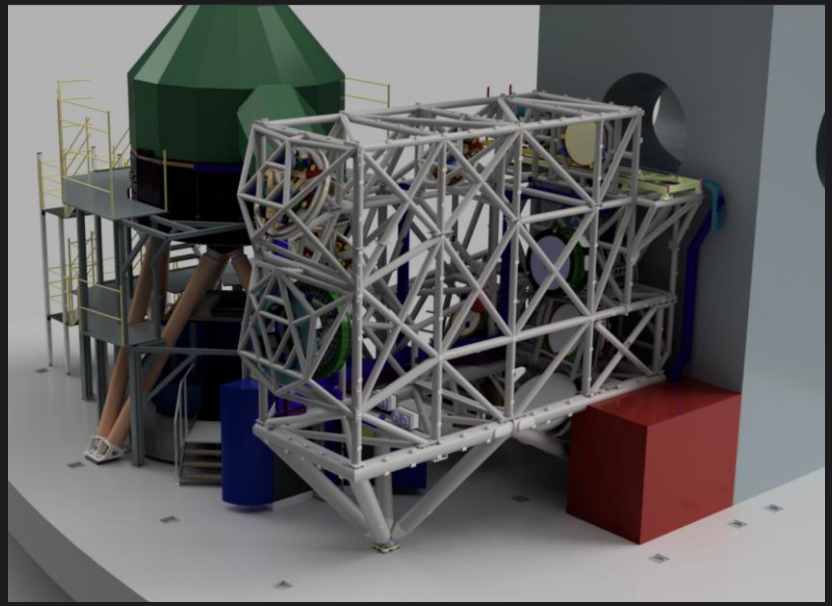
Multiconjugate adaptive Optics Relay For ELT Observations

MORFEO Sys Eng

Maorc Riva e Lorenzo Busoni

What is MORFEO

- MORFEO (Multi-conjugate adaptive Optics Relay For ELT Observation) is the MCAO module of the ELT
- It's called an ELT instrument, but it has no focal plane
- Large field diffraction limited correction for:
  - MICADO – NIR imager and long-slit spectrograph
  - HARMONI – NIR Integral Field Unit

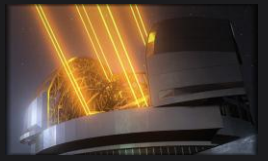


Morfeo - Micado - Harmoni

MICADO – NIR spectro imager
- SCAO and MCAO mode fed by MORFEO
- 20" (1.5 mas/px) + 53" (4 mas/px)
- I to K
- 16-48 mas long slit R=<20000
- 50 uas relative astrometry

HARMONI – IFU
- SCAO and MCAO mode
- FoV 1.3/5.3" - 6/25 mas/spaxel
- I to K
- R=7100
- Originally standalone- Now fed by MORFEO

3 projects - 1 system (?)

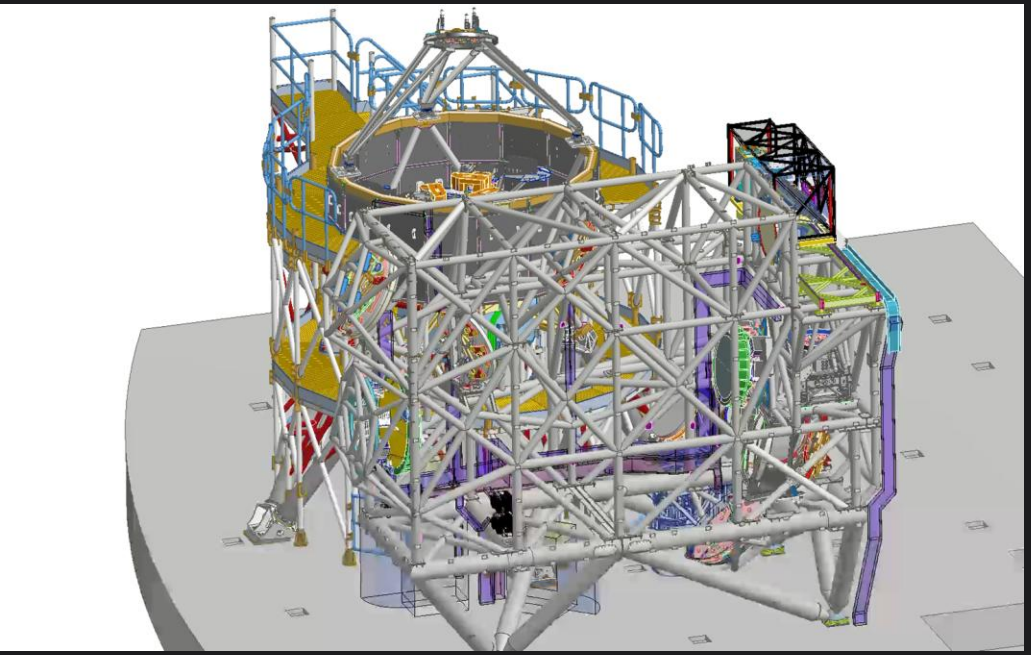


	MICADO MCAO	HARMONI MCAO	MICADO SCAO	HARMONI SCAO
ELT M4 DM	Y	Y	Y	Y
MORFEO DMs	Y	Y	static	static
MORFEO LGS WFS	Y	Y		
MORFEO NGS WFS	Y	same design ?	N	N
MORFEO RTC	Y (HEART)	same SW – copy HW ?	N (DAO)	N (Cosmic)
MORFEO CU	Y	Y + hosting ?	hosting	hosting ?

MORFEO contract

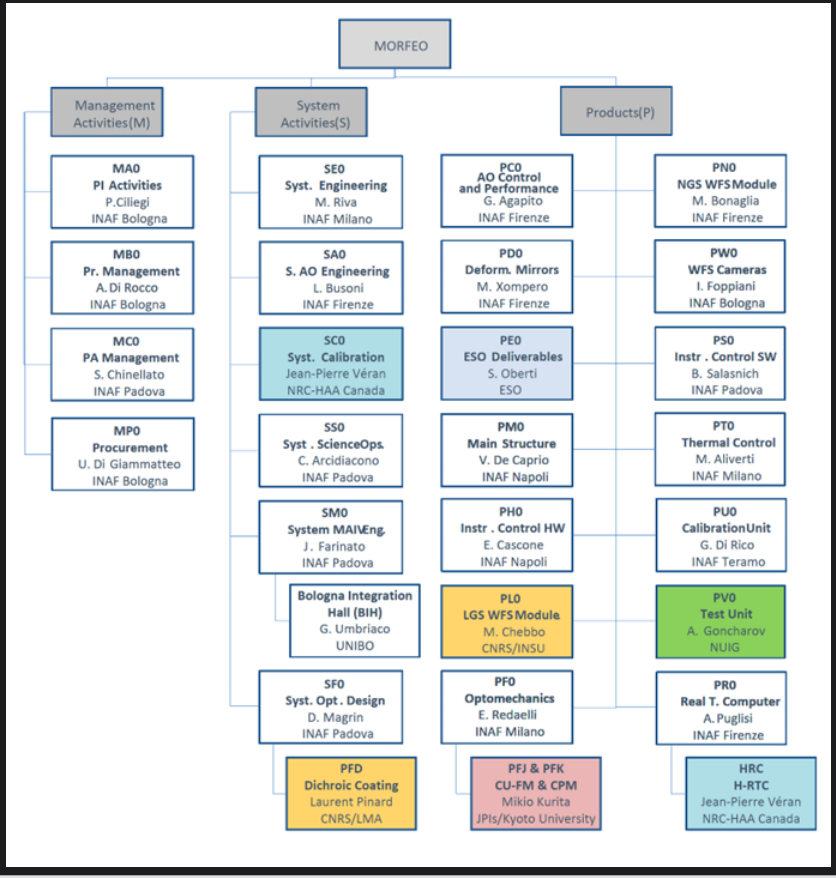
- Interdependence require tight consortia collaboration
- ESO created an MMH team to assist AO activities (S. Oberti & co)
- Great potential for reuse of HW
- Commonalities at system level: analysis, design and test
- MORFEO, HARMONI and MMH teams share common platforms (e.g. PASSATA / TIPTOP / SPECULA simulator)
- SCAOs excluded from this effort

MORFEO in short

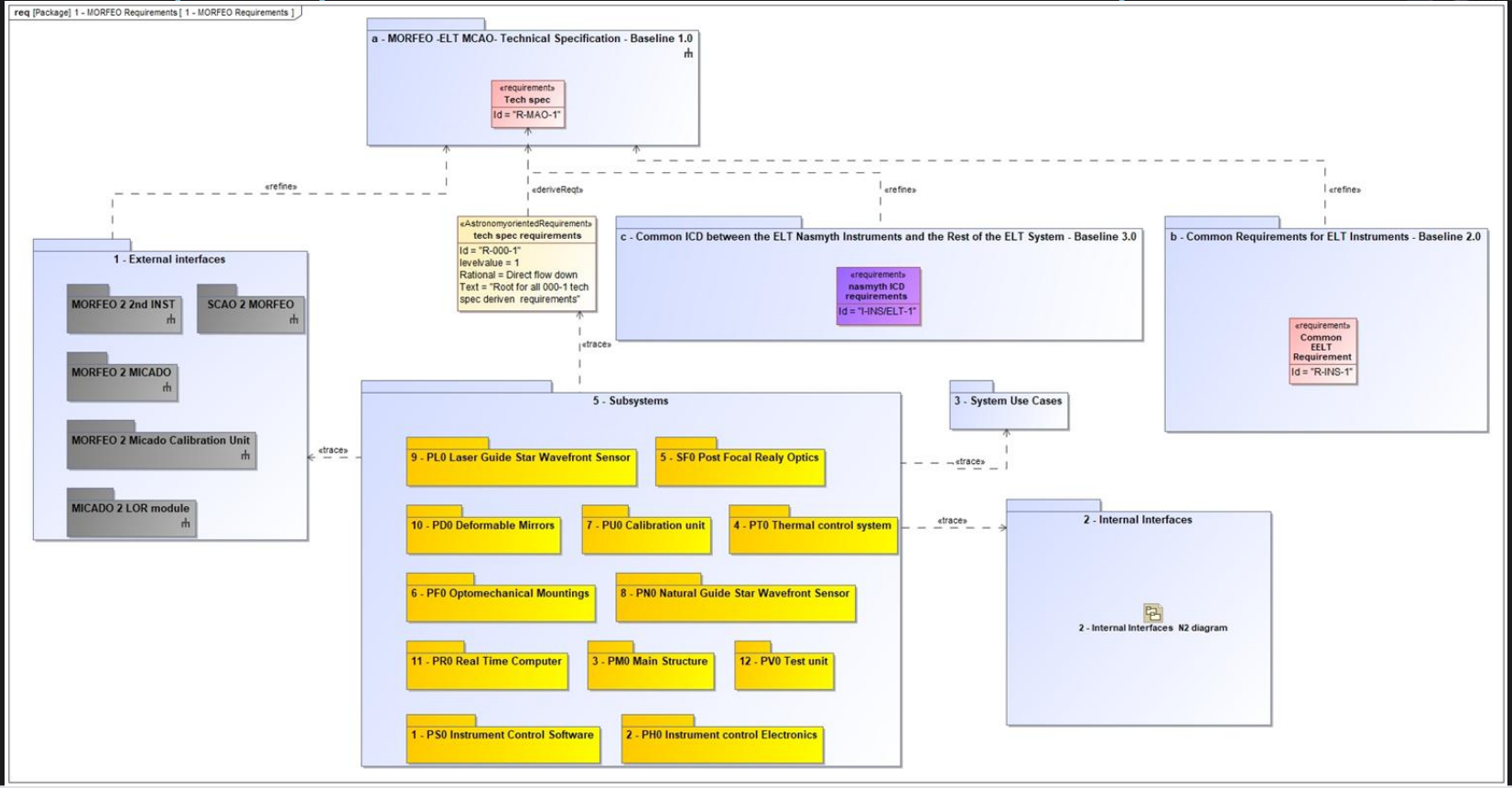


- 3 DMs (M4 + 2 post-focal DMs, ~7000 acts)
- 7 large mirrors + dichroic (~1m Ø)
- 6 LGS WFSs (~50000 signals)
- 3 NGS WFSs for:
  - Tip/Tilt/Focus (J+H)
  - Reference loop (R)
  - Derotated by MICADO
- Calibration Unit for AO and Instruments
- Gravity invariant
- Thermal passive insulation
- 7x7x4m – 30 tons

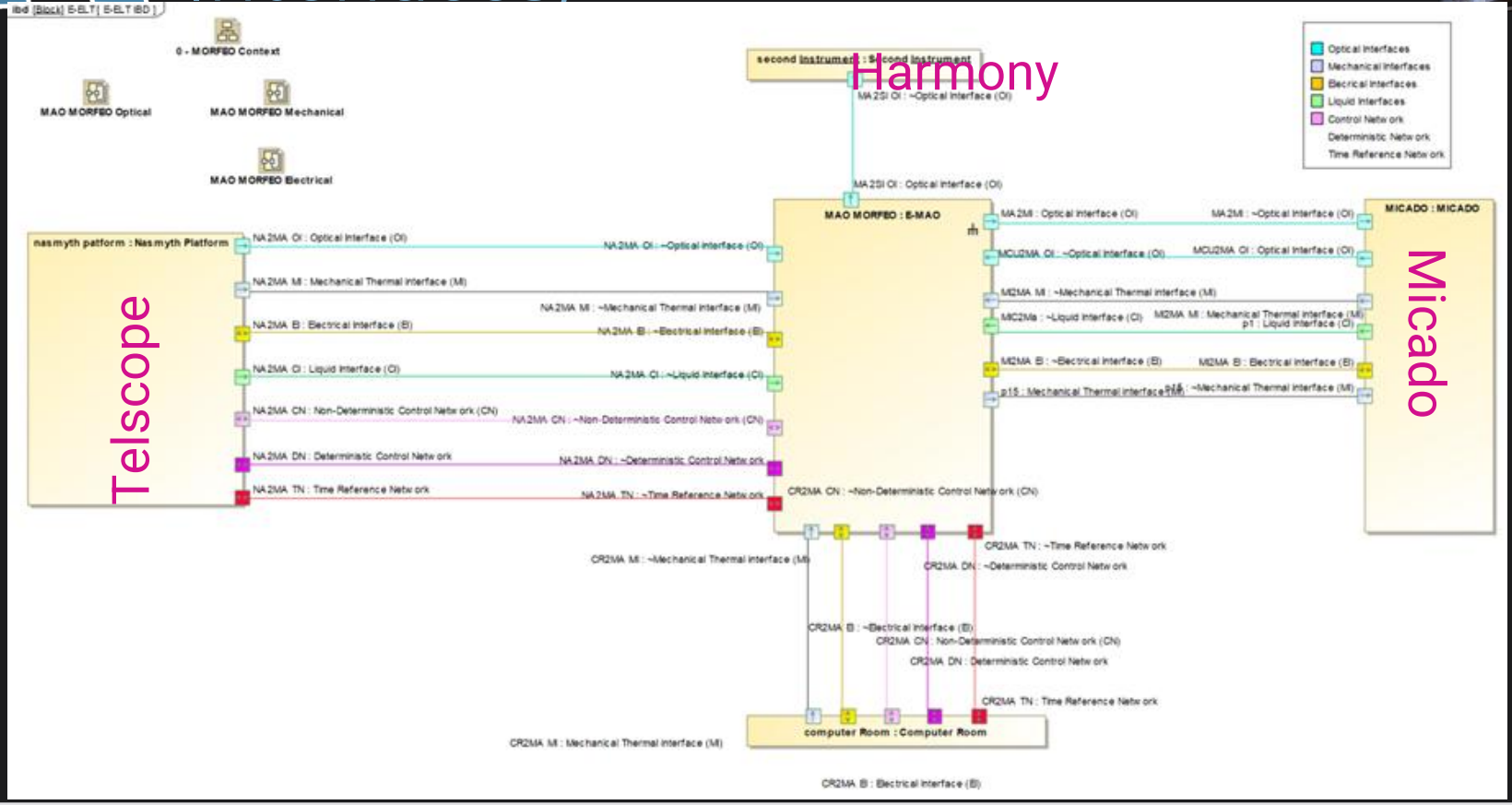
MORFEO as a system (WBS)



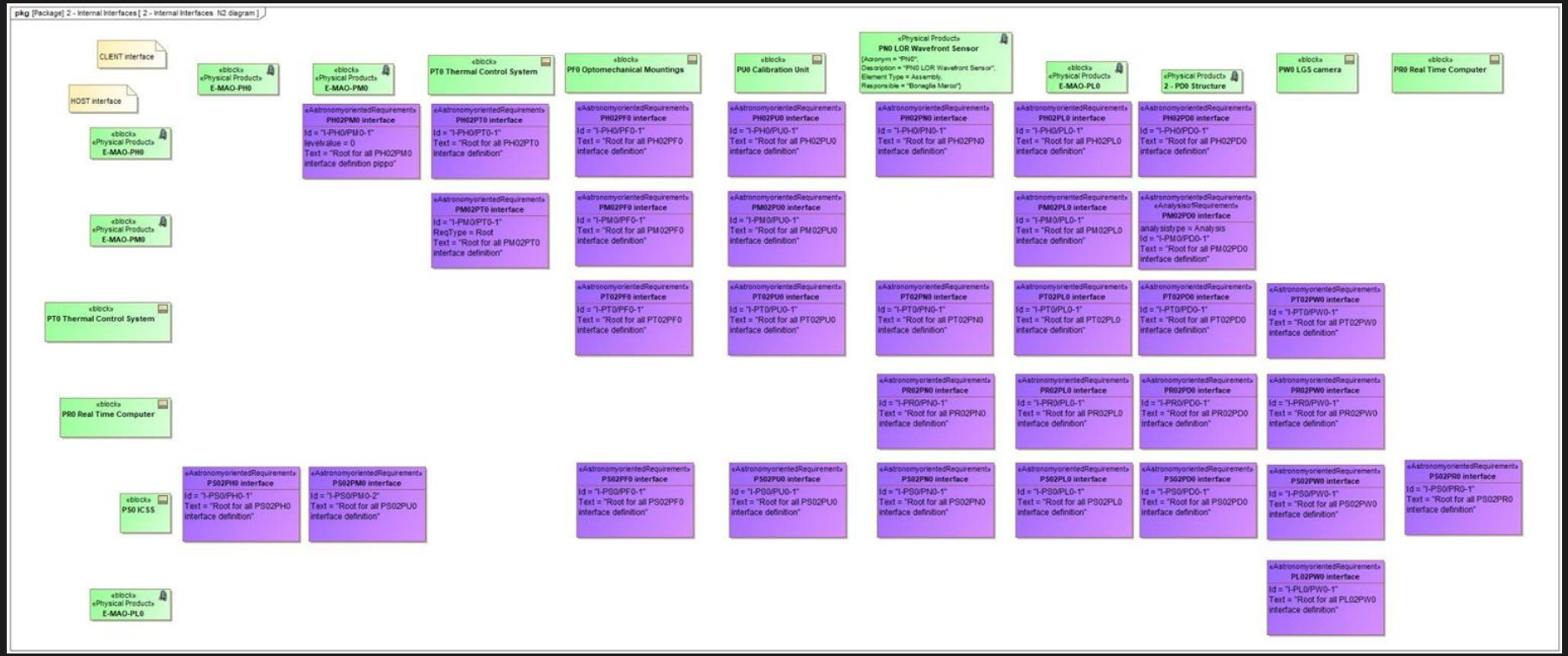
MORFEO as a system (Requirements flow down)



MORFEO as a system (External Interfaces)



MORFEO as a system (Internal Interfaces)



MORFEO as a system (Budgets)

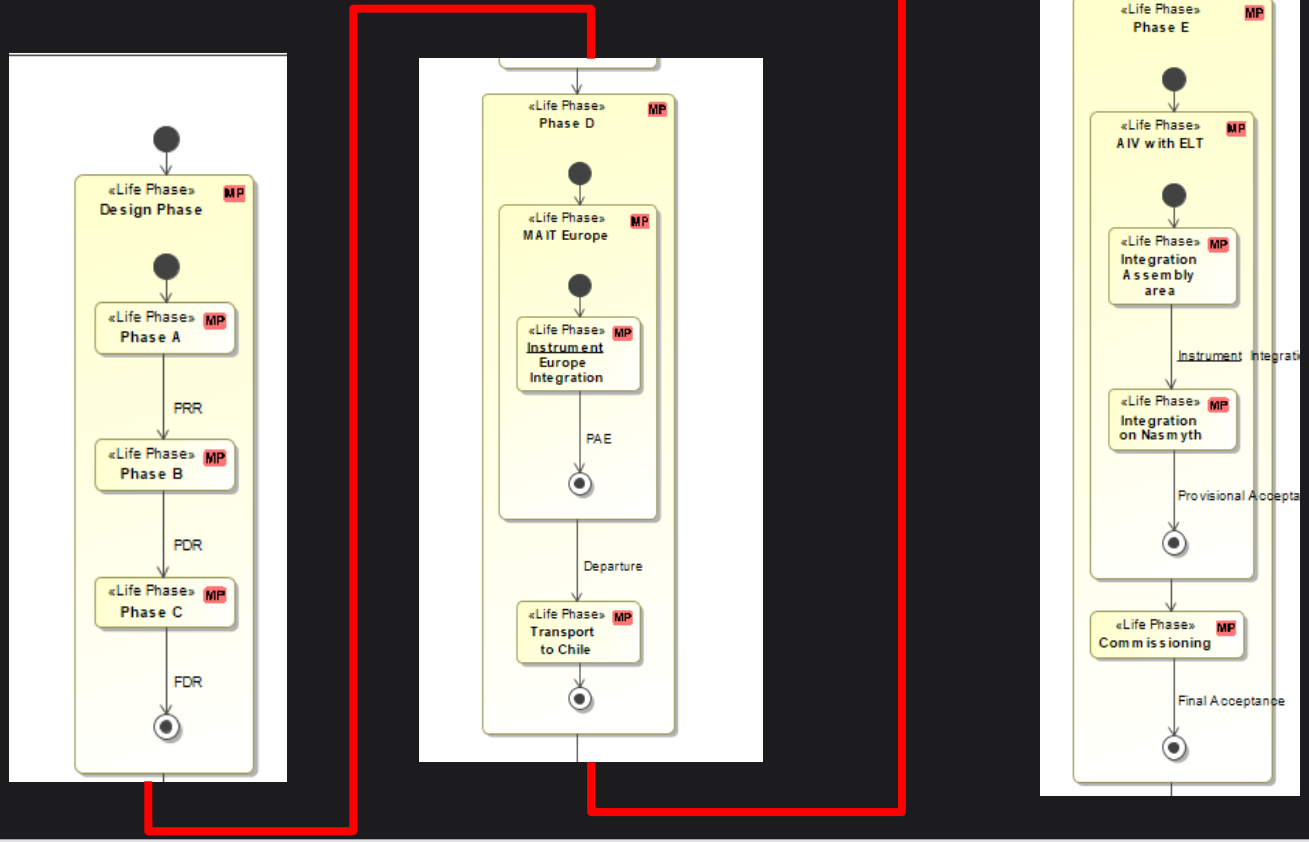
WP	Mass Kg
wp main structure	12430,00
wp optomech	2930,00
wp DM	1744,00
wp CU	385,00
wp ngs	998,00
wp lgs	625,00
wp electronic	3727,00
wp thermal control	350,00
tools	2000,00
total	*25189,00*
totl withmargin	*29546,70*
Requirement	*30000,00*

Subsystem	Peak power consumption (W)	Average power consumption (W)	Safety power (W)
PD0 - Deformable Mirrors	3100	2800	0
PF0 - Post Focal Relay Optics	1030	70	
PH0 - Instrument Control Hardware (Power Distribution Cabinet)	600	400	
PH0 - Management of cabinets (PEC, PFROC, AC and 8th cabinet)	600	600	
PL0 - LGS WFS	2200	1700	
PM0 - CU selector	1800	10	
PN0 - NGS WFS	2200	1100	
PT0 - Thermal Control System	2100	510	
PU0 - Calibration Unit	1500	1100	
PW0 - LGS cameras	900	900	
Total	16030	9190	0
Total with contingency	17633	10109	0
Requirement	25000	10400	500

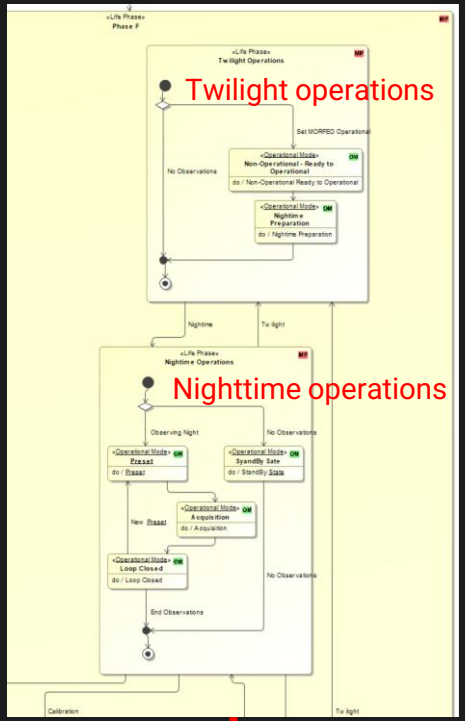
Unit	Power (W)	Flow [l/min]
cabinets	4369	8.53
Enclosure	3924	18.20
Recirculation	1440	2.73
MORFEO Sub-Total	**9733**	**29.46**
With Cont.	10706	32.40
MORFEO Tech Specs	**14800**	**30**

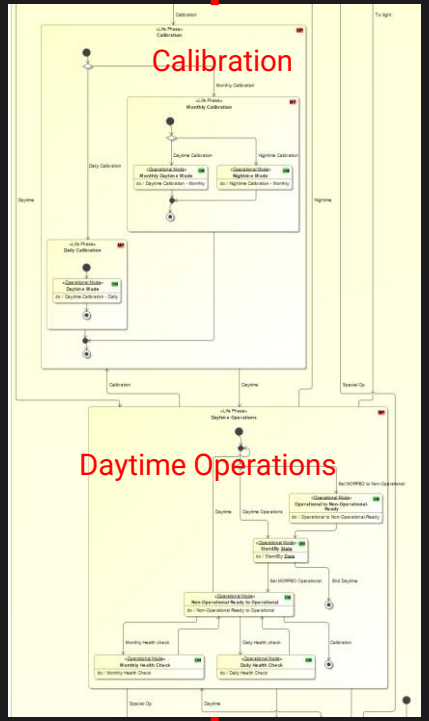
Unit	Power (W)	Flow [l/min]
cabinets	3179.9	6.1
Enclosure	3443.75	15.1
Recirculation	240	1.2
MORFEO Sub-Total	**6919**	**22.34**
With Cont.	7610	24.6
MORFEO Tech Specs	**10400**	**30**

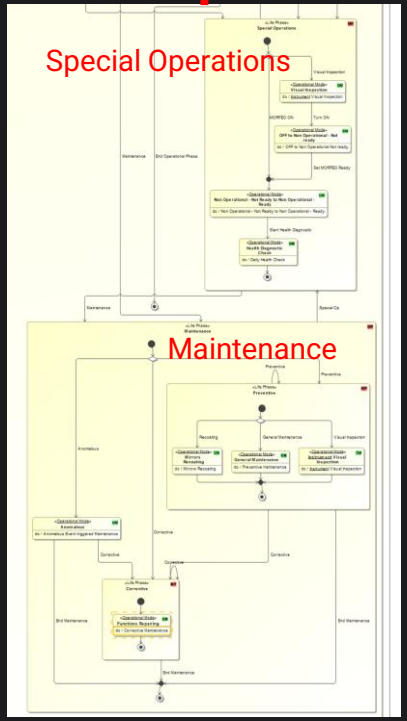
MORFEO as a system (Operations)



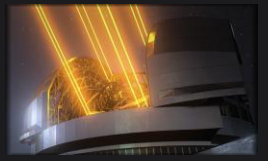
MORFEO as a system (Operations)







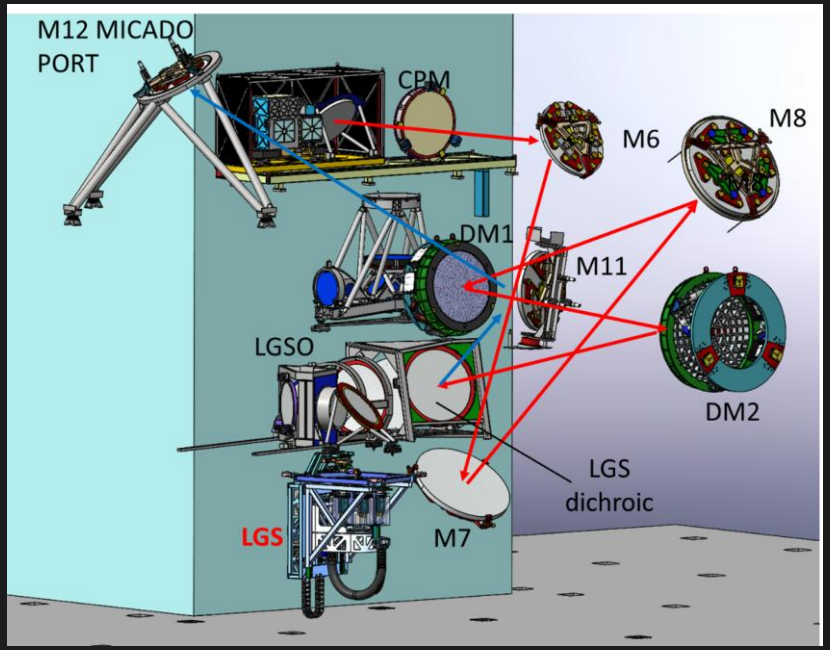
Risks and Issues



- (inter)Facing to a telescope not yet in operation
  - requirements in evolution
  - “standards not clear”
  - Adaptivity
- Mix of various project is a potential killer
  - Different evolution phases
    - Micado
    - Harmony
  - Different attitudes
    - Politics
    - Consortia Vs Industry
  - Different Approach
    - Request changed over time
- Late decisions have huge effect on schedule and costs

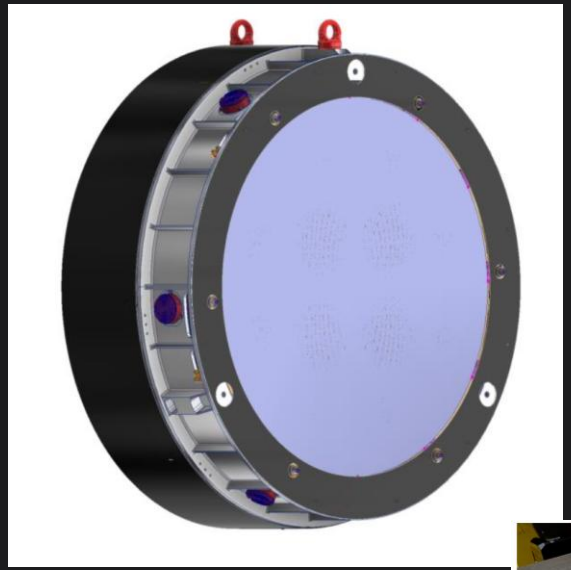
Optical design

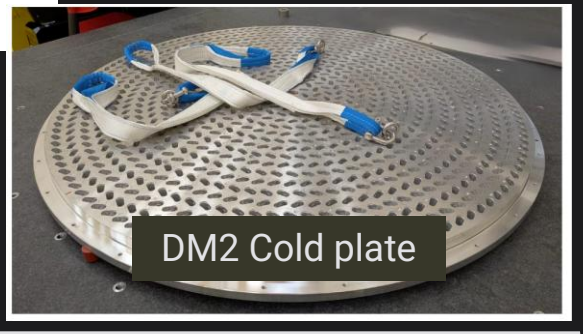
- Relay 1-to-1 with 5 mirror + 2DM+ dichroic (589nm transmitted).
- F/17.7 - flat output focal plane.
- Can serve 2 ports.
- 160” Ø transmitted field.
- LGSO r=45”, F/5 telecentric
- Throughputs:
  - INS 0.79 – to MIC input
  - LGS 0.24 – incl. QE
  - NGS 0.32 – incl. QE
- Optics under procurement now



Deformable Mirrors DM1 / DM2

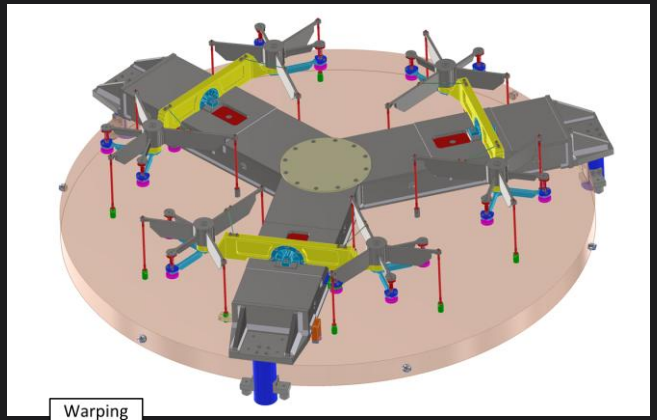
- Optical conj. 17.5 / 6.5 km
- # Actuators 1026 / 1147
- Spherical Convex / Concave
- Diameter 930 / 1224 mm
- AdOptica voice-coil technology
- In manufacturing phase
  - DM2 delivery Oct 27
  - DM1 delivery May28

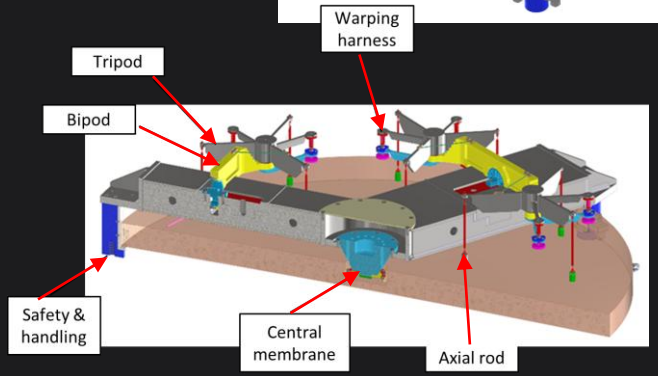




Aspherical Mirrors M7M M8M

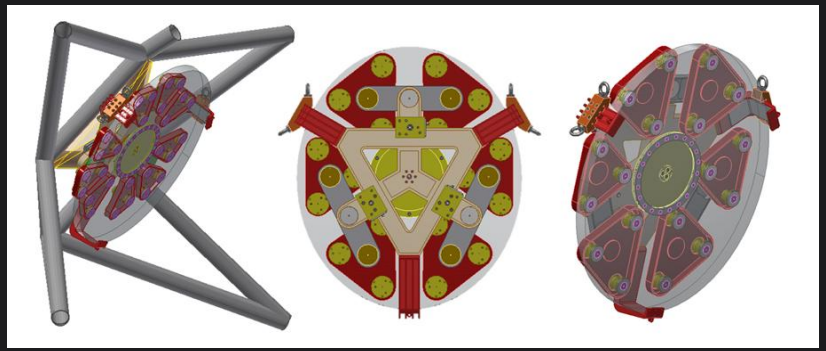
- ASpherical Concave
- Diameter 1190/ 1230 mm
- Radius of curvature 38403
- Zerodur
- In final design phase
  - LLI review passed



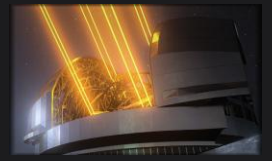


Flat Mirrors M6M M11M M12M FM1 and FM3

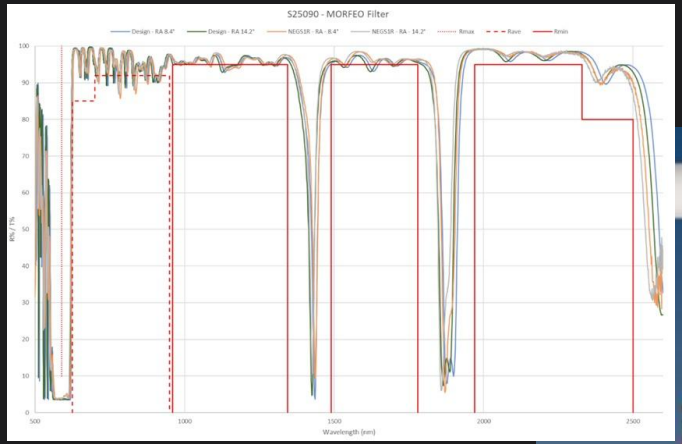
- Flats
- Max dimension 950/1200/724/1060mm
- Radius of curvature infinity
- Zerodur
- M11 and M12 active tip tilt (0.4deg,1arcsec)
- M11 port selector
- cft Technical evaluation

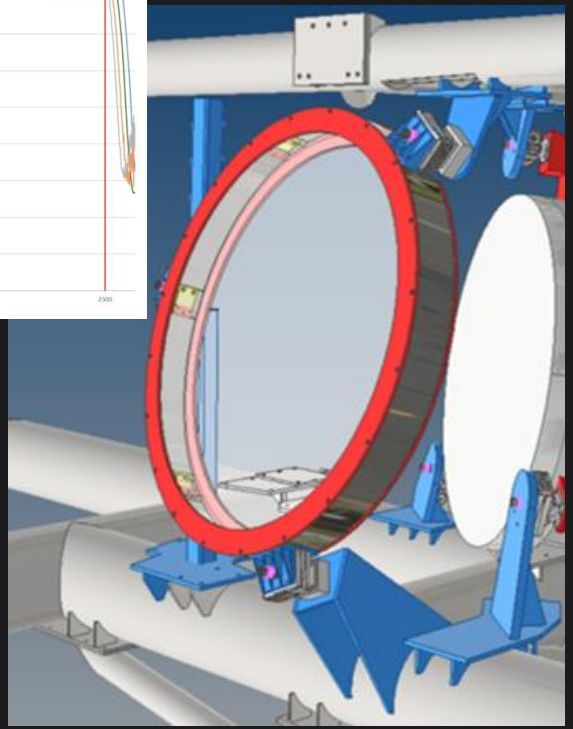


Dichroic



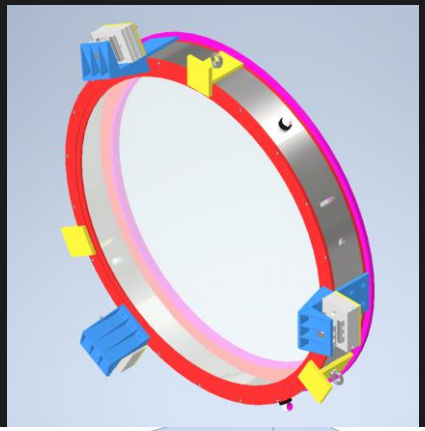
- Flat
- Diameter 890 mm
- Radius of curvature infinity
- Silica
- Reflect all but 590nm
- Under Final design

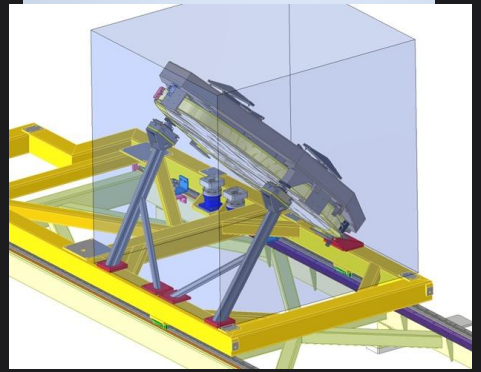




Japan contrib FMCU CPM

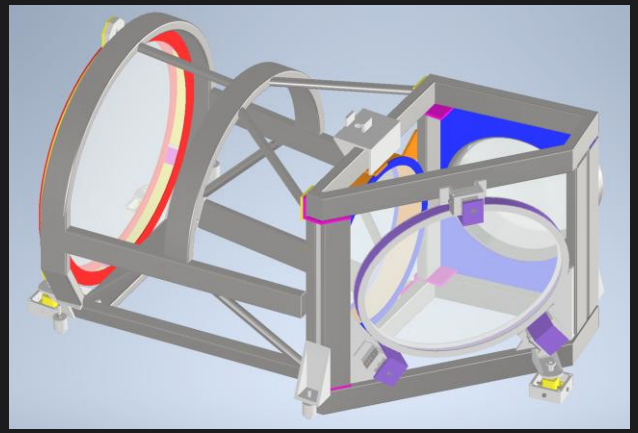
- Flat + Flat/Aspheric offaxis
- Max dimension 950/800mm
- Zerodur/Suprasil
- under final design

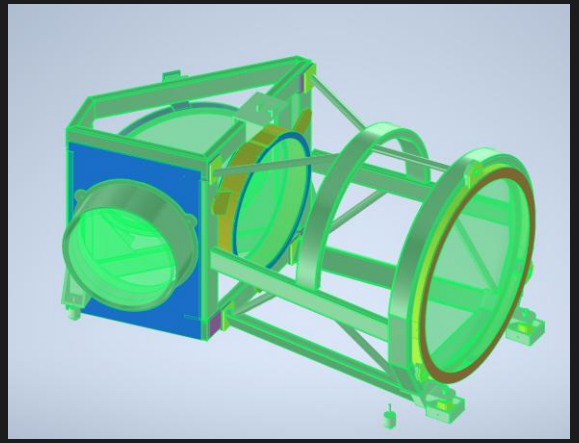




Laser Guide Stars Objective

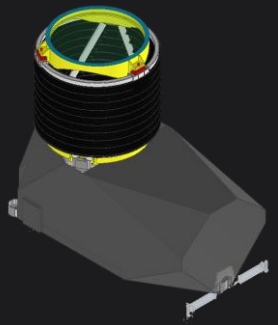
- Transmits 589nm
- Delivers
  - F/5 Beam
  - Telecentric
  - Gravity Invariant
- Optimized for
  - 45”
  - 84 to 180km conj

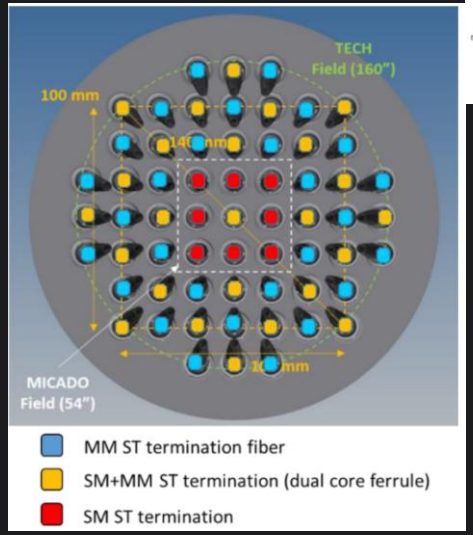


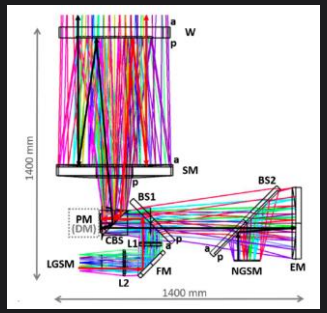


Calibration Unit

- NGS Mask
- LGS moving Mask
- OFDR passed
- KOM soon

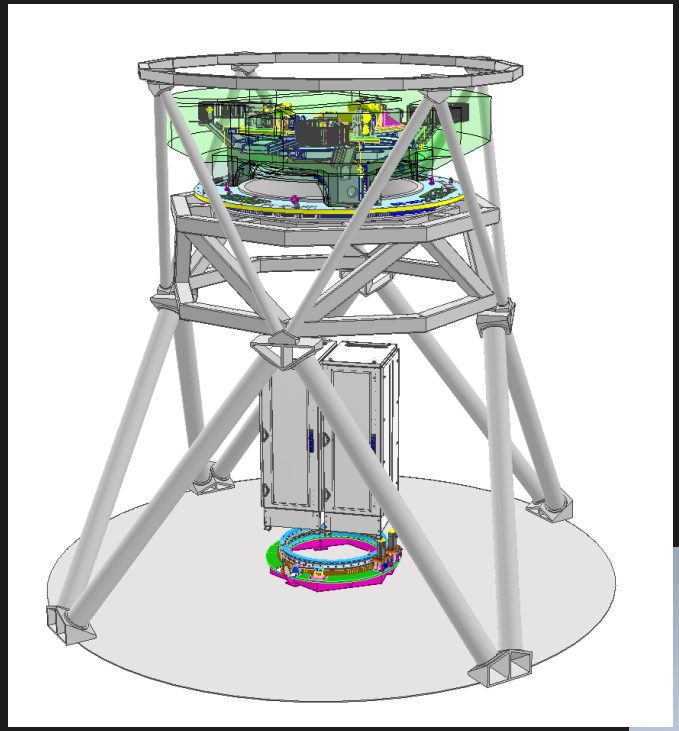


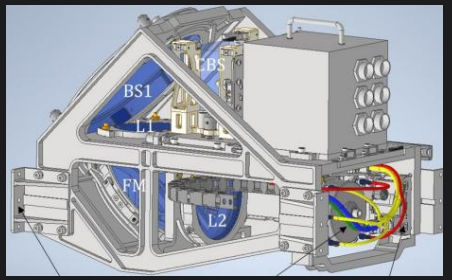


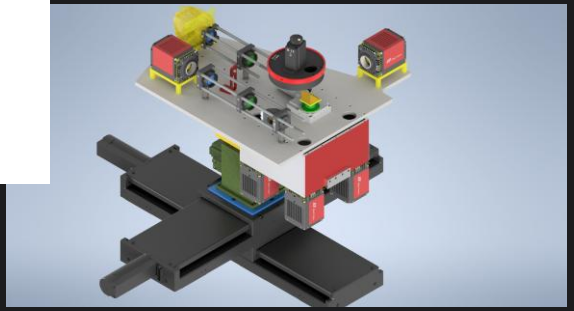


Test Unit and test equipment

- CU + DM
- MES-TAC-Minitac



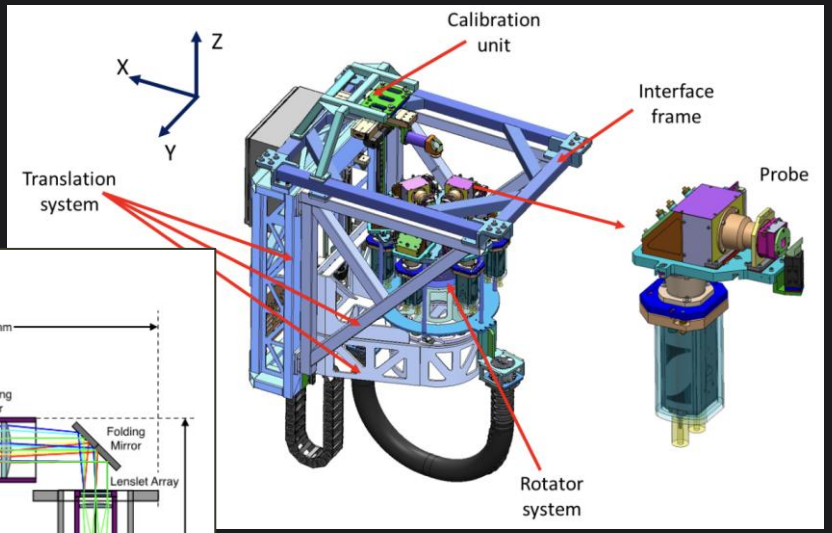


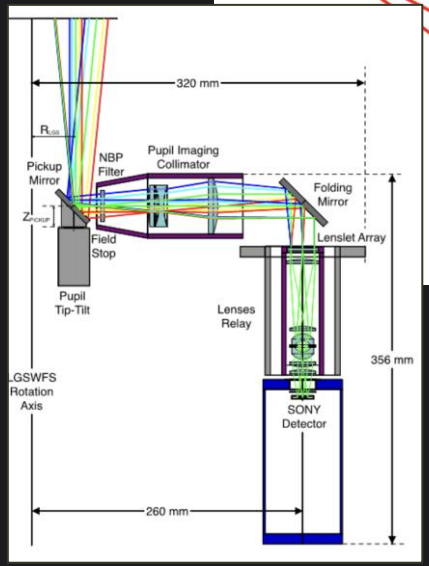


LGS WFS Module

LGS WFS module

- 6 LGS WFS @ 45” radius fixed
- SONY IMX425 detector, 1100x1600px 500Hz (e.g. First Light C-blue)
- 68×68 subaps, 1.17"/px
- 16.4" FoV square aligned with spot elongation
- Common focus to track elevation
- Derotator to track pupil
- Individual pupil steering mirrors
- FDR completed (waiting for board report)

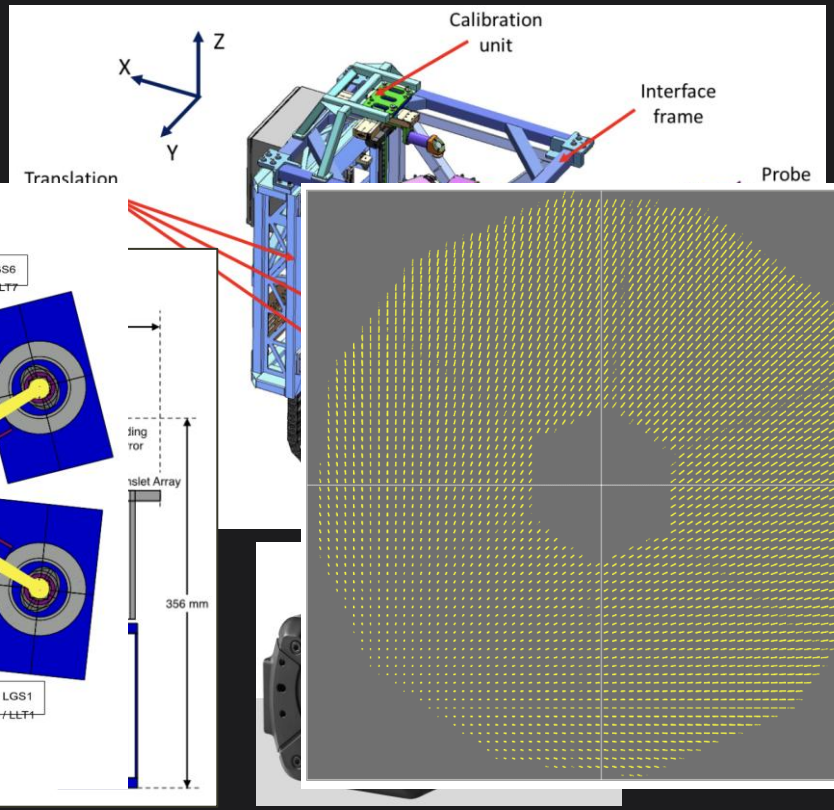




LGS WFS Module

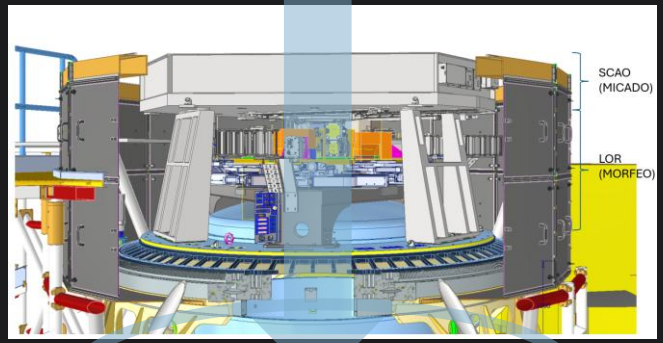
LGS WFS module

- 6 LGS WFS @ 45” radius fixed
- SONY IMX425 detector, 1100x1600px 500Hz (e.g. First Light C-b
- 68×68 subaps, 1.17"/px
- 16.4" FoV square aligned v elongation
- Common focus to track el
- Derotator to track pupil
- Individual pupil steering m
- FDR completed (waiting fo report)



NGS WFS Module

From M12



SCAO
WFS

MORFEO
NGS WFS

rotator

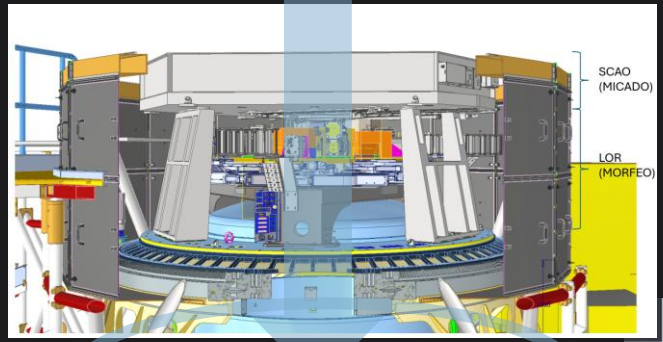
MICADO

NGS WFS module

- 3 Low Order and Reference units
- Partially overlapping 160” patrol field
- Field derotated by MICADO
- LO: J+H band, 1kHz, ADC, FREDA
  - 1x SH 2×2
  - 2x Full Aperture with LIFT
- Ref: R+I band, SH 8×8, 4.5" FoV, 10Hz, ALICE
- Each unit has XYZ positioning and pupil steering
- FDR completed (waiting for board report)

NGS WFS Module

From M12

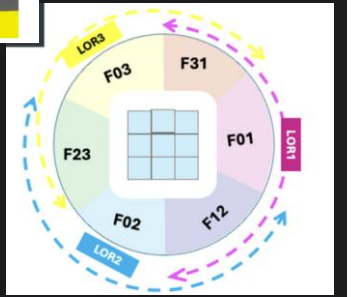


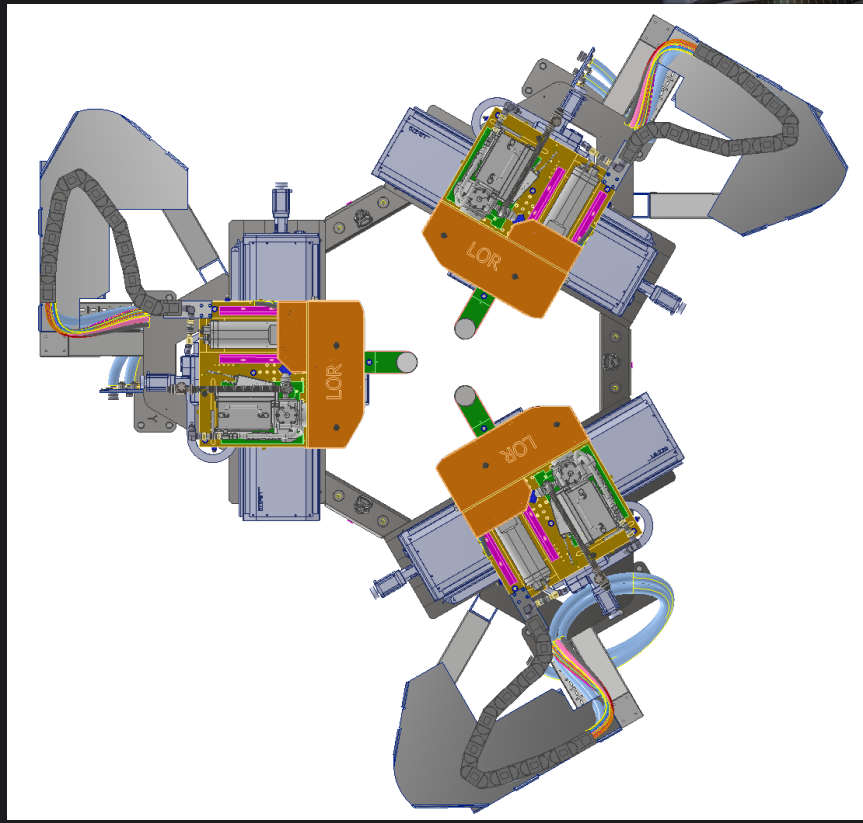
SCAO
WFS

MORFEO
NGS WFS

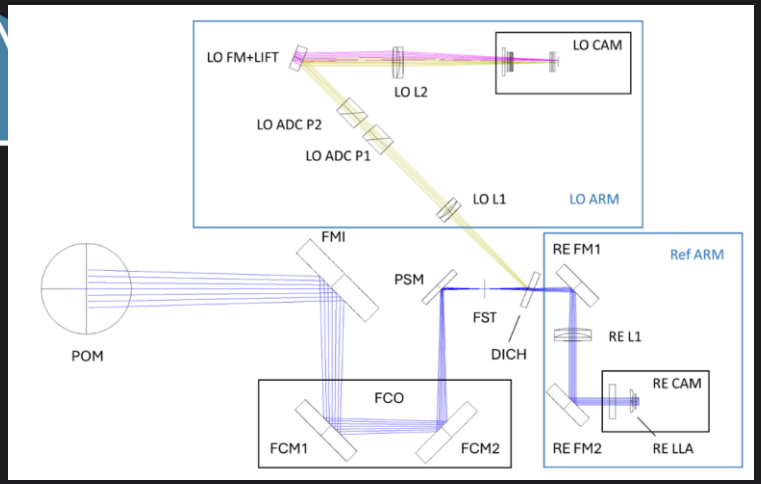
rotator

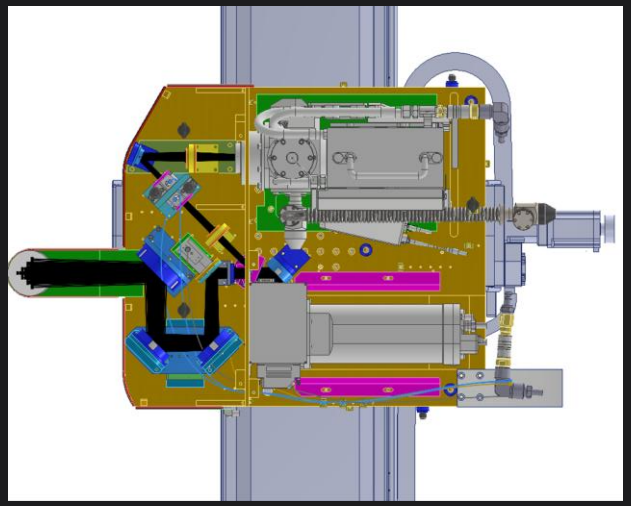
MICADO





NGS WFS Module



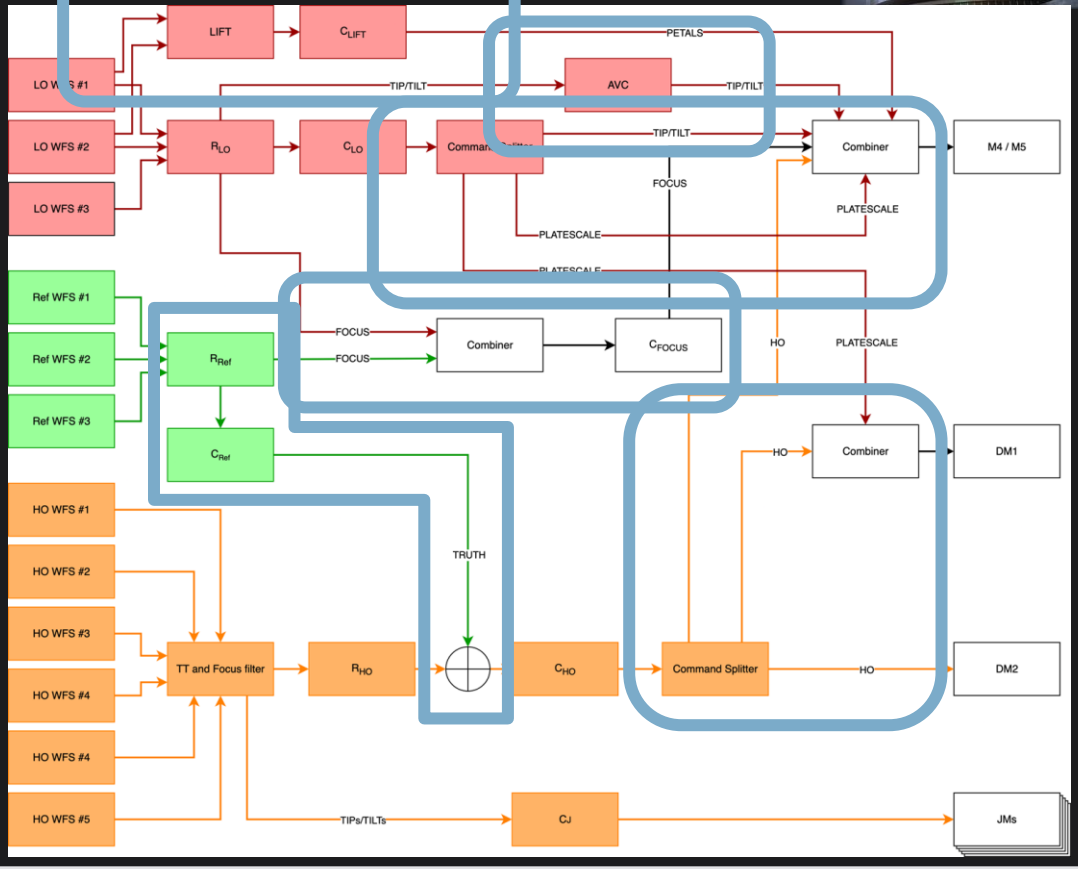


NGS WFS module - LOR

- 3 Low Order and Reference units
- Partially overlapping 160” patrol field
- Field derotated by MICADO
- LO: J+H band, 1kHz, ADC, FREDA
  - 1x SH 2×2
  - 2x Full Aperture with LIFT
- Ref: R+I band, SH 8×8, 4.5" FoV, 10Hz, ALICE
- Each unit has XYZ positioning and pupil steering
- FDR completed (waiting for board report)

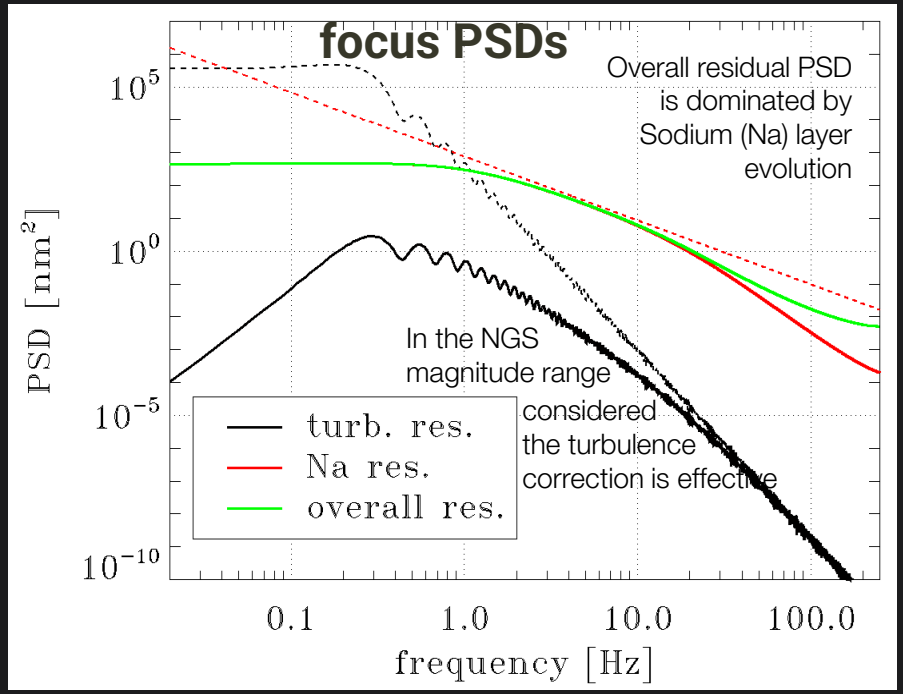
MORFEO AO control

- Reconstruction MMSE estimator (w/ noise priors) on virtual DMs
- Projection to actual DMs is optimized for the desired science FoV.
- Pseudo-open loop control (POLC).
- Tomography is split between high order modes and low order modes.
- Tomographic truth sensing.
- TT temporal control:
  - IIR filter with ≥2 poles and ≥2 zeros.
  - Adaptive Vibration Cancellation.
- Focus from Ref WFS or 2x2 LO WFS
- Petalometer



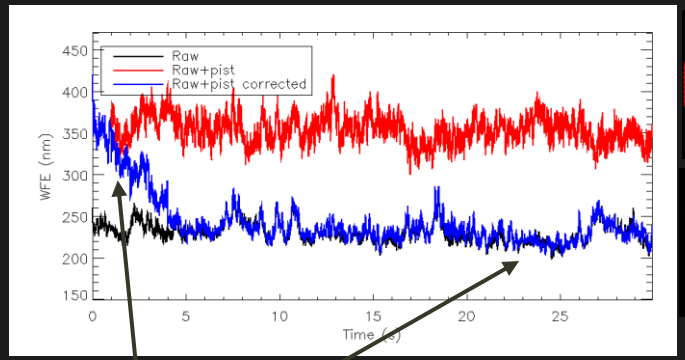
Focus control

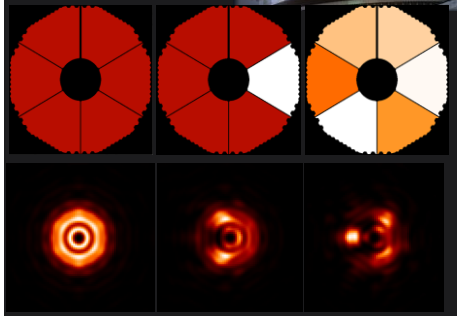
- Focus induced by sodium altitude evolution is faster than atmospheric focus for ELT → Focus from NGS to correct field-averaged Focus.
- High sensitivity to Sodium Profile lateral variations (5nm RMS/m) → Focus from LGS is filtered out.
- On the ELT we can talk of LGS Tilt & Focus indetermination



Phasing and Low Wind Effect

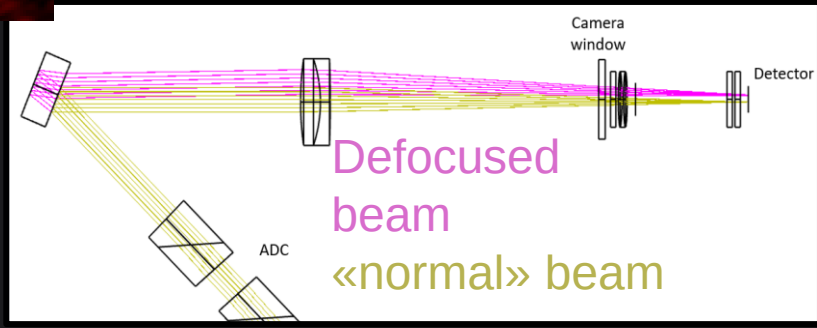
- Need a petal sensor to keep the system phased and sense Low Wind dome turbulence
- LIFT on both Tip/Tilt LO WFS creating a defocused spot on the FRIDA detector
  - 10% flux
  - spaced 0.6" from focused spot
- 2 units -> multiwavelength to extend the capture range
  - Narrow bands (30nm) at H boundaries
- New ESO dome seeing volumetric simulation to be analysed





Co-phased LIFT spot | LIFT spot with petal | LIFT spot with scrambled telescope

On-axis PSF in K



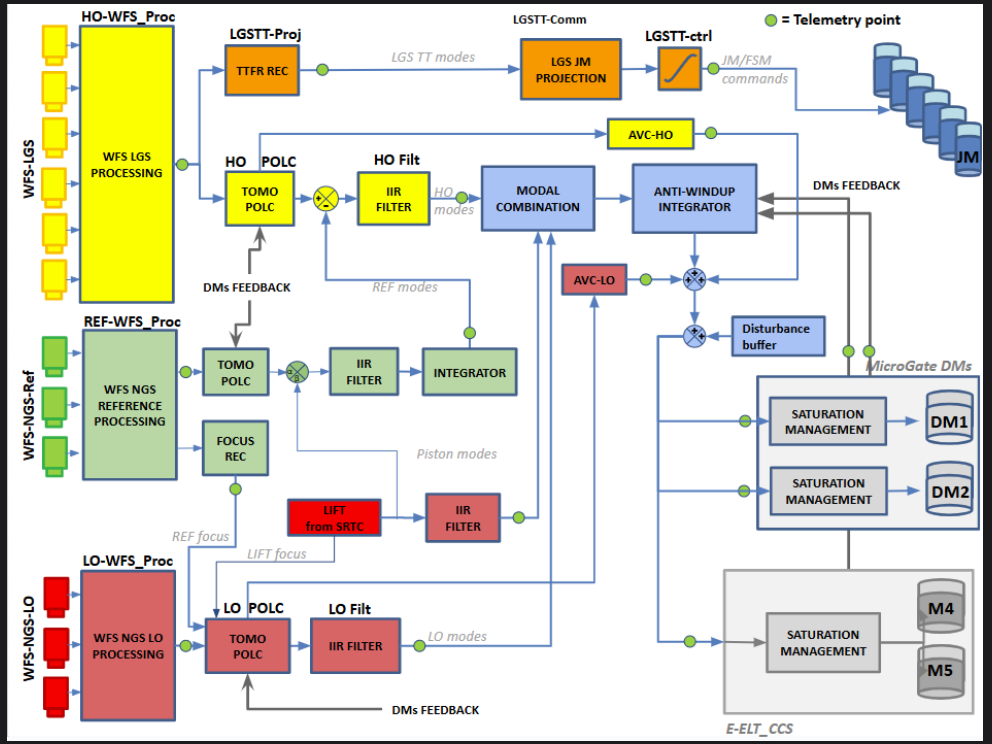
Real Time Computer

HRTC (Hard Real-Time Core) based on HEART, developed at NRC

- AO pipeline from 12 WFSs to 4 DMs and 6 JMs: slope computation, modal reconstruction, truth sensing, loop control, petal control, LGS jitter loops.
- 4 dual-socket AMD EPYC

SRTC (Soft Real-Time Cluster) based on the ESO RTC Toolkit, customized at INAF

- 68 (!) auxiliary loops: control matrix recalculation, LIFT (petalometer), misregistration monitoring, offload computations, LO gain optimization, …
- HRTC configuration and supervision, PSF-R data recording and storage, performance estimation, interface with ICS
- 3 dual-socket AMD EPYC + single NVIDIA GPU + 3 Xeon



N-dim performances

MORFEO performances depend on many parameters

- Seeing
- Cn2 profiles
- LGS asterism radius
- Elevation
- Scientific field size
- NGS asterism shape
- NGS magnitude

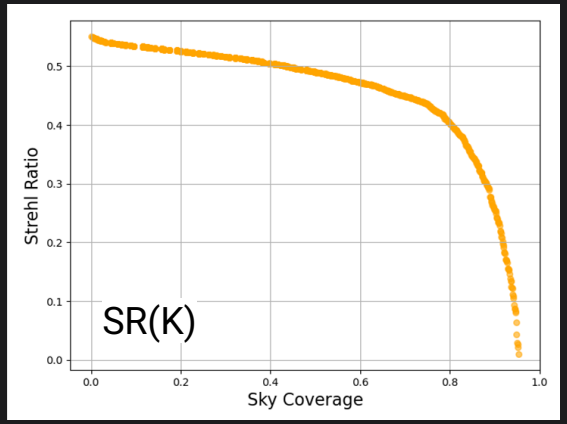
A few configurations

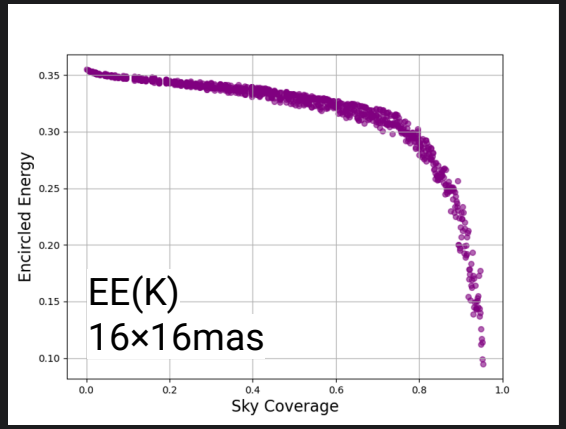
Huge variety of combinations

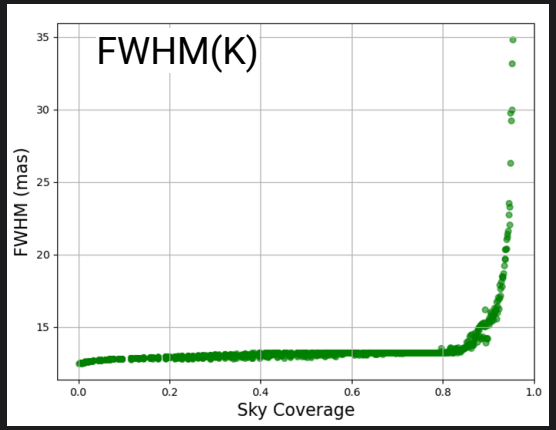
A statistical approach

- Choose a configuration
- Simulate once the High Order AO correction in the field
- mimic 1000 asterisms at SGP and
- compute Low Order performance with semi-analytical approach
- Histogram performances (cumulative distribution function)

MORFEO Performances







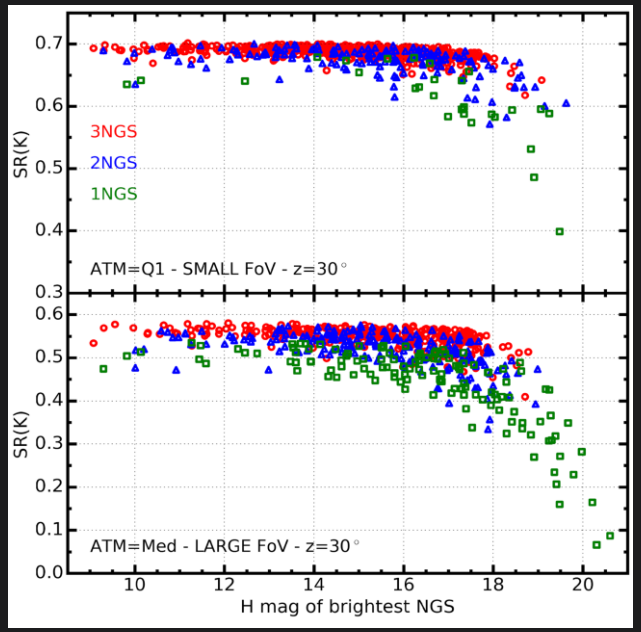
Cumulative Distribution Function:

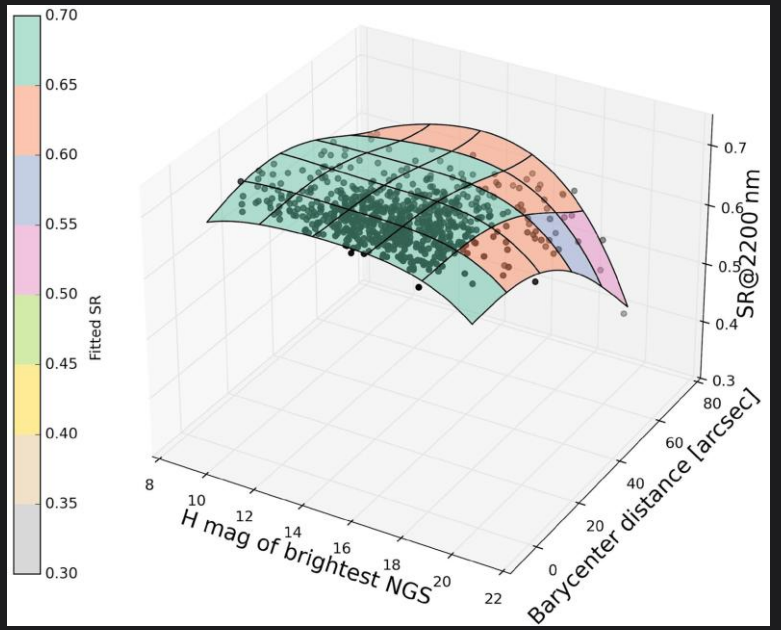
- 1000 pointing at South Galactic Pole
- median atmospheric conditions - seeing 0.64”
- 60” scientific field
- Z=30°

.. and similar plots for
atmo profile (Q1/median/Q3),
MICADO field (small/large)
wavelength (I to K)

Performance drivers

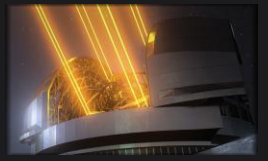
- Performance is primarily determined by the **brightest NGS magnitude**, then by the **NGS barycentre distance** from the center.
- In the bright regime, 2NGS and 3NGS provide similar performance





credit S. Oberti, E. Valenti

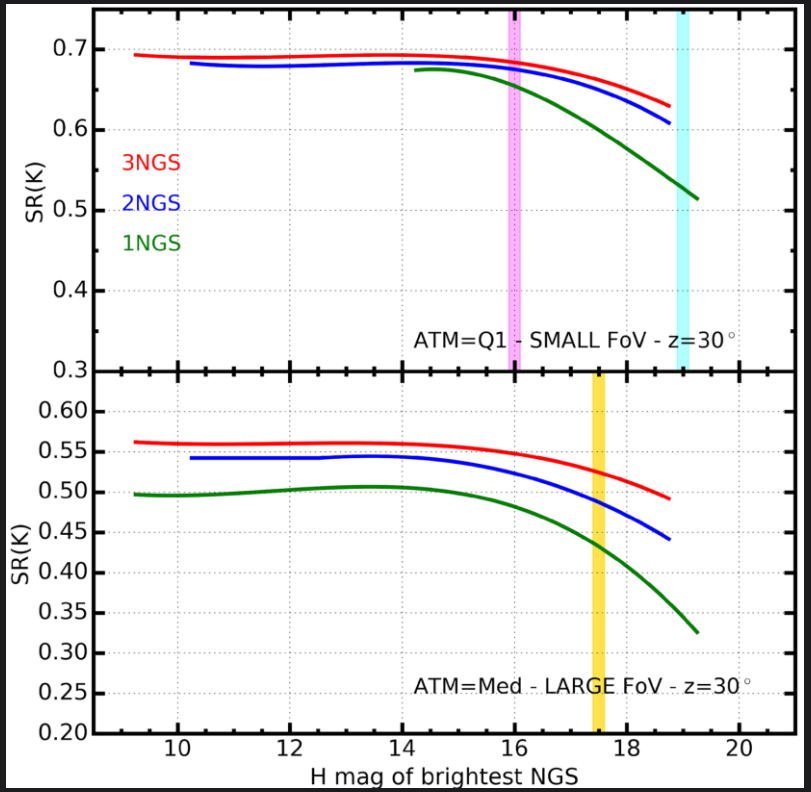
From statistical analysis to Tech Specs



New refined specs: science driven, unambiguous, verifiable, and deterministic

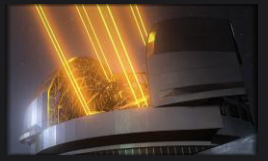
Different performance regimes:

- Best conditions / small FoV
- Medium conditions / large FoV
- Bad conditions / small FoV
- Best conditions and 1 faint NGS



credit E. Valenti

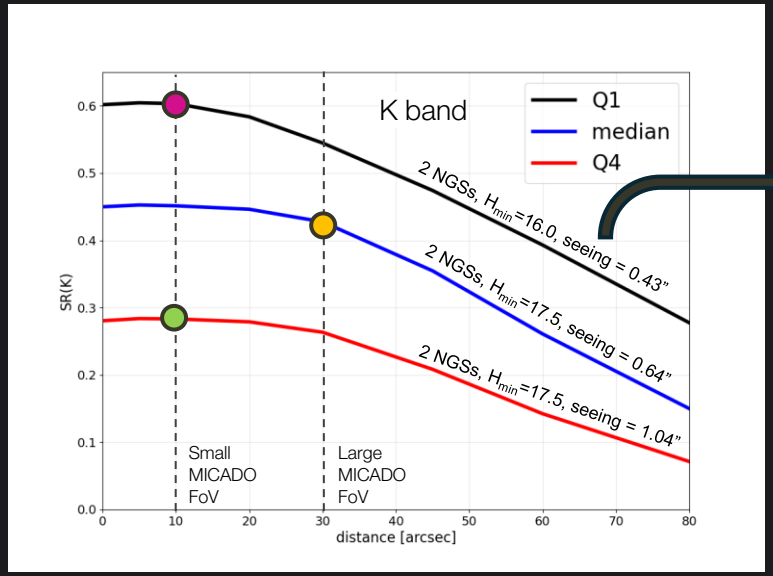
Technical Specifications recap



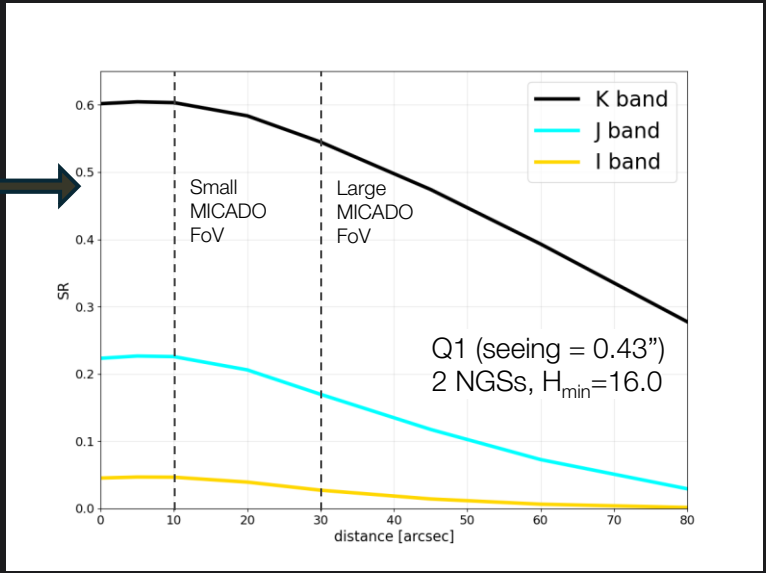
	Good atmo	Medium atmo / Large field	Bad atmo	High Sky Cov
Atmospheric profile	Q1	**Median**	**Q4**	Q1
Scientific Field size	20”	**60”**	20”	20”
NGS	2+	2+	2+	**1+**
Brightest NGS [m_H]	<16	**<17.5**	<17.5	**<19**
NGS barycenter	<40”	<40”	<40”	**<65”**
Sky Coverage @ SGP	>50%	>50%	>75%	>85%
Strehl Ratio (K)	60	44	28	50

MORFEO performance

SR in the field vs atmo & NGS



SR in the field vs wavelength



MICADO sky coverage on sparse field

MCAO and SCAO Sky Coverage of MICADO on Sparse Science Fields

Doc. Number: ESO-662349
Doc. Version: 1
Released on: 2026-03-23
Page: 2 of 21

Authors

Name	Affiliation
Elena Valenti	ESO

Figure 4: Illustration of how users can rapidly overlay selected targeted sources (red crosses) onto the generated MEF using its WCS information to assess observational feasibility. The example displays MCAO (left) and SCAO (right) MEF for the COSMOS field.

Table 2: Total number and density of available NGS within the targeted fields, for both SCAO (i.e., GaiaRP≤16) and MCAO (i.e., 9≤H≤21, and R≤23) modes.

		SCAO		MCAO	
Field Name	**Area [deg²]**	**Stars [counts]**	**Density [counts/arcmin²]**	**Stars [counts]**	**Density [counts/arcmin²]**
HUDF	2.5	1026	0.12	8772	0.99
COSMOS	3.4	1803	0.15	17694	1.46
UDS-CANDELS	1.8	642	0.10	7123	1.12
HDFS	0.9	651	0.21	4817	1.53
Abell2744	1.5	444	0.08	3649	0.66

The luminosity function (i.e., magnitude distribution) of the suitable NGS for both SCAO and MCAO mode is reported in Figure 1.

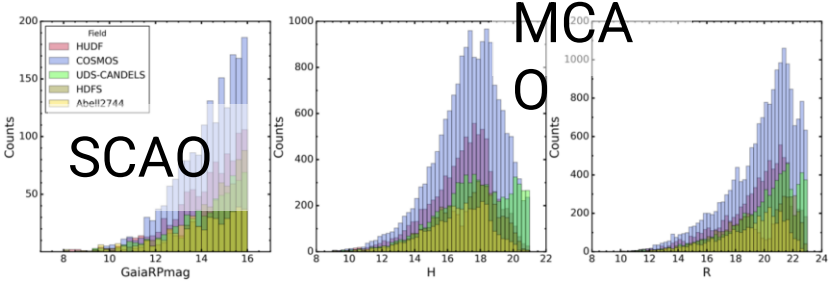


Figure 1: Luminosity function of the potential NGS found within the targeted fields for both the SCAO (left) and MCAO (middle and right) case.

MICADO SCAO vs MCAO

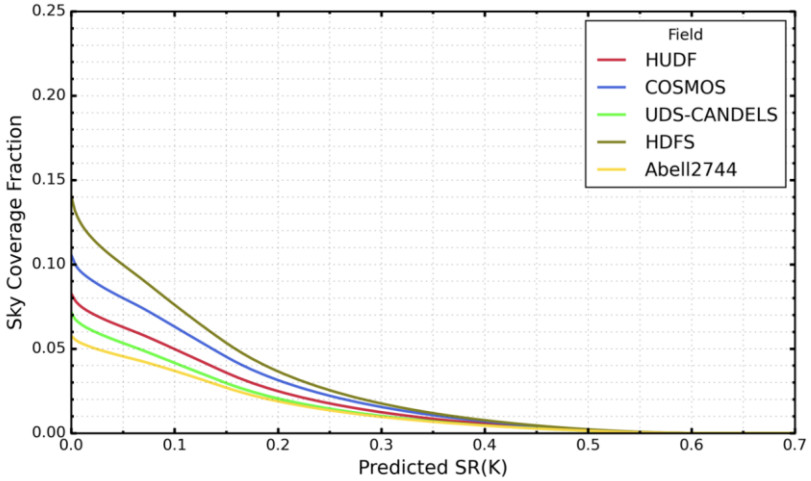


Figure 8:SCAO sky coverage fraction as a function of the predicted average SR(K) for ATM=Med (RD5) and z=30°. Colours refer to different science fields as shown in the legend.

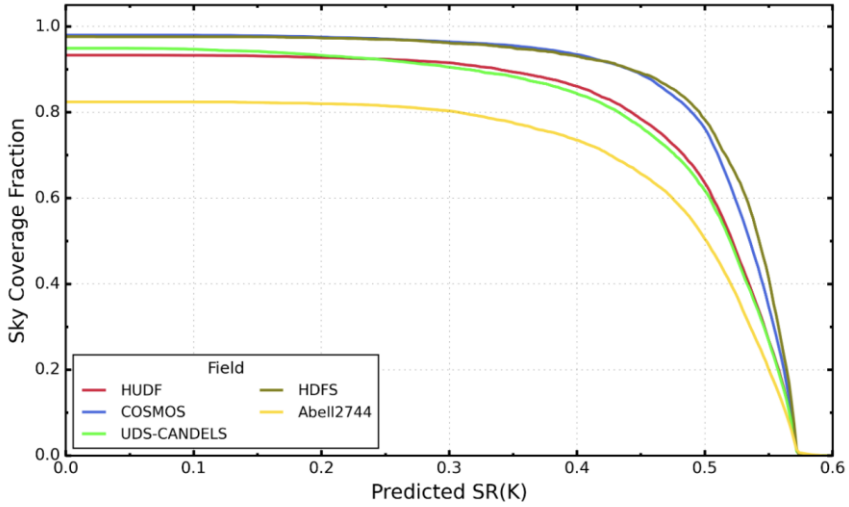


Figure 13: MCAO sky coverage fraction as a function of the predicted average SR(K) for ATM=Med (RD5) and z=30°. Colours refer to different science fields as shown in the legend.

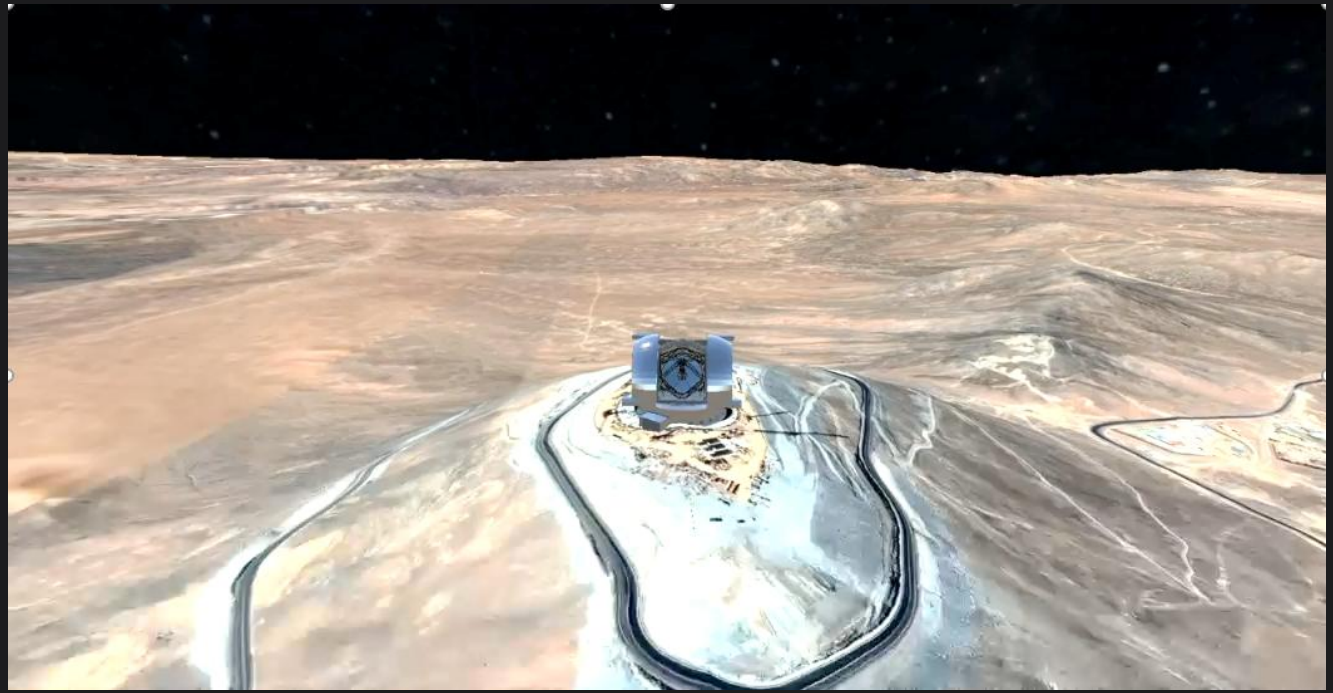
credit Elena. Valenti

WFE budget

- Most of the terms are evaluated in the E2E simulation with PASSATA
- For good & median seeing the dominant term is tomographic error
- In bad seeing the large TTF are caused by bad IQ on the NGS WFS
- A TT cascading control cooperating with the ELT WFSs should improve performance in the cases dominated by the wind shake

	R-MAO-80	R-MAO-82	R-MAO-83
Total	245	317	449
High Orders	164	215	271
Tomographic error	124	135	155
Generalized fitting error	57	107	161
HF fitting error	77	108	112
Measurement noise error	32	33	34
Temporal error	36	60	100
Reference Loop	37	56	53
Correction residual	-55	-55	-55
Truncation error	60	70	60
Sodium Profile Variations	15	15	15
Propagation of atmo disturbances	21	30	44
Non common field aberrations	10	10	10
MORFEO relay	91	91	91
Res. Des., Manuf. and Align. PFRO	70	70	70
Optical effects of air in the PFRO	20	20	20
Fitting error on DM1	30	30	30
Fitting error on DM2	30	30	30
Vibrations of post focal DMs	35	35	35
Calibration errors	31	32	33
Actuators / sub-apertures mismatch	30	30	30
Periodic update of RTC control matrices	7	10	14
Telescope	70	49	49
Residual HO Telescope (M1 & M2)	45	45	45
Telescope dome seeing residual	20	20	20
Low-Wind Effect	50	0	0
Telescope Off-Axis aberrations	8	24	8
Atmospheric Chromatism	17	24	27
Rayleigh scattering	20	36	20
Low Orders	96	140	274
Residual Windshake	63	112	250
Tomographic error	50	64	82
Temporal + Measurement noise error	52	54	112
Field average focus	52	116	179
Temporal + Measurement noise error	33	99	171
Anisoplanatism error	40	60	53
Others	50	50	50
Contingency	50	50	50

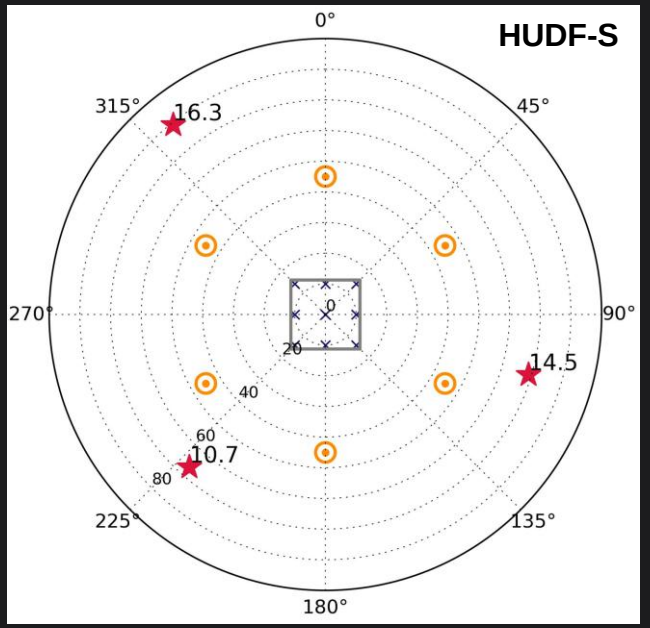
Thank you!



Best conditions

	Best conditions		
wl [nm]	SR	EE(16mas)	FWHM
2200	0.60	38	13
1250	0.20	19	9
850	0.05	6	8

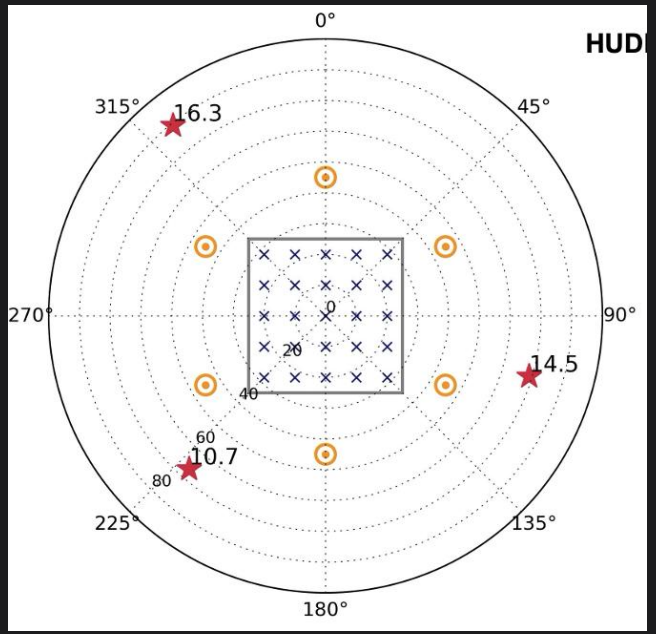
Atmospheric profile	Q1
Scientific Field size	20”
NGS	2+
Brightest NGS	mH<16
NGS barycenter	<40”
Sky Coverage @ SGP	>50%



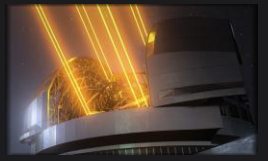
Medium condition - large field

	Medium conditions		
wl [nm]	SR	EE(16mas)	FWHM
2200	0.44	28	14
1250	0.08	10	9

Atmospheric profile	Median
Scientific Field size	60”
NGS	2+
Brightest NGS	mH<17.5
NGS barycenter	<40”
Sky Coverage @ SGP	>50%



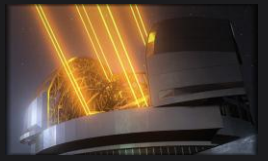
Worst conditions



wl [nm]	SR	EE(16mas)	FWHM
2200	0.28	16	14

Atmospheric profile	Q4
Scientific Field size	20”
NGS	2+
Brightest NGS	mH<17.5
NGS barycenter	<40”
Sky Coverage @ SGP	>50%

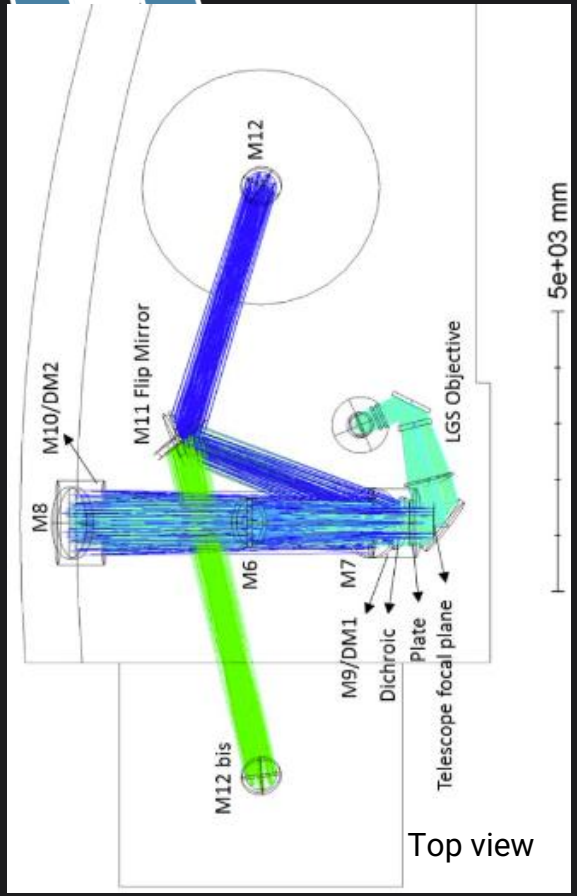
Faint single NGS – High SkyCov

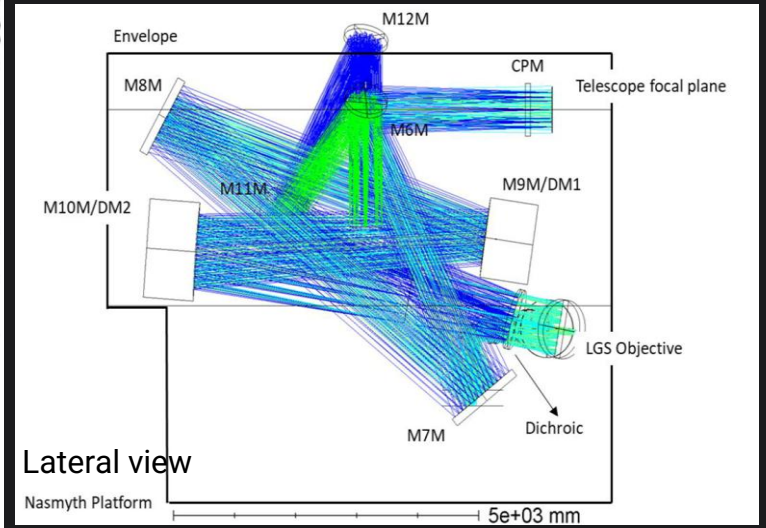


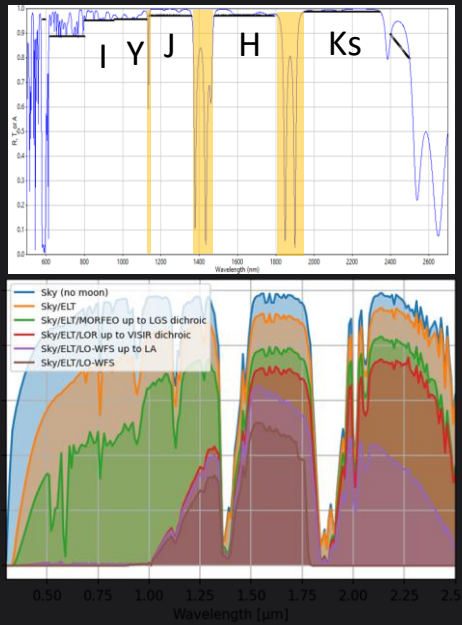
wl [nm]	SR	EE(16mas)	FWHM
2200	0.50	34	14

Atmospheric profile	Q1
Scientific Field size	20”
NGS	1
Brightest NGS	mH<19
NGS barycenter	<65”
Sky Coverage @ SGP	>85%

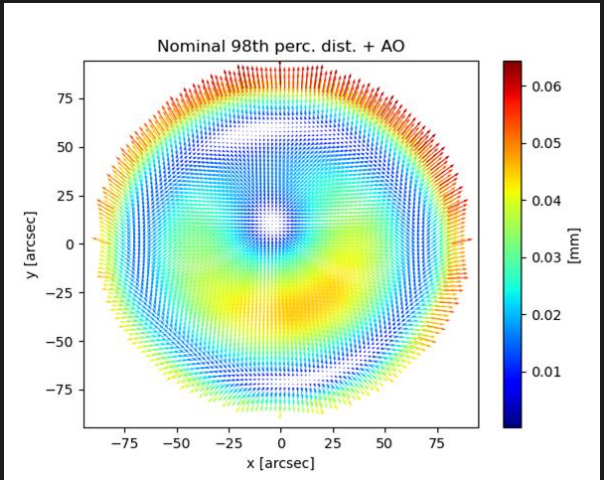
Optical layout

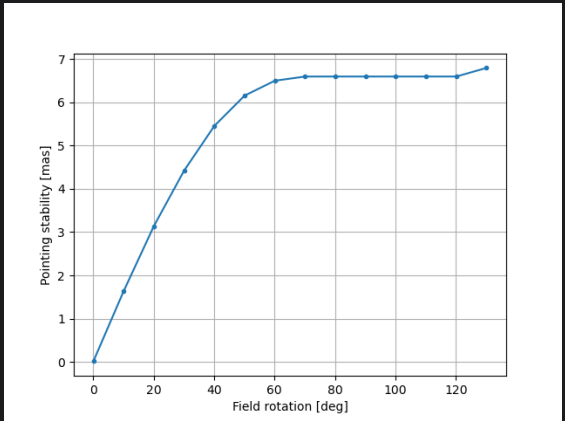




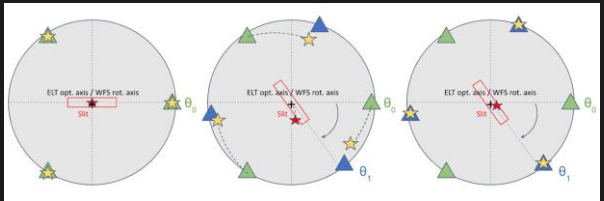


Pointing stability



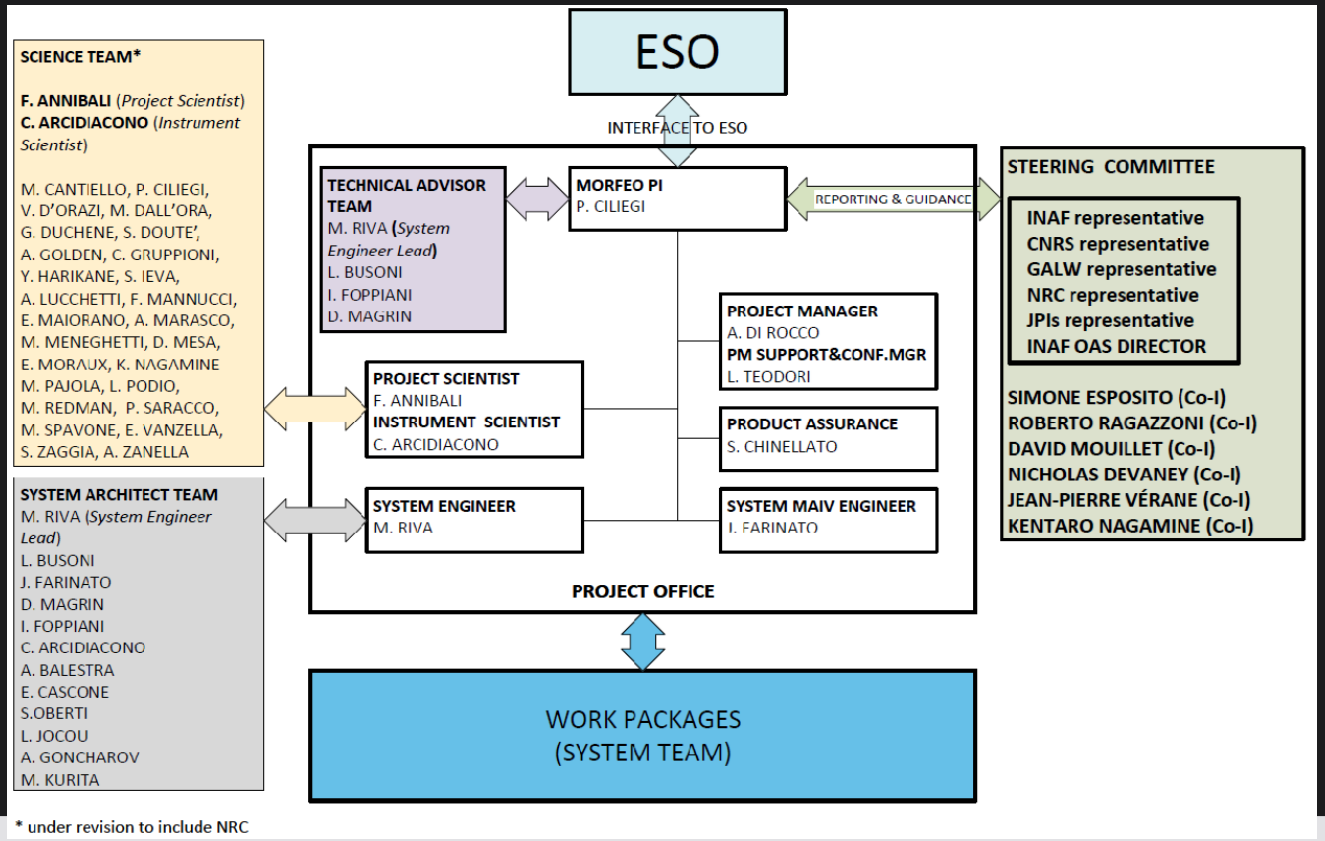


Source	Pointing stability [mas]	
	15 minutes	1 hour
Stability of LO WFS	1.5	6
MORFEO relay distortions	1.14	4.9
Atmospheric refraction	0.45	1.8
Total [mas]	**3.09**	**12.7**



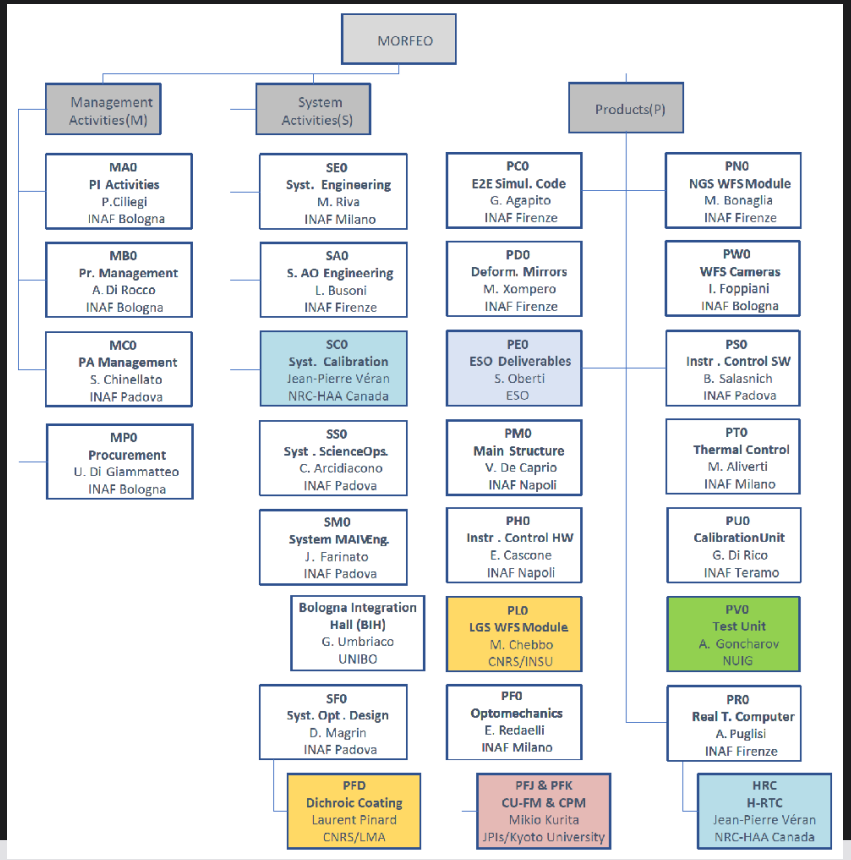
- Both MICADO and HARMONI don’t have flux-in-slit feedback
- Collaboration MORFEO/HARMONI

MORFEO Organization

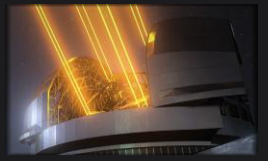


* under revision to include NRC

MORFEO WBS


MORFEO
Management Activities(M)
System Activities(S)
Products(P)
MA0
PI Activities
P.Ciliegi
INAF Bologna
MB0
Pr. Management
A. Di Rocco
INAF Bologna
MC0
PA Management
S. Chinellato
INAF Padova
MP0
Procurement
U. Di Giammatteo
INAF Bologna
SE0
Syst. Engineering
M. Riva
INAF Milano
SA0
S. AO Engineering
L. Busoni
INAF Firenze
SC0
Syst. Calibration
Jean-Pierre Véran
NRC-HAA Canada
SS0
Syst . ScienceOps.
C. Arcidiacono
INAF Padova
SM0
System MAIVEng.
J. Farinato
INAF Padova
Bologna Integration Hall (BIH)
G. Umbriaco
UNIBO
SF0
Syst. Opt . Design
D. Magrin
INAF Padova
PFD
Dichroic Coating
Laurent Pinard
CNRS/LMA
PC0
E2E Simul. Code
G. Agapito
INAF Firenze
PD0
Deform. Mirrors
M. Xompero
INAF Firenze
PE0
ESO Deliverables
S. Oberti
ESO
PM0
Main Structure
V. De Caprio
INAF Napoli
PH0
Instr . Control HW
E. Cascone
INAF Napoli
PL0
LGS WFS Module
M. Chebbo
CNRS/INSU
PF0
Optomechanics
E. Redaelli
INAF Milano
PFJ & PFK
CU-FM & CPM
Mikio Kurita
JPIs/Kyoto University
PN0
NGS WFS Module
M. Bonaglia
INAF Firenze
PW0
WFS Cameras
I. Foppiani
INAF Bologna
PS0
Instr . Control SW
B. Salasnich
INAF Padova
PT0
Thermal Control
M. Aliverti
INAF Milano
PU0
CalibrationUnit
G. Di Rico
INAF Teramo
PV0
Test Unit
A. Goncharov
NUIG
PR0
Real T. Computer
A. Puglisi
INAF Firenze
HRC
H-RTC
Jean-Pierre Véran
NRC-HAA Canada

Calibration Unit



CU & TU

- 18 H band sources.
- 61 R band sources.
- 6 sources at 589nm with 2 conj. alt. (104 and 150km).
- TU can host a ground DM