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NGS WFSs module for MAORY at E-ELT

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Abstract. We report on the natural guide star (NGS) wavefront sensors (WFS) module for MAORY, the multi-cojugate adaptive optics (MCAO) system for the ESO E-ELT. Three low–order, near–infrared (H-band), Shack–Hartmann sensors provide fast acquisition of the first 5 modes (tip, tilt, focus, astigmatism) on 3 natural guide stars over a 160 arcsec field of view. Three moderate-order (20x20), visible (600-800 nm), pyramid WFSs provide the slow Truth sensing to correct LGS wavefront estimates of low–order modes. These sensors are mounted onto three R–θ stages to patrol the field of view. The module is also equipped with a retractable, on-axis, high–order (80x80), visible, pyramid WFS for the single–conjugate AO (SCAO) mode of MAORY and MICADO. The visible WFSs share the same 80x80 pyramid WFS design. This choice enables also a MCAO NGS capability. Simulations show that Strehl ratios (SR) over 40% are reached with MCAO and three, 2x2 sub-apertures, NIR low-order WFSs working with H-mag=20 reference stars. In SCAO mode, 90% SR for a 8mag stars with a contrast down to 10^{-5}, and 45% SR for a 16mag star, are achieved.

Key words. Instrumentation: wavefront sensors – Instrumentation: Adaptive Optics – Instrumentation: MAORY – Instrumentation: E-ELT

1. Introduction

The paper describes the natural Guide Star (NGS) Wavefront Sensor module of the Laser Guide Star (LGS) based multi conjugate AO system of the European Extremely Large Telescope (E-ELT) called MAORY (Diolaiti et al. 2014). The MAORY instrument is designed and realized by a consortium of institutes led by INAF (PI E. Diolaiti). MAORY has to provide diffraction limited images from J to K band for the E-ELT first light instrument MICADO. Quantitatively the MAORY system is required to deliver a goal of 40% Strehl Ratio (SR) at K band over a field of view of 1 arcmin diameter. This requirement has to be met with average seeing conditions and over 50% of the sky. The high sky coverage call for a necessarily sophisticated natural guide star wavefront sensors able to work with very faint reference stars. As a second goal the MAORY system has to provide a SCAO wavefront sensor and operating mode able to achieve >70% on axis SR in K band with average seeing conditions. The Arcetri Observatory Adaptive Optics group undertook the task to design and realize the NGS wavefront sensing module including the NGS wavefront sensor for the LGS-based MCAO operations and the SCAO wavefront sensor (Quiròs-Pacheco et al. 2011). This last unit is jointly developed with the AO group of LESIA (France). The NGS module design is described in the sections below.

2. NGS WFS module

2.1. Functionalities

The NGS wavefront sensors module provide many different capabilities, both to MAORY and MICADO, via a set of subsystems. This module hosts:

- 3 fast low-order wavefront sensors for tip/tilt, focus, and astigmatism (5 modes) over a 160 arcsec diameter field of view
- 3 slow moderate-order Truth wavefront sensors for detrending LGS wavefront estimate of low order modes, over a 160 arcsec diameter field of view
- 1 SCAO on-axis wavefront sensor (in collaboration with LESIA).

MAORY deliver a 160 arcsec field of view to the NGS WFS module. The central 80 arcsec diameter area is used to feed the scientific field of MICADO without vignetting. The annular area from 80 to 160 arcsec are used by the NGS WFS. In the SCAO mode, visible light is reflected off a dichroic.

Different design options were available for these wavefront sensors, including different wavelengths (visible vs. near-infrared), number of sub-apertures, type (Shack-Hartmann vs. Pyramid). After analysis and simulations (see Section 3), a baseline has been defined as given in Table 1. The Truth and SCAO WFSs can share the same design (visible pyramid WFS with on-chip binning) to increase commonalities and flexibility. Moreover it enables a new operating mode, i.e. a NGS high-order MCAO WFS. It is worthwhile to note that the low-order WFS will benefit from the LGS precorrection to improve its sensitivity (and sky coverage).

The fast low-order WFS design has been driven by two main trade-offs: (a) visible vs. near-infrared wavelengths, influenced by detector noise, sky background, and PSF precorrection, and (b) sub-aperture sampling (or number of sensed modes) vs. SNR (or limiting magnitude). Sampling modes analized were 2×2, 3×3, 4×4, and 5×5.

A visible (0.6–0.8 μm), 80×80, pyramid WFS module has been designed. One ore more of these modules will share the low-order pick-off system, and light will be split by a dichroic beamsplitter between the two arms. On-chip rebinning (4×) will enable a moderate-order, Truth, 20×20 WFS. No rebinning is required for the SCAO module. This configuration opens the possibility to use the Truth WFS with no-rebinning as a NGS MCAO WFS.

2.2. Opto-mechanical design

This module is placed between the last mirror of the AO relay optics (MAORY) and MICADO, the AO imaging camera. The allocated volume is a torus with a 2.6 m diameter and 0.7 m height. The science beam is crossing this space along its axis.

A 5×5 Shack-Hartmann WFS has been designed with a 5mm pupil, where a F/29, 1 mm pitch, lenslet array, is placed, just in front the infrared detector. As baseline, the Firstlight C-Red , e-APD, 320x256, 24 μm pixel, sub-electron readout noise, fast detector has been selected. A cold stop in front of the lenslet will keep thermal background at minimum.

The design of a 80×80 visible pyramid WFS has been done, including some relay optics to convert the F/17 beam from MAORY to a slower F/35 beam, hosting an ADC. The design is based onto a double-pyramid design, as adopted on LBT, MMT, and TMT/NFIRAOS. The detector is the Firstlight OCAM^{2}K, high-speed, 240x240, 24 μm pixel, sub-electron readoud noise, high-QE, cooled EMCCD. This is provided fully integrated into a standard or custom fully sealed head.

For each NGS star, one low-order SH WFS and one high-order pyramid WFS will be mounted onto a $R - \theta$ stage to patrol almost half of the 160 arcsec technical field of view of MAORY. Three of these stages, at 120 degrees, will cover the full 160 arcsec field, with a generous overlap between adjacent stages.

For the SCAO mode, on-axis visible light is reflected by a 320 mm diameter dichroic beam-

Table 1. NGS WFS design parameters

	Low-order	Truth	NGS MCAO	SCAO
Wavelength *(μm)*	1.5–1.8	0.6–0.8	0.6–0.8	0.6–0.8
Sub-apertures	2×2	20×20	80×80	80×80
Type	SH	Pyramid	Pyramid	Pyramid
Field of view diam. *(arcsec)*	1	1.9	1.9	1.9
Framerate *(Hertz)*	200	1	500 (TBC)	1000
Source acquisition	pick-off	pick-off	pick-off	dichroic

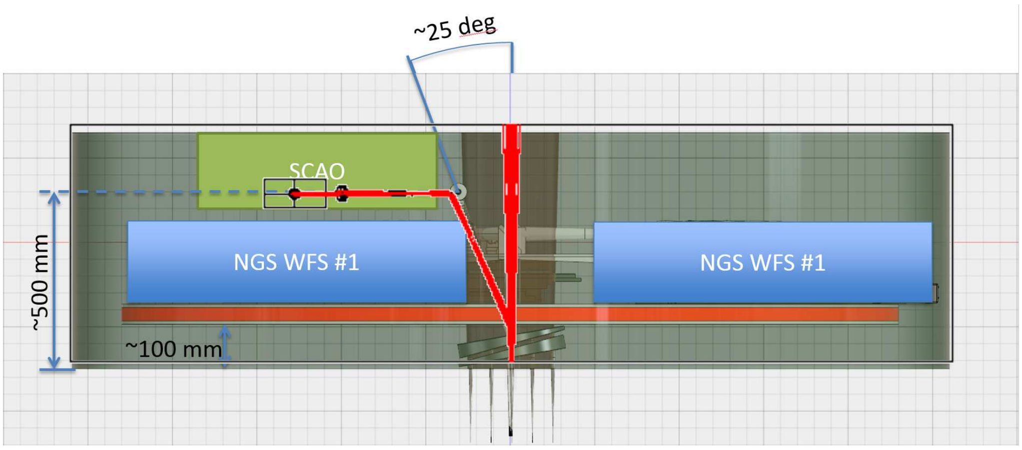

Fig. 1. MAORY NGS WFS module layout. Three low-order and Truth WFSs lie on top of a counter-rotating plate, while a SCAO WFS is on top.

splitter placed near the focal plane, at a 12 degrees incidence angle. It reflects light from 600 to 800 nm to the SCAO WFS and transmits the 800-2400 nm to MICADO. While in transmission, a corrector wedge is added, to control aberrations. Infrared and CaF_2 have been selected for these two elements for their good optical and mechanical properties.

The overall mechanical layout is shown in Figure 1. Three identical low-order/Truth WFS are placed over a counter-rotating plate (to correct for field rotation). The dichroic beamsplitter for SCAO is rectracted while in MCAO mode.

3. AO simulations

We present some numerical simulation aimed to explore the various parameters of the NGS low order wavefront sensors and to estimate the on-axis performance of a SCAO system. We report our results in the two sections below.

3.1. LO WFS performance

End-to-end simulations have been done to compare the MAORY system performances when using a low-order WFS working in the visible (R band) or in the infrared (H band). As a second point we investigated the trade off between the sensor number of sub-apertures (so the number and accuracy of corrected modes) versus the star limiting magnitude (or the achievable sky coverage). The results showed that the 2x2 sub-aperture configuration is the best one as limiting magnitude and sky coverage. IR sensors perform better than visible.

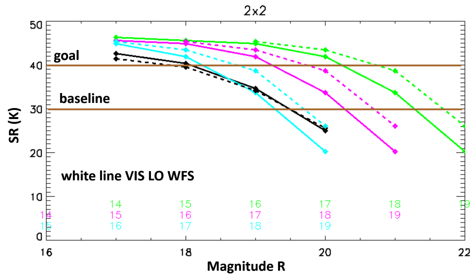

Fig. 2. Simulated Strehl ratio vs. R magnitude for NGS stars with 3 different IR colors. Solid and dotted lines are for different SH sensor field of view.

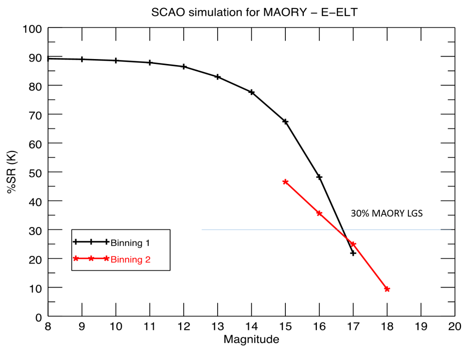

Fig. 3. SCAO Strehl ratio vs. R magnitude.

The results for the 2x2 case are summarized in Figure 2. The plot shows that a 2x2 sub-apertures wavefront sensor measuring tip, tilt, focus and the two astigmatism achieves the SR goal of 40% by using an R band reference star magnitude of 18.7 or an H band magnitude 19.7 that correspond to a color index of 1. Computation of the achievable sky coverage for such a star magnitude and the available patrolling field of the MAORY NGS module are currently ongoing.

3.2. SCAO system performance

We did also end-to-end simulations of the SCAO system performances. Our first assumption is to use a modulated pyramid wavefront sensor working at visible wavelengths. The detector for such a stystem is supposed to be a 256x256 EMCCD. The pupil sampling is 80x80 and the system uses modal control correcting for a maximum of 3654 KL modes. The achieved SR vs. reference star magnitude in R band is reported in Figure 3 and shows that a maximum SR in K band of 90% is achieved, so fulfilling the system goal. As a second point we evaluated the PSF contrast. Our simulations show that the achieved contrast is 10^{-5} betweeen 0.25 and 0.45 arcsec without any coronographic suppression or other high contrast data reduction like ADI. The results are consistent with the techical specifications of MICADO requiring a contrast of 10^{-4} at 0.1 arcsec and 10^{-5} at 0.5 arcsec.

4. Conclusions

In the paper we presented the design current status of the NGS AO module of the MCAO system MAORY. The AO module has been identified in having 3 low-order NGS WFSs working in H band, 3 truth sensors, each one with 20x20 sub-apertures, and a SCAO WFS with 80x80 sub-apertures. These last WFS work in the visible. The first iteration of the opto-mechanical design of such units has been done and it fits in the allocated volume. We note that the truth sensor and SCAO sensors are both pyramid sensors, sharing the same optical design. Initial end to end simulations shows that the AO module, as it is currently designed, allows to reach the technical requirements of the overall system MAORY in terms of SRs and contrast.

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