperatures;
- The WFE gets worse when introducing the bench deformation;



The Relay Optics

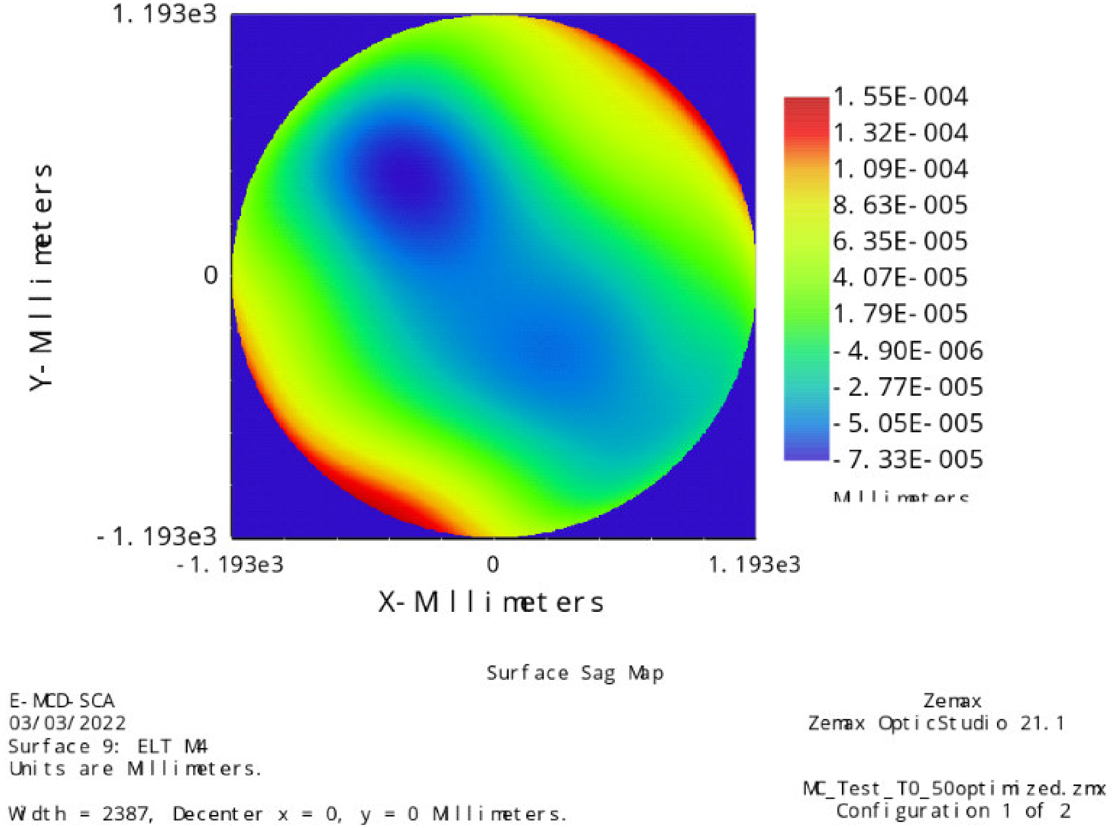
WFE values

- We are still non-compliant (requirement of < 100 nm_{RMS})



Can SCAO correct the rest?

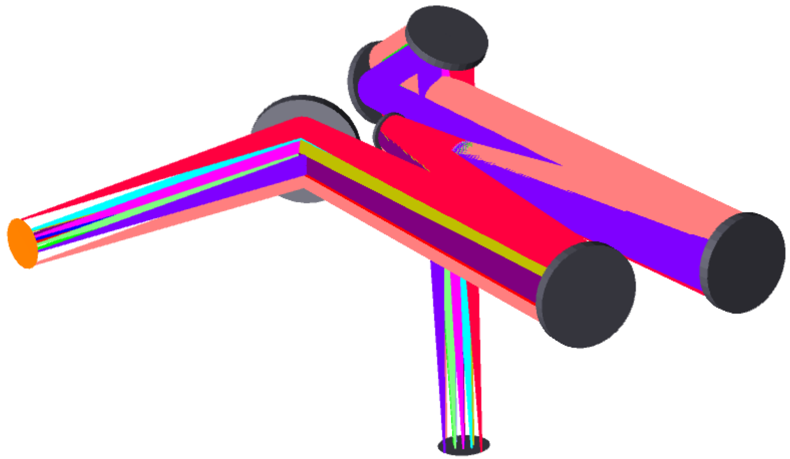
- In theory yes;
- In practice...



Recapping

The process

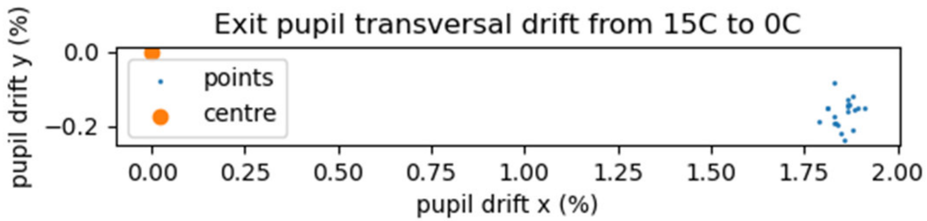
- Apply random manufacturing tolerances;
- Apply static mount induced deformations (at 20ºC);
- Apply post-AIV tolerances;
- Optimize for the WFE suing RO-M4 TTP;
- Apply small wobble to RO-M4 TTP to mimic positioning tolerances;
- Move RO-M4 in Piston by a pre-calculated value (to cover a larger range of temperatures);
- Lower the temperature to within the operational range (usually 15ºC):
    - Apply the adequate thermal Zernikes on the mirrors;
    - Expand/contract the RO bench;
- Apply mechanical bench deformation;
- Perform diagnostics;
- Repeat for another temperature;
- Verify compliancy.



Compliancy

We are fully compliant (almost)

- Non compliances are:
  - WFE (due to bench/Nasmyth deformation);
  - Pupil drift (due to thermal effects and bench/Nasmyth deformation):



Still to be done

Finish study of geometrical distortions

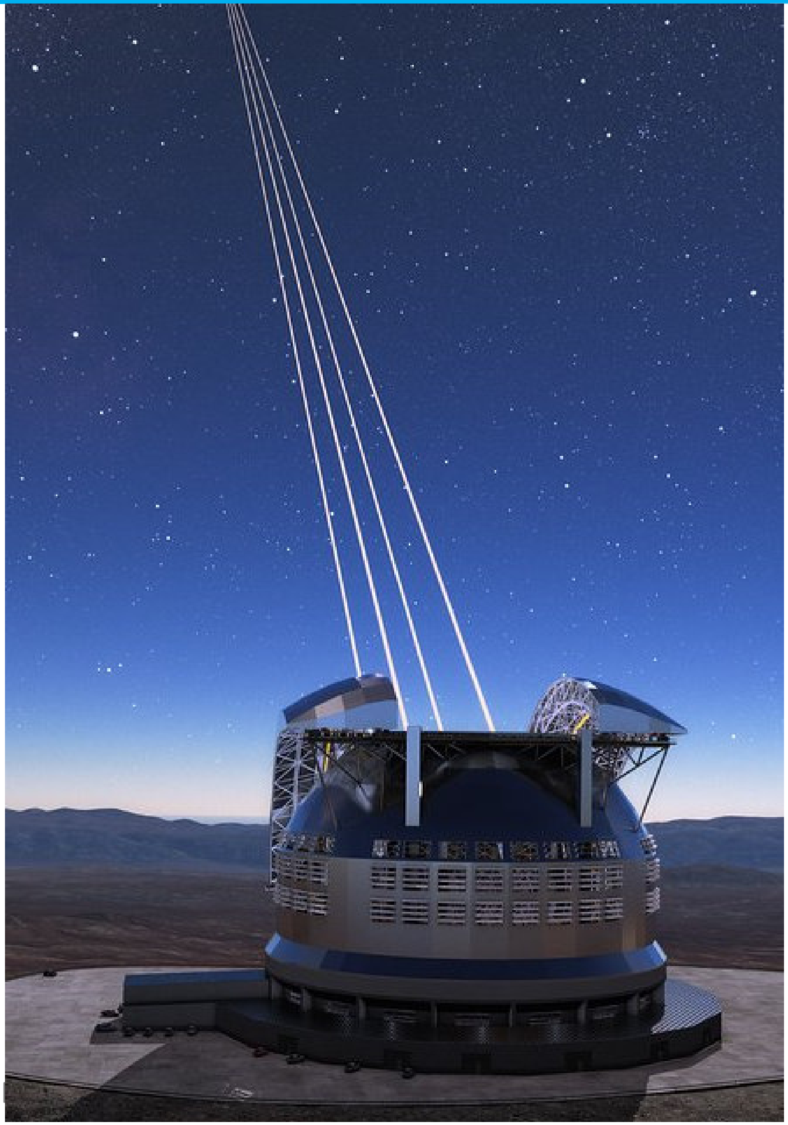
- Distortions caused by the Nasmyth->bench deformations are considerable (we require frequent calibrations during the night);
- Distortions caused by the conjugation between external and internal alignments are larger than expected;

Pupil imager

- A pupil imager and simulator would allow for testing most of the RO pupil requirements;
- As of now, it seems such imagers are feasible, but a more dedicated analysis must be done:
  - Sensibility, tolerances, etc.

Final mirror procurement specifications

- Use latest mechanical mount models on new simulations, and finalize and send the mirror procurement specification document to partners and manufacturers.



Conclusions

Simulation

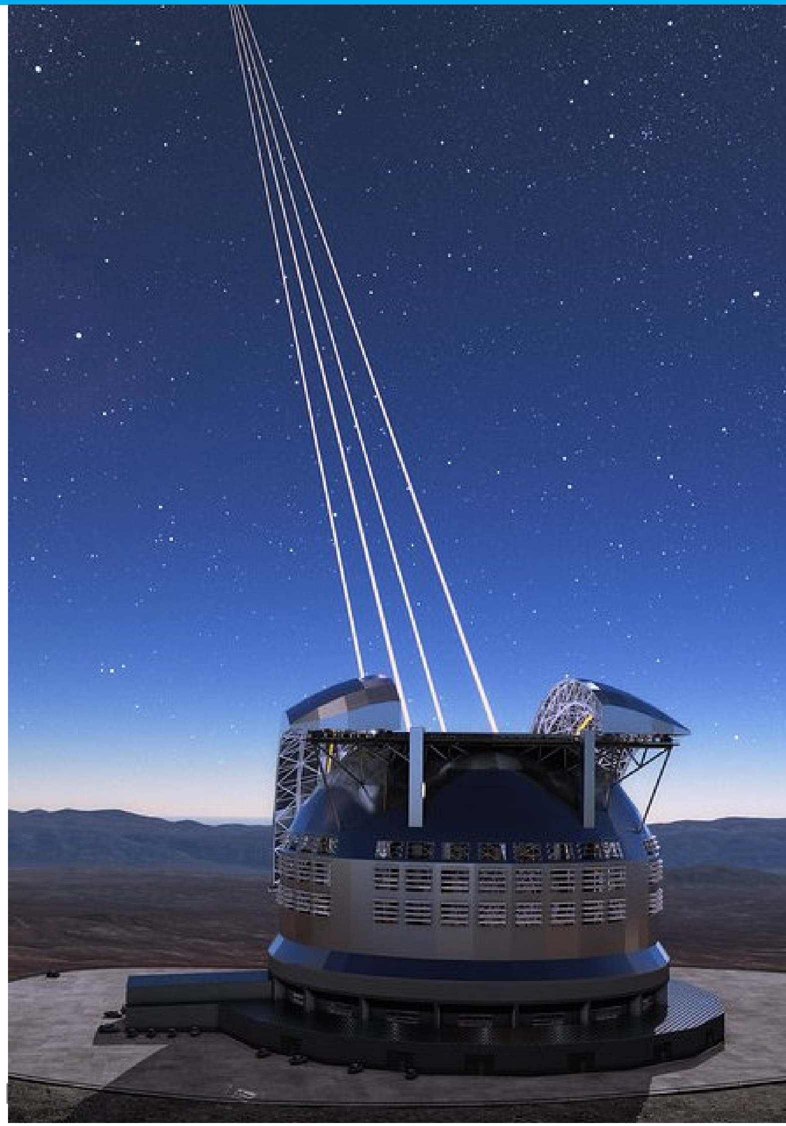
- External alignment tolerances are calculated in separate from the rest;
- External misalignment and RO-caused effects are difficult to decouple;

RO-M4 motorized solution

- It’s the most efficient solution to reduce WFE;
- Requires changes to the bench;
- Requires complex control system;
- It is an expensive solution;

Nasmyth platform deformation

- Occurs during observations;
- It is not yet fully understood;
- It has the most impact on the optical quality of the RO;
- High impact on optical distortion and WFE;
- SCAO can’t correct for distortion;



Thank you for your attention