Status of HARMONI SCAO system at mid-Final Design

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ABSTRACT

HARMONI (High Angular Resolution - Monolithic - Optical and Near-infrared - Integral field spectrograph) is one of the first-light instruments for the ESO-European Extremely Large Telescope. HARMONI will use two AO modes: the classical Single Conjugate AO mode (SCAO), offering a high performance correction but over a low field, and a Laser Tomography AO (LTAO) mode, with much larger sky coverage. We present in this paper the SCAO system in an advanced design phase. The SCAO system is based on a fast and sensitive pyramid Wave-front sensor, taking advantage from the visible photons to measure the residual turbulence. In this paper, we will present the SCAO on-sky performance in different conditions (guide star magnitude, atmospheric seeing, object extension) and the tolerancing effects (pyramid defects, chromatic residuals). On top of this, the calibration scheme and operation scheme will be described. A particular care is brought to the complex but crucial interactions with the ELT telescope and its adaptive quaternary mirror.

Keywords: adaptive optics, extremely large telescopes, atmospheric turbulence

1. INTRODUCTION

HARMONI is the High Angular Resolution Monolithic Optical and Near-Infrared Integral Field Spectrograph (IFS) for the Extremely Large Telescope of Europe (ELT). It will function as the telescope's workhorse instrument for spectroscopy in the wavelength range 0.47–2.45 µm. This versatile instrument will offer a set of spatial scales to optimise observations for a wide range of science programmes and observing conditions. In particular, HARMONI will be optimised to exploit the best image quality delivered from a post-focal laser tomographic adaptive optics module.

HARMONI will take benefit from two Adaptive Optics flavor. The first one, Single Conjugate Adaptive Optics (SCAO) procures a high Strehl Ratio performance on axis (or close to it) on bright Natural Guide Stars (NGS), therefore with a limited sky coverage. The second one, Laser Tomography Adaptive Optics (LTAO) procures a larger sky coverage with a good performance. In this paper, I focus on the SCAO requirements, performance analysis and design, as we are in the middle of the Final Design Phase (FDR).

1.1 Science objectives

Integral field spectroscopy provides an extremely efficient way of obtaining spectra of targets within a modestly sized field-of-view (FoV). This is particularly relevant when using adaptive optics (AO) correction at an extremely Large Telescope (ELT), as the quasi-diffraction limited spatial resolution of the telescope is substantially smaller than both the seeing and the typical level of differential atmospheric refraction. In addition, rapidly varying night night sky and thermal backgrounds, both of which can be comparable to the source brightness in the extraction aperture, imply strong

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benefits to simultaneous observation of the entire data cube, resulting in a homogenous data set with well-behaved noise characteristics (low levels of systematics effects).

HARMONI will cover the three key areas of the ELT science drivers: stars, planets and galaxies. The image showed on Figure 1 includes simulated observations made with HARMONI in these key areas. The images show Io, a star field in a local group galaxy, and emission line kinematics of high redshift galaxies (as observed using the H-alpha line at redshifts of 2-3).

HARMONI provides a range of spaxel scales and spectral resolving powers, which permit the user to optimally configure the instrument for a wide range of science programmes; from ultra-sensitive to diffraction limited spatially resolved physical (via morphology), chemical (via abundances and line ratios) and kinematic (via line-of-sight velocities) studies of astrophysical sources. Specifically, it will provide medium resolution of ~3500, ~7500 and ~20000 spectroscopy at spatial resolutions ranging from seeing limited to diffraction limited, across the visible and near-infared wavelength range (0.5 to 2.4 µm).

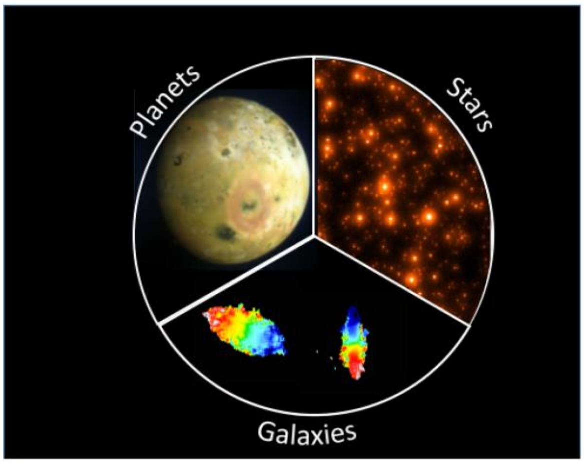

Figure 1: HARMONI simulated images for the three key areas of ELT: stars, planets and galaxies.

1.2 SCAO requirements

The requirements of SCAO are those of a diffraction limited imaging system, and are expressed as the following ones:

- Provide a > 67% Strehl Ratio on-axis for R magnitude < 12
- Be able to close the loop on extended object up to 2.4 arcsec
- Be able to close the loop on an NGS 15 arcsec away from science

The performance roughly corresponds to a diffraction limited instrument in K band, perfectly matching the workhorse capacity of a first generation instrument on a new telescope. The performance shall be met with an ELT that is today only known by the mean of models and numerical simulations. A data package has been provided by ESO to show the typical perturbation that might be brought by the ELT, after a first stage of correction brought by its internal sensors and the pre-focal station wave-front sensors.

The error budget for SCAO is roughly 200nm RMS, balanced between:

- the atmospheric residuals corrected by M_4/M_5, typically around ~100nm RMS
- the telescope contributions, also around ~100nm RMS
- the instrumental related aberrations, also around ~100nm RMS.

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1.3 HARMONI instrument

The HARMONI instrument will be sitting on the Nasmyth platform of ELT. The light coming from the telescope is around 6m height, the focal planes of the LGS are propagated to the LGSS sub-system ensuring the laser WFS, and the NGS is propagated to the rest of the instrument through an optical relay performing a 1:1 magnification of the telescope focal plane.

The laser beam is reflected by a large dichroic toward LGSS sub-system, containing the 6 LGS WFS.

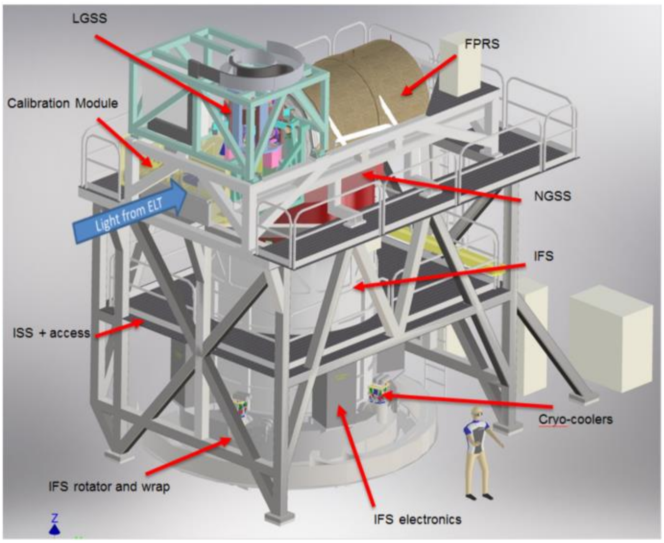

Figure 2: HARMONI instrument, as assembled on the Nasmyth platform. Height of the optical axis is 6m.

1.4 SCAO in NGSS

SCAO is the first system met by the light in the NGSS sub-system. Its global role is to provide a control of the M4/M5 adaptive components of ELT, so as to guarantee an AO-corrected wavefront to the science path. In order to reach this goal, SCAO include a high-order photon-sensivive wave-front sensor based on a slightly modulated pyramid principle. This wave-front sensor is the most sensitive today, and will allow a large limiting magnitude for H-SCAO).

This choice, made at PDR and compared to usual Shack-Hartmann solutions, comes with different mandatory complementary systems, represented on Figure 4 :

- A modulation mirror is required to improve the dynamic range of pyramid measurement. This mirror, typically a fast tip-tilt mirror runs at the loop framerate (up to 1kHz) and performs one cycle during one WFE exposure, so that the light is spread uniformly between the four quadrants of the pyramid prism.
- An ADC is required to provide a correction of atmosphere chromatic dispersion, and to concentrate the star flux on the pyramid top, within a fraction of the size of the modulated PSF.
- In order to deal with the large differential tip-tilt between the SCAO optical path and the science optical path (mainly driven by the deterministic atmospheric chromatic deviation), a differential tip-tilt is required to ensure the stability of the PSF on the slicer during the scientific exposure.

On top of these functionnalities really driven by the pyramid choice, some other functionnalities are added to the SCAO system :

- An object selection mirror allows to guide on NGS up to 15 arcsec from the science target.

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- A derotator is added in order to stabilize the pupil image on the WFS. This allows to optically stabilize the M4 with respect to the WFS pixels. This task could be done numerically, but doing it optically allows one to release a constraint for the real-time computer.
- I order to deal with the NCPA created by the moving parts of SCAO, as well as the NCPA between SCAO and science path, a Low Order Loop is added to the SCAO system as close as possible to the entrance in order to stabilize the wave-front on the science path.
- A pupil zoom allows to stabilize the pupil size on the WFS detector. The pupil size varies across the patrol field of SCAO due to the object selection mirror situated at the bench entrance.
- A pupil shift allows to stabilize the M4 position on the WFE detector. This position evolves due to flexure inside ELT structure, and to moving elements in the SCAO.

SCAO pyramid will take the red part of visible light from 700 to 1000nm, with a possibility of 700 to 800nm option.

SCAO Low Order Loop will take a narrow band at 650nm to feed the Low Order WFS (Shack-Hartmann 8x8).

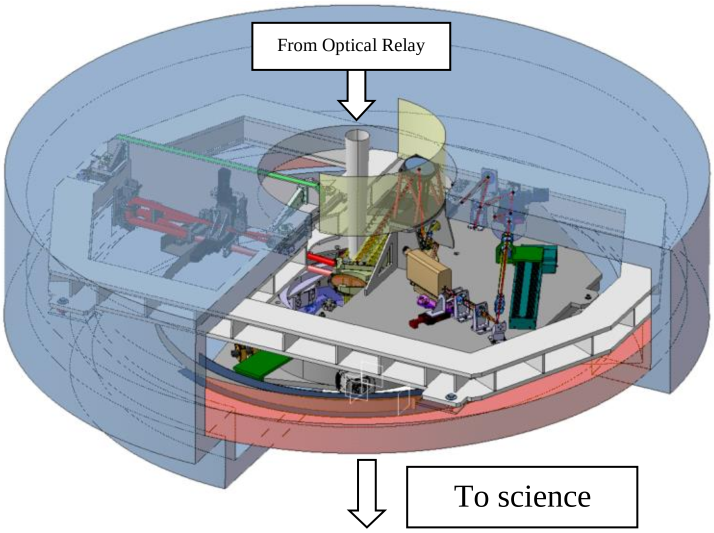

Figure 3: NGSS sub-system 3D view, showing the SCAO bench in transparency as designed at CDR

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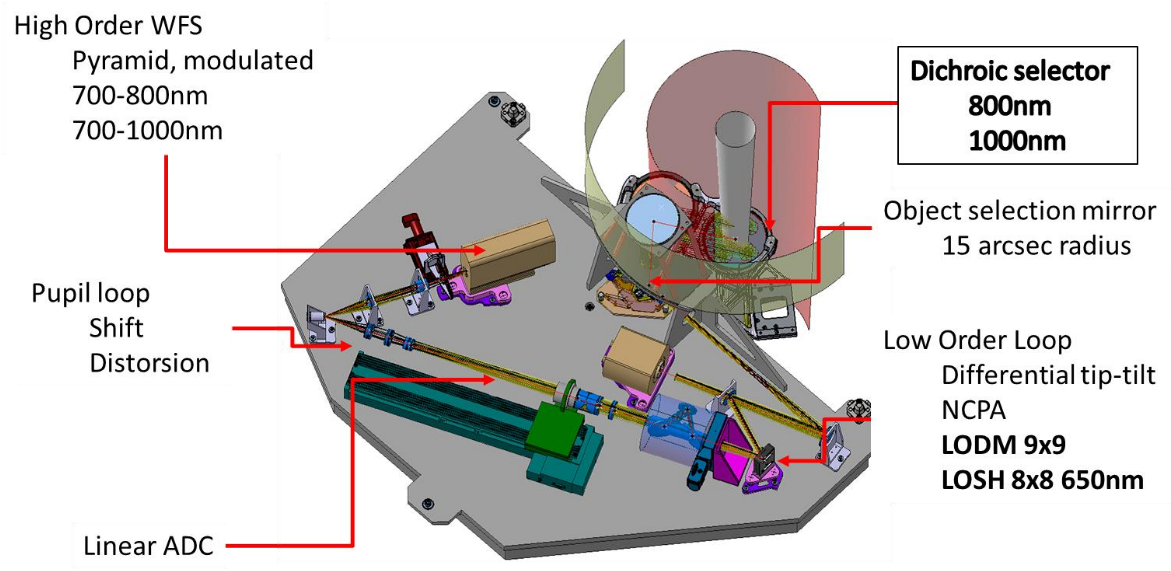

Figure 4: SCAO module as designed at CDR. The lights comes down from the optical relay

2. SCAO SUB-SYSTEM PERFORMANCE

2.1 Overall performance

The overall performance are plotted in the Figure 5, expressed as the Strehl Ratio obtained on science path in K band. This performance includes different terms

- **Atmospheric contribution**: the atmospheric turbulence residual after SCAO correction, is simulated by an end-to-end software modelizing the Pyramid wave-front sensor, the M4 deformable mirror, the real-time control delay and the calibration processes. Different conditions are considered for the seeing condition (from 0.44 to 1.06 arcsec), and for flux on the WFS (R magnitude from 8 to 20).
- **Telescope contribution**: all the error term coming from the ELT data package have been processed, and their residuals filtered by SCAO loop have been added to the error budget. It includes dynamic effects (transient, wind shake, main structure deformation) as well as static high order effects (polishing, scalloping, segment phasing).
- **Instrument and calibration contribution**: error terms coming from the instrument part (Non common path aberrations residual) but also calibration errors (due to mis-registration residuals, on-sky calibration residuals) are taken into account in the final budget.

The Strehl shows a plato for high flux guide stars up to R magnitude of 12, higher than 70% Strehl in median condition. The limit magnitude is estimated at R = 15 (for a mid-performance), which is obtained by taking benefit from a large dichroic 700 to 1000nm.

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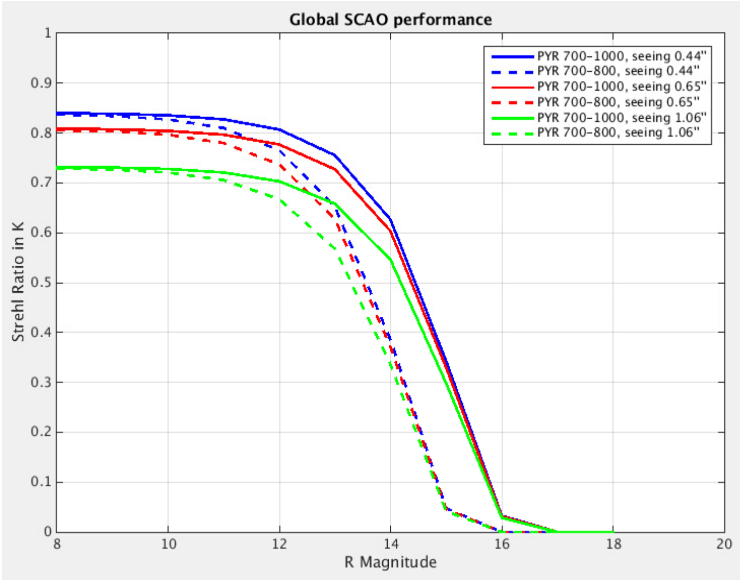

Figure 5: SCAO overall performance, depending on NGS magnitude. Different cases of seeing / dichroic are compared. The performance includes telescope residuals, calibration residuals, instrumental residual NCPA.

2.2 Updates since PDR phase

2.2.1 Extended object performance

Since PDR, we have analyzed the performance of the SCAO loop on extended object. Since this kind of simulation requires a lot of computing power (representing a 2.3 arcsec object paved with ELT-diffraction limited object in the visible represents more than 100000 points), we have realized a reduced scale E2E simulation on a 10 meter class telescope. The simulation result, shown on Figure 6, gives an example of the WFS signal (left) on a faint source, 10 photons / subaperture / frame. The right image shows the extended object simulated (a circular disk, 4 arcsec diameter, with a half area darkened to mimick a structured object).

The performance obtained on such extended object is very similar to the one obtained on a point-like source (typical residual of ~100nm for turbulence contribution), for the same amount of photon than on the NGS case.

The calibration is assumed to be made on the object itself. This assumption, even if not completely realistic, has to be further studied.

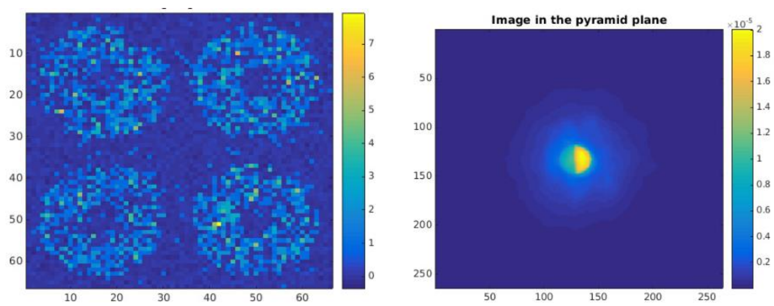

Figure 6: example of SCAO simulations on extended object. The case of a simply structured object is studied, in a case of very low flux. [left] WFS signals on 1 frame, [right] extended object as seen in SCAO closed loop.

2.2.2 Island effect mitigation and performance

The Island effect has been further studied since PDR. This AO-generated mode is created by the AO loop, that provides a poor measurement to the wavefront discontinuities beyond the spider arm. The Fried parameter r_0 is much smaller than

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the spider in the visible wavelength, hence producing phase discontinuities in the WFS. The impact of this particular AO-generated mode has been analysed for large seeing conditions, and presented in the poster of Noah Schwartz, this conference.

2.2.3 Optical gain strategy

The pyramid WFS comes with optical gains, which means a sensitivity depending on the level of aberration to measure. This well-known effect, considered as a non-linearity, has been studied for SCAO. We have identified as a first rough solution to adapt the gain of the loop depending on the seeing conditions. The higher the seeing, the lower the pyramid sensitivity, hence the higher the loop gain has to be increased. For a 1.2 arcsec seeing, the loop gain is increased by a factor 3 to reach a decent performance.

The result is also presented in the poster of Noah Schwartz, this conference. The strategy for dealing with the optical gain is to implement the method of Vincent Chambouleyron, also presented in this conference. The gain in performance of this method has still to be studied.

2.2.4 Pyramid specifications

The optical design of the pyramid prism has been refined thanks to fruitful discussion with TMT team. The concept of a double prism, able to compensate efficiently the chromatism, has been chosen. The detailed design with the choice of glasses and prism angles has been given in the poster of Noah Schwartz, this conference.

2.2.5 Main High Order Loop framerate analysis

The interest for fast frame rate is double.

- First, it allows to increase the performance of the system, and reduce the residual close to the optical axis. This gain in performance is particularly interesting for the High-Contrast mode of HARMONI, where planets are searched close to their star.
- Second, it allows to measure the environment (atmosphere, telescope, vibrations) with a higher framerate. Even if a high framerate is not used to close the loop, it will help to understand the environment and the final performance of the system.

A detailed analysis has been done on the impact of different framerate and latency on the system. The simulation results are shown in the poster of Noah Schwartz, this conference, and shows that the choice of a 1000Hz framerate is interesting for High-Contrast performance, only if the global delay of the loop is sufficiently small, typically close to 2 frames delay. A 3 frames delay would turn into a performance comparable with 500Hz framerate, 2 frames delay and therefore be useless in term of performance.

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2.2.6 Low Order Loop specification

Since PDR, we have specified the Low Order Loop. This slow loop (1Hz), composed of a 8x8 shack-hartmann (650nm) and a low order DM (9x9), and situated at the entrance of the SCAO system (just downstream of the Object Selection Mirror) allows to stabilize the wave-front on the low orders (tip, tilt, and up to a few tens of Zernike modes). This loop will allow one to compensate all varying aberrations that might be brought by the moving parts of SCAO (ADC, K-mirror, Pupil shaping). This loop allows releasing the constraint on all the moving parts, by absorbing the slowly-evolving aberration that they are creating.

We have implemented this loop in our end-to-end simulator, and showed its efficiency on the compensation of a large defocus in the Figure 7. This defocus of 100nm is introduced on the pyramid path. Without Low Order Loop, it would be:

- Seen by the pyramid WFS,
- Corrected by M4,
- Introduced on the science path and degrading its optical performance.

Thanks to the low order loop, and starting from this previous situation, this focus term is now

- Seen by the Blue Shack
- Compensated by the LODM
- Seen (opposite sign) by the Pyramid
- Removed from M4 commands, and not anymore degrading the optical performance on science path.

The principle of the low order loop is demonstrated here, we still have to analyse its robustness to a number of parameters. Among them:

- Rotating M1 pupil, as the LOL is situated upstream of the K-Mirror its pupil is not corrected from rotation
- Zoom of M1 pupil, as the LOL is situated upstream of the beam shaping module its pupil is not corrected from zoom
- Atmospheric dispersion, as the LOL is situated upstream of the ADC its light is not corrected from dispersion

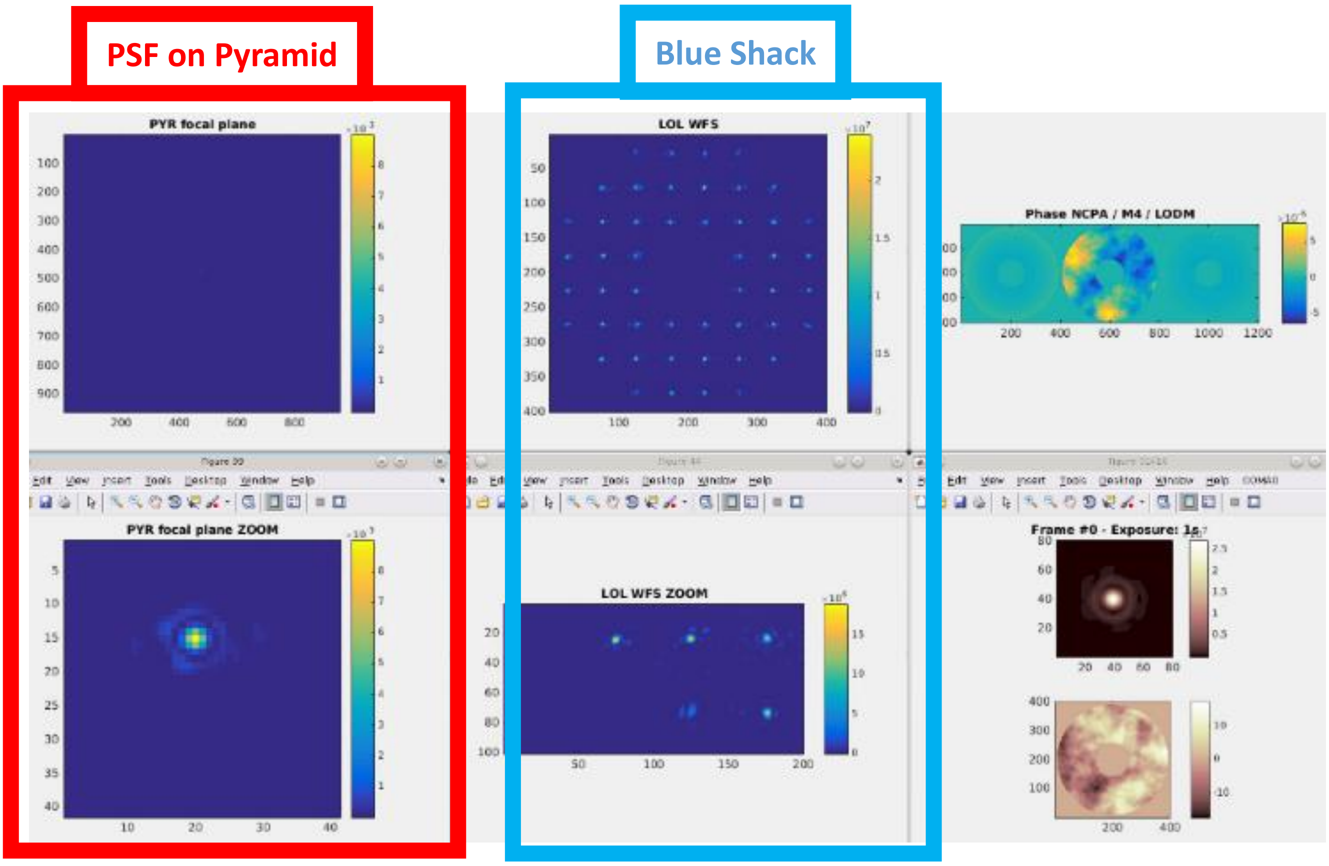

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Figure 7: Illustration of the different focal and pupil planes in SCAO during a loop closure. In the red box, the pyramid focal plane (full and zoomed). In the blue box, the Low Order WFS signals (full and zoomed. Right side / top : the status of introduced NCPA / M4 shape / Low Order DM shape. Right side / bottom: the science PSF and residual aberrations seen in closed loop.

2.2.7 Prototyping activities

We have initiated for SCAO two prototyping activities. The Object Selection Mirror, and the Pyramid Modulator Unit, have been estimated as critical components for SCAO. Their specifications are tight and require to be tested in particular in cold environment. They both correspond to tip-tilt movement, but with very different regimes.

- OSM requires a large, precise, and slow tip-tilt motion, performed once per observation to select the NGS with respect to the science.
- PMU requires a fast and small modulation of the beam, performed continuously during a closed loop in order to improve the pyramid linear range.

Both these prototypes result are presented in the poster of Kacem El Hadi, this conference.

The Figure 8 shows the picture of the modulator (left) and a first result of the modulation signal as seen by a camera in its focal plane. The circular modulation, of angle radius of 5 lambda/D, are shown on the right for 500Hz and 1000Hz modulation, respectively. The prototype is validated at ambient temperature.

The Figure 9 shows the picture of the OSM (left) and a linearity measurement (right) on the complete dynamic.

Figure 8: [left] Pyramid Modulator Unit for SCAO, prototyped at LAM. The PI component has been run at ambient temperature at 500 and 1000Hz, with a modulation radius of 5 diffraction sizes. [right] the signal averaged on a 2ms / 1ms exposure time. The discretization of the modulation signal at 10kHz is only visible on the 1000Hz case.

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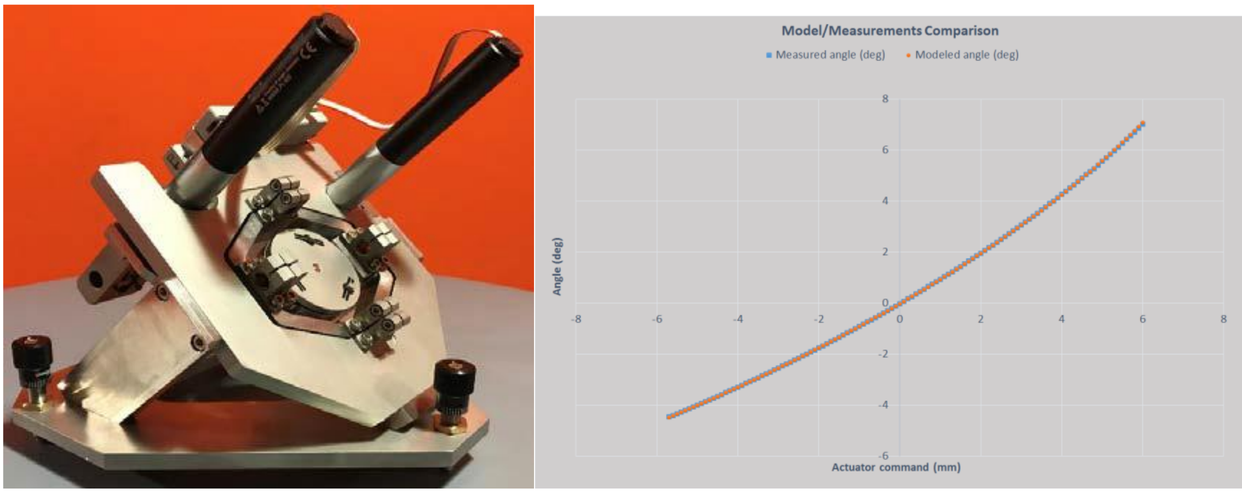

Figure 9: [left] prototype of the OSM at LAM. [right] measurement of the OSM deviation according to the actuator command. A model of the deviation is added.

2.2.8 Conclusions

In conclusion, a large amount of work has been provided since PDR on HARMONI SCAO, in order to validate its performance in degraded conditions, and to extend the specification of its components. Specific prototyping activities are ongoing of critical components of Object Selection Mirror and Pyramid Modulator Unit at ambient temperatures. this work has been partially funded by the ANR program "ANR-18-CE31-0018-01- WOLF", and by ONERA research program VASCO and European Opticon H2020.

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