The SCAO module of the E-ELT imaging camera MICADO

Y. Clénet[a], P. Bernardi[a], F. Chapron[a], E. Gendron[a], G. Rousset[a], Z. Hubert[a], R. Davies[b], M. Thiel[b], N. Tromp[c]

[a] LESIA, UMR 8109 CNRS, Observatoire de Paris, Université Paris Diderot, 5 place Jules Janssen, 92190 Meudon, France
[b] Max Planck Institut for extraterrestrial Physics, Postfach 1312, 85741 Garching, Germany
[c] NOVA-ASTRON, PO Box 2, Dwingeloo, Netherlands

ABSTRACT

SAMI, the SCAO module for the E-ELT imaging camera MICADO, could be used in the first years of operation of MICADO on the telescope, until MAORY is fully operational. We present the results of the study made in the framework of the MICADO phase A to design and estimate the performance of this SCAO module.

1-SAMI top-level requirements

- WFS bandpass: 0.45-0.8 µm (visible WFS)
- Patrol field of view: 45"
- Repositioning accuracy: 2 mas for small (±0.3") and large (few arcsec) dithers
- Relay optics image quality: SR=80% @ 0.8 µm
- Relay optics magnification: 1
- SAMI transmission : 80% in the NIR
- SAMI above MICADO in gravity invariant position
- SAMI thermal emission lower than 50% of the sky+telescope thermal emission (goal 10%)

2-Pupil and field derotation

- WFS rotates with M4 for a proper conjugation of the microlenses with the M4 actuators
  - Alternative: microlenses rotation with respect to M4 actuators + real-time control matrix update, but too risky for a 1st light instrument
- WFS + dichroic plate + MICADO fixed together and rotate with the field

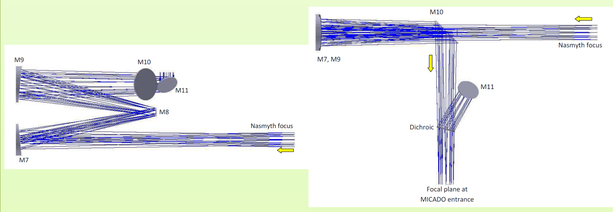
⇒ X/Y stages for offsets and pick-off

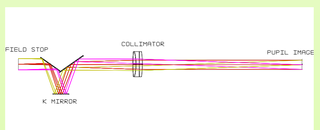
⇒ Pupil rotation stage: K-mirror

Alternative: rotate the WFS assembly, but too complex given the rotation amplitude

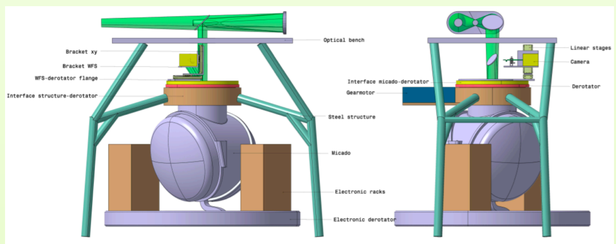
3-Opto-mechanical design

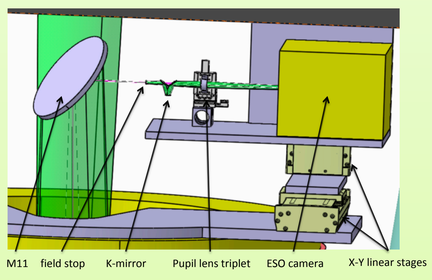
- Optical design
  - Relay optics
    - Offner relay (M7, M8, M9) on its bench
    - Folding mirror (M10)
  - Field derotator (for MICADO and WFS)
  - Dichroic plate
  - WFS
    - Offner Pupil steering mirror (M11)
      - Correction of tilt due to optical relay exit pupil position not at infinity
      - Correction of E-ELT pupil run-out
      - Correction of K-mirror misalignment
    - Field stop
    - K-mirror
    - Pupil imaging lenses
    - No needed ADC





- Mechanical design
  - Maximum vertical deflection for a load of 50000 N (derotator + WFS + cryostat) + 15000 N (optical bench + optics) + 1000 N (calibration unit): 1.81 mm
  - Von Mises constraints: 69 MPa (four times weaker than the usual steel elastic limit)

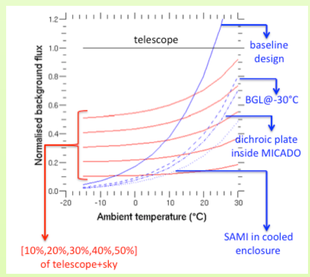




- Cost and mass

Item	Mass (kg)	Cost (k€)
Mounting structure	2000	68
Derotator	610	36
Optical relay	1471	96
WFS	168,5	374 (camera:140)
Total	**2610**	**574**

- K-band thermal background analysis
  - Baseline design: 50% requirement met at T<17°C, 10% requirement at T<6°C
  - With a background limiter at -30°C, 10% requirement met at T<2°C
  - With SAMI in an enclosure cooled at -30°C, 10% requirement met at T<9°C
  - With the dichroic plate inside MICADO cryostat, 10% requirement met at T<5°C



4-Adaptive optics performance

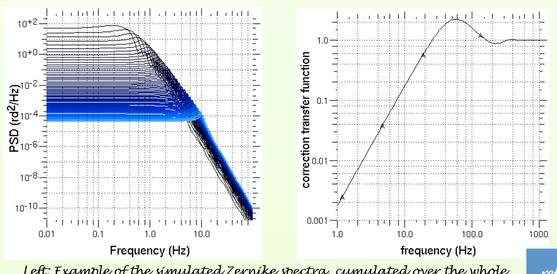
- Median turbulence case atmospheric parameters from ESO document: seeing 0.65" at 0.5 µm and zenith, zenith angle 30°, L_0=25m, v_{mean}=16.4m/s, h_{mean}=4007m
- Error budget:

$$\sigma^2_{tot} = \sigma^2_{fitting} + \sigma^2_{diff\,ref} + \sigma^2_{chrom} + \sigma^2_{aliasing} + \sigma^2_{temporal} + \sigma^2_{noise} + \sigma^2_{DM\,sat} + \sigma^2_{calib} + \sigma^2_{NCPA} + \sigma^2_{aniso}$$

- Temporal and noise errors
  - Single Shack-Hartmann subaperture end-to-end simulation tool to estimate the noise error
  - Simulation of an on-axis SCAO system on Zernike polynomials
    - From the PSD of a given Zernike mode j, computation of the sum of the PSD of the whole Zernike order, taking into account the outer scale effect
    - For each radial order, computation of the real transfer function for a given loop delay and integrator gain, assuming that in a given radial order all Zernike modes have the same transfer function
    - Computation of the temporal residual error of the whole order by integrating over frequencies the product between this transfer function and the cumulated PSD of all Zernike modes in this order
    - Propagation of the noise error obtained from the single subaperture simulation onto the Zernike assuming for each Zernike a law in $\sigma_j^2=0.3\cdot\sigma_\psi^2/(n+1)^2$ and then $\sigma_{n^2}=0.3\cdot\sigma_\psi^2/(n+1)$ for the full radial order, resulting in the knowledge of the level of the noise PSD
    - Modal optimisation: computation of the noise variance propagated into the loop through the transfer function from an analytical formula for several loop gains and selection of the gain leading to the best performance, i.e. the best compromise between the noise error (increasing with gain) and the temporal error (decreasing with gain)
    - As a by-product of this process, derivation of the temporal error, noise error, optimum system bandwidth for each radial order, and efficiency of the compensation for each radial order
    - Tip-tilt treatment:
      - Windshake PSD added to the atmospheric PSD, using an analytical formula fitting the windshake PSD provided by ESO
      - Simulation of the temporal compensation done by a Kalman filter of an high order using a ν^4 law attenuation transfer function

$$\|H_{cor}(\nu)\|^2 = \begin{cases} \nu^4/BP^4 & \nu < BP \\ 1 & \nu > BP \end{cases}$$

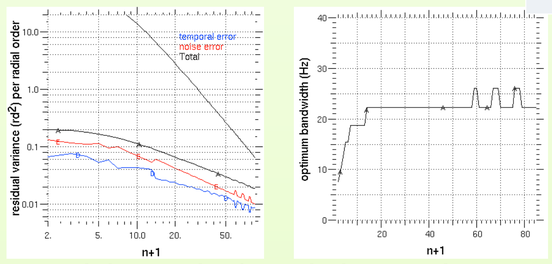
      - Computation of the propagated noise and modal optimisation of this filter as described above for the other orders
  - Simulation results
    - The four quadrant configuration (2×2 pixels/subaperture) almost always give the lowest noise but other numbers of pixels per subaperture lead to similar noise values
    - Given the specific issues of gain calibration of a four quadrant configuration, we could favour the 4×4 configuration



Left: Example of the simulated Zernike spectra, cumulated over the whole radial orders, for D=42 m and L_0=25 m, for n=1 to 84.
Right: Example of the simulated loop transfer function for a 500 Hz sampling frequency, 2 ms delay and an integrator gain of 0.3

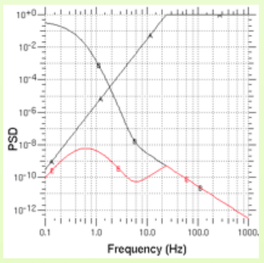
- Fitting error
  - Turbulence term: $\sigma_{fitting}(nm) = 166 \times seeing(")^{5/6}$
  - M1 cophasing error: 50 nm rms assumed
- Aliasing error: 35% of the fitting error
- Anisoplanatism error
  - Analytical computation from Chassat (1992)

Distance from reference source (")	5	10	15	20	25	30	35	40	45	50	55	60
Anisoplanatism error for L_0=25m (nm rms)	101	184	253	305	354	396	433	475	518	571	554	579
Strehl loss at 2.2 µm (%)	92	76	59	47	36	28	22	16	11	7	8	6



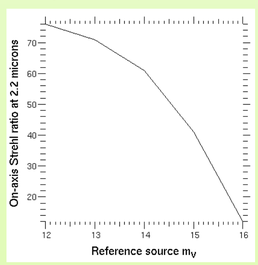
Residual error examples. Left: temporal and noise errors. The upper black curve is the uncorrected Zernike variance. Right: optimum bandwidth for r_0=15 cm, D=42 m, 330 nm rms input WFS noise

- Differential refraction error: equivalent to an anisoplanatism error, with an anisoplanatism angle equal to the angular distance between the WFS reference sources at the different wavelengths ⇒ 10 nm rms error using Chassat (1992)
- Chromatism error: 25 nm rms from ATLAS Phase A study (Fusco et al. 2011, this conference)
- DM saturation, calibration and NCPA errors: 80 nm rms assumed
- Error budget



Example of the fitted windshake PSD (in arcsec²/Hz), the modelled transfer function (with a bandpass of 25 Hz) and their product (in red)

	m_V=12	m_V=13	m_V=14	m_V=15	m_V=16
Turbulence fitting error	125				
M1 cophasing fitting erorr	50				
Differential refraction error	10				
Chromatism error	25				
Aliasing error	44				
DM saturation, calibration & NCPA error	80				
Temporal & noise errors	80	122	181	284	487
Total error	183	205	245	328	514
Corresponding Strehl at 2.2 µm	76%	71%	61%	41%	12%



Global estimated SAMI performances for 84×84 subapertures, 4×4 pixels/subaperture, ~1.3"/pixel, RON = 3 e⁻, QE = 80%

5-Calibrations

- Reference slopes:
  - Calibration performed with a fibre at the WFS field stop, moving the WFS in X-Y in front of this fibre
  - Check for the alignment of this fibre by rotating the K-mirror. Alternative: average out the measurements when rotating the K-mirror
- Interaction matrix:
  - Requires the use (and implementation) of a visible point-like source at the E-ELT intermediate focus between M2 and M3
  - Requires to delineate physically the pupil ⇒ pupil mask in front of the micro-lenses
- Non-common path aberrations
  - Phase diversity using (and implementing) an IR point-like source at the E-ELT intermediate focus
  - Alternative: phase diversity on sky (bright source)
- Pupil monitoring
  - Option 1: by measuring the subpupil illumination at the edge of the Shack-Hartmann. Though, with the pupil mask on the micro-lenses, pupil shifts will be measured only from the lack of illumination of the subpupils at the edge ⇒ not as robust as using also the ones outside the pupil
  - Option 2: from on-sky interaction matrix measurements, but low accuracy if faint reference sources
  - Option 3: using sources around the M4 mirror and dedicated (4-quadrant) detectors inside the WFS

6-Conclusions

- We have presented a possible implementation of a visible SCAO module for MICADO
- SAMI TLR fulfilled !
- Still few points to study/confirm in a possible phase B: need for an WFS ADC, pupil shift monitoring
- First performance estimations: SR=75% for an on-axis m_V=12 reference star