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HARMONI at ELT:
Prototyping for Single-Conjugate AO Sensor subsystem

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ABSTRACT

HARMONI is the first light visible and near-IR integral field spectrograph for the ELT. It covers a large spectral range from 450nm to 2450nm with resolving powers from 3500 to 18000 and spatial sampling from 60mas to 4mas. It can operate in two Adaptive Optics modes - SCAO (including a High Contrast capability) and LTAO - or with NOAO. The project is preparing for Final Design Reviews.

The SCAO Sensors subsystem (SCAOS) is located within the Natural Guide Star Sensors (NGSS) system which includes several wavefront sensors (WFS) to cover the needs of the different HARMONI observing modes and operates in a cold, thermally stabilized (+2°C) and dry gas environment for thermal background limitation. To reach the required performance, the SCAOS will use different modules and mechanisms among which, two particularly critical devices have been prototyped and are tested: The SCAOS Pyramid Modulator Unit (SPMU) and the SCAOS Object Selection Mechanism (SOSM). Both devices are tip-tilt mirrors but have very different specifications (amplitude and speed). In this work, we will present and discuss the design, the assembly and the full test (performance, control) of the two systems, in both ambient and cold environments.

Keywords: ELT HARMONI, Adaptive Optics, SCAO, Wave-Front Sensing, Pyramid, modulator, Tip-Tilt Mechanism

1. INTRODUCTION

The Laboratoire d'Astrophysique de Marseille (LAM) is involved in the development of ELT instruments, for example, as deputy-PI of HARMONI[1], an ELT visible and near-infrared integral field spectrograph (IFS), or still as the PI of MOSAIC[2], the ELT Multi-Object Spectrograph.

HARMONI[3, 4] is a visible and near-infrared integral field spectrograph providing the ELT's core spectroscopic capability. It uses image slicers to provide spectra for each one of its 204x152 spaxels covering a single contiguous field. Spaxel scale is adjustable from 4x4 mas, Shannon sampling the NIR diffraction limit, to 60x30mas, for wide-field, near seeing-limited operation. The instrument will exploit the specific scientific niche opened by the ELT, starting at first light.

To benefit fully from the sensitivity and spatial resolution offered by the nearly 40 m diameter pupil of this giant telescope, HARMONI will work at the diffraction limit thanks to its two complementary adaptive optics observing modes[3], SCAO (Single Conjugate AO) and LTAO (Laser Tomographic AO).

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In a third AO mode, HCAO, a high-contrast facility extends the SCAO capabilities to allow for exo-planet characterization. Finally, a fourth mode, NoAO, allows operation assisted only by secondary guiding allowing coarse-scale imaging with minimal guide star requirements.

While the deformable mirror performing real-time correction of the atmospheric disturbances is located within the telescope itself, HARMONI is in charge of providing the wavefront measurements controlling this correction.

Two HARMONI systems are dedicated to wavefront error (WFE) sensing:

- The LGSS[5] (Laser Guide Star Sensors) will sense high order WFE using 6 laser guide star modules for LTAO operation.
- The NGSS[6] (Natural Guide Star Sensors) will measure WFE including position and focus. The NGSS includes several wavefront sensors (WFS) to cover the needs of the different HARMONI observing modes, LTAO, SCAO, and High-Contrast. To limit thermal background in the science channel, the system is built in a cold and controlled environment, operating at a stabilized temperature of +2°C.

To reach the required performance, the HARMONI SCAO Sensor (SCAOS) sub-system[7] will include different modules (Dichroic Exchange Module, Object Selection Module, Low-Order Loop, Beam Correction Module, Pyramid Sensor Module) among which we have identified two critical components to be prototyped: both are tip-tilt type devices, the SCAOS Pyramid Modulator Unit (SPMU) and the SCAOS Object Selection Module (SOSM).

In this paper, we present the work conducted at LAM as part of the SCAOS sub-system development. After briefly introducing an instrument overview, the SCAO/SCAOS requirements and functions, we describe the prototyping activities on the SPMU and SOSM devices. The study in terms of environment testing, both at ambient and cold operations, as well as the electronic control are presented and the test results discussed. A plan for the remaining work is also presented.

2. HARMONI OVERVIEW

2-1 Instrument main capabilities

In Table 1 are summarized the main capabilities of this integrated field spectrograph for the ELT.

Table 1. HARMONI main capabilities.

Different capabilities	Description and parameters
Spectral range	0.8 to 2.4 microns
Spectral scales	3 scales from R=3000 to 20000
Spatial scales	214 x152 spaxels, 4 scales from 4mas to 60mas
Adaptive Optics	SCAO & LTAO modes
High Contrast	Requirement: 10e-6 @ 150mas

The Figure 1 shows the instrument AO modes performance in terms of Strehl Ratio (K-band) and Sky Coverage.

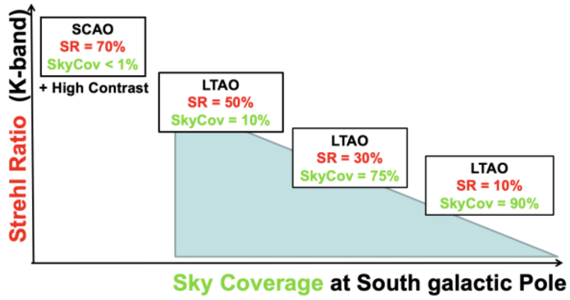

Figure 1. HARMONI AO modes with strehl ratio performance and sky coverage.

2-2 Instrument main systems

The HARMONI main systems are listed and briefly described in Table 2.

Table 2. HARMONI main systems.

Acronyms	Description
LGSS	Laser Guide Star Sensors: including 6 LGS WFS
NGSS	Natural Guide Star Sensors: including several observing modes, LTAO, SCAO and High-Contrast. It is made from 5 sub-systems: ESE (External bench Structure and Enclosure), ISB (Internal Structure Bench), SCAOS, HCM (High-Contrast Module) and LOWFS (Low Order Wavefront sensor). The NGSS is operating at +2°C.
CARS	Calibration and Relay System including Calibration Module (CM), Focal Plane Relay Sub-system (FPRS), and Instrument Support Structure (ISS, Top Frame & Main Frame)
IFS	Integral Field Spectrograph
	Science software???
HCS	Harmoni Control System: including Instrument Control Electronics (ICE) and Instrument Control Software (ICS) with its Adaptive Optics Control System (AOCS).

The Figure 2 are shown: on the left side, a view the instrument opto-mechanical design with illustrations of the different systems described above and, on the right side, the details of NGSS broken into sub-systems.

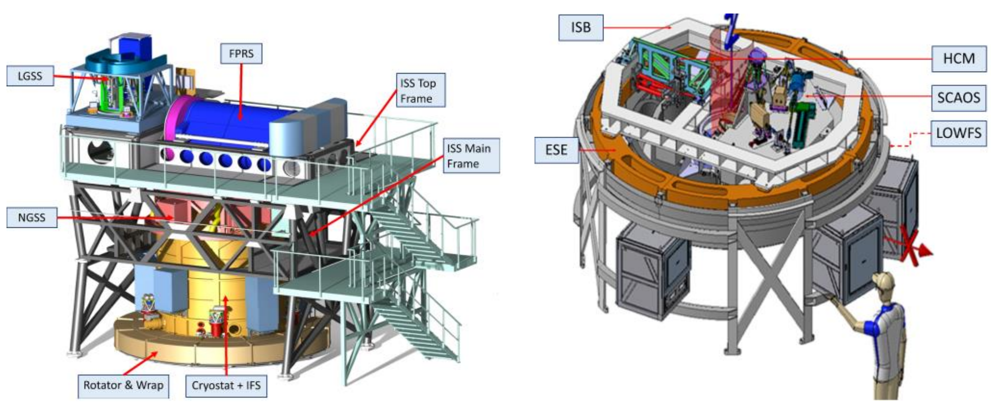

Figure 2. [Left] HARMONI opto-mechanical overview with main systems: LGSS, NGSS, FPRS, ISS, IFS. [Right] Overview of the NGSS with its 5 sub-systems: ESE (top cover removed for showing the interior sub-systems), ISB, HCM, SCAOS and LOWFS.

3. SCAO/S OVERVIEW

3-1 SCAO observing mode

The main SCAO observing mode functions are to:

- Provide a corrected wave-front to science (>67% Strehl Ration in K band, median seeing conditions, 12 R-mag NGS))
- Provide high performance wave-front sensing (NGS and extended object)
- Patrol field of +/- 15 arcsec on sky.

3-2 SCAOS main modules

To reach the required performance, the SCAOS sub-system will include different modules among which the main ones and their functionalities are:

- Pyramid Sensor (PyrS): including an achromatic double pyramid prism, an OCAM2k camera and Pyramid Modulator to provide high performance wavefront sensing with high sensitivity and Strehl ratio.
- Linear ADC: to correct for atmospheric dispersion
- BlueSack/LODM: low-order loop Shack Hartmann wavefront sensor combined a low-order deformable mirror to allow low-order modes correction.
- K-Mirror derotator to fix the pupil orientation.

In the Figure 3 is illustrated the actual SCAO mechanical design[8] showing the main modules.

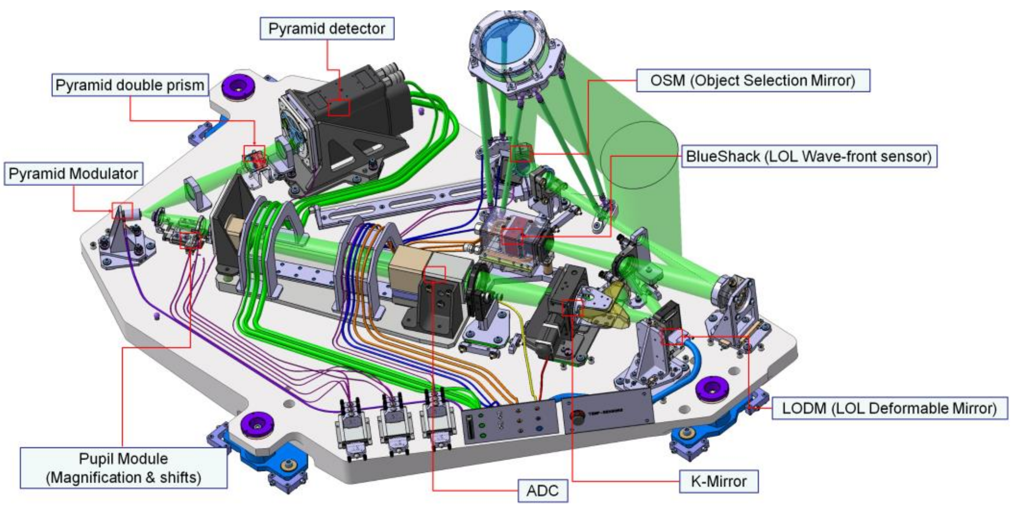

Figure 3. View of the SCAOS mechanical design showing the main actives devices, particularly the Pyramid Modulator Unit (PMU) and the Object Selection Mirror (OSM).

4. SCAOS PROTOTYPING

4-1 SCAOS critical elements

Among all the different devices that constitute this sub-system, we identified two critical ones, the pyramid modulator (SPMU) and the Object Selection Mirror (SOSM). Both of them are tip-tilt (TT) mirrors, with very different specifications (amplitude & frequency)

- The SPMU requires a very fast (500 - 1000Hz) and small (milli-arcsec on sky) movements
- SOSM with a slow (observation time) but large deviations (± 4.5 arcsec on sky) and an absolute positioning at the level of a mas precision.

For each device, we need to demonstrate performance on two aspects:

- Test device performance at +2°C
- Demonstrate Beckoff standard control compatibility.

Then the need of their prototyping appears obvious to make sure of their performance and control.

4-2 SPMU: device, test and results

To prototype our pyramid modulator, we have selected the commercial off-the-shelf components (mirror, tip-tilt platform and controller) shown in Table 3.

Table 3: Selected pyramid modulator elements.

Selected elements	**Specifications**
Mirror	34386 (Edmund optics)
Tip-Tilt system	S-331.2 SH (Physik Instrumente)
Controller	E-727.3SDAP (Physik Instrumente)

A number of experiment series was used to characterize the PMU for different purposes and in nominal SCAO configurations, in particular:

- Linearity, hysteresis, stability and repeatability.
- Different speed regimes (up to 1 kHz).
- Various angular ranges (from 0 to 15 λ/D).
- Stability and shape of movements.

The Figure 4 shows the pyramid modulator fully assembled (TT platform + mirror and PI diver) and integrated in the PMU test bench.

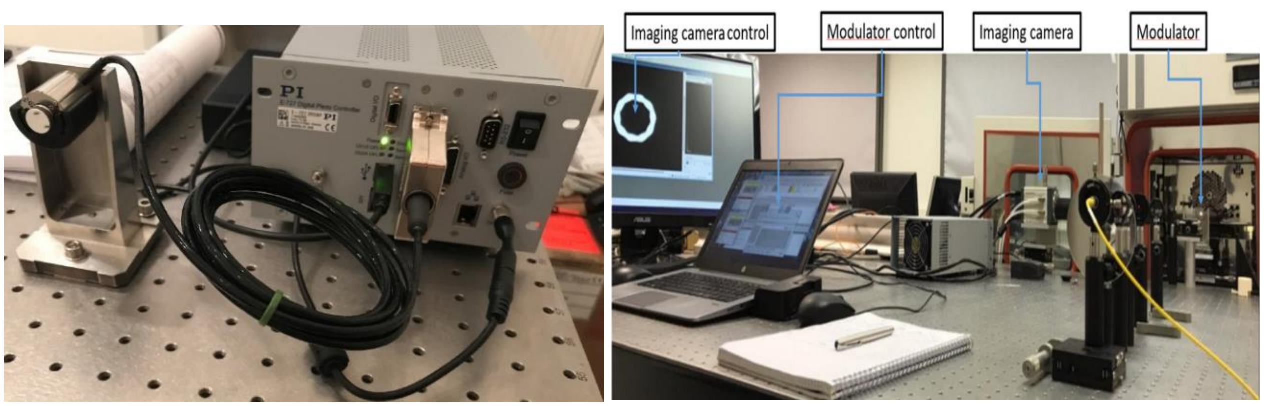

Figure 4. [Left] PMU fully assembled; [Right] PMU test bench showing the modulator and its driver controller, an imaging camera and control station.

The Figure 5 [left] shows a 5λ/D modulation signal at 500Hz and 1kHz. The effect of the controller framerate at 10kHz is mainly visible at 1kHz where the 10 successive positions of the mirror appear as almost discretized spots. This effect is not a problem for the pyramid, as this shape remains constant and perfectly repeatable from one frame to the other. The shape of the circular modulation is good at better than 10% and therefore fulfils the requirements, validating the open loop regime for the controller. A modulation of 5λ/D can be reached at 1kHz which might help to perform high contrast operation even in degraded turbulence regime. The Figure 5 [right] shows the modulation signal at 1kHz for different modulation radii. Even if only a 1 λ/D radius is required for high contrast (this mode will only address the smallest turbulence regimes), this test shows that a 5 λ/D radius can be reached, which is the nominal value for SCAO for reaching all the turbulence regimes up to 1.2 arcsec seeing.

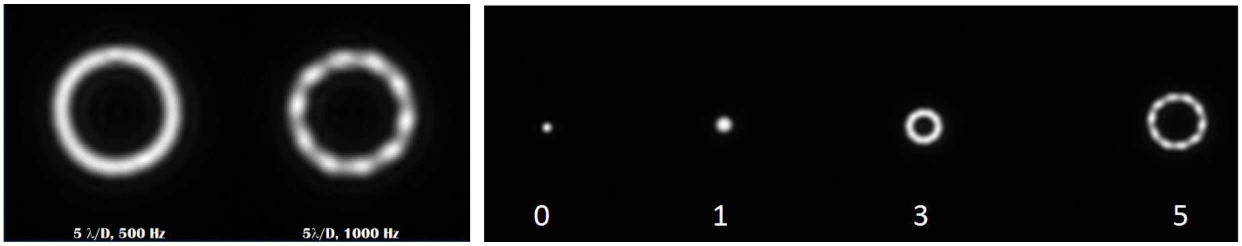

Figure 5. Images in visible (632nm) of a point source in a focal plane after reflexion on the modulator mirror. [Left] Modulation signal for 500 and 1000Hz, 5 λ/D (discretization visible @1000Hz). [Right] Modulation signal at 1kHz, for 0 to 5 λ/D. The spatial scales are not the same in both images.

The Figure 6 [left] gives a view of the PMU test bench during cold testing where we achieved, in this example, down to -20°C operation. As shown in the right side of the Figure 6, where of the modulation shape is compared between ambient and -12°C, a reduction of the modulator stroke about 10% was observed in cold operation. An extrapolation to the case of +2°C gives a reduction of the stroke of around 5%.

Figure 6. [Left] Cold operation testing down to -20°C (window). [Right] Comparison of modulation shape between ambient and -12°C, with a reduction of the modulator dynamic (about 15%).

On the other side, the surface quality was also checked in cold temperature and showed a slight degradation (about 50 nm made from focus+astigmatism). However, the optical quality and impact on stroke are either within specifications and/or correctable by the low-order loop. In addition, another positive point, is that today the operating temperature of the NGSS is now fixed at +2°C (stabilized). Consequently, few more tests at +2°C are needed and planned for a full characterization (optical quality, stroke, …). But we can already conclude that the overall performance of the modulator is perfectly compliant (Table 4).

Table 4: SMPU specifications/measurements compliance (*test not completed, **at the limit, in case, re-do mirror gluing).

Specifications	Value	Unit	T° (amb)	T° (cold)
Modulation amplitude / frequency	1 @ a freq<1kHz 3 to 10 @ a freq < 0.5kHz	λ/D λ/D = 4.5mas (λ of the WFS)	Measured	Measured
Deviation to the circular modulation	< 1/10th	of the modulation radius	Measured	Measured
Repeatability of the signal	< 1/100th	of the modulation radius	Measured	Measured
Absolute position (after a complete OFF cycle)	< 1	λ/D	Measured	*
Maximum WFE below 4 cycle / pupil	< 50	nm RMS	Measured	**

4-3 SOSM: device, tests and results

The prototyping of the OSM has started in early 2019 with a home-made system[9] using commercial actuators from PI (M-227.10). Due to the large angular displacement required (+-4.5° on the component), we proposed a design with guimbals aiming at transforming the linear displacement of the PI actuator into an angle. The results have shown a double problem of regular nonlinearity of lead-screw (500µm period, 10 µm amplitude: 100 times the required precision) and backlash (4-5 µm), excluding any operation because this effect is not easy to calibrate nor to be modelled.

Investigating other options to overcome this issue, we tested a second actuator from PiezoMotor (LL06): even if the test results showed a much better behavior in terms of repeatability, the measured value was higher than announced in its datasheet (2.3 µm RMS instead of 1µm) and the ultimate repeatability (0.16 µm from Manufacturer) requires an additional guiding. Whatever the conditions, the repeatability was more than a micrometer on a 3mm range, which is not compatible with the SOSM need.

We finally found a very promising alternative with a SmarAct-based prototype, using a double goniometer (CGO-77.5/CGO-60.5). The Figure 7 below shows and summarizes the different devices we used for our prototypes.

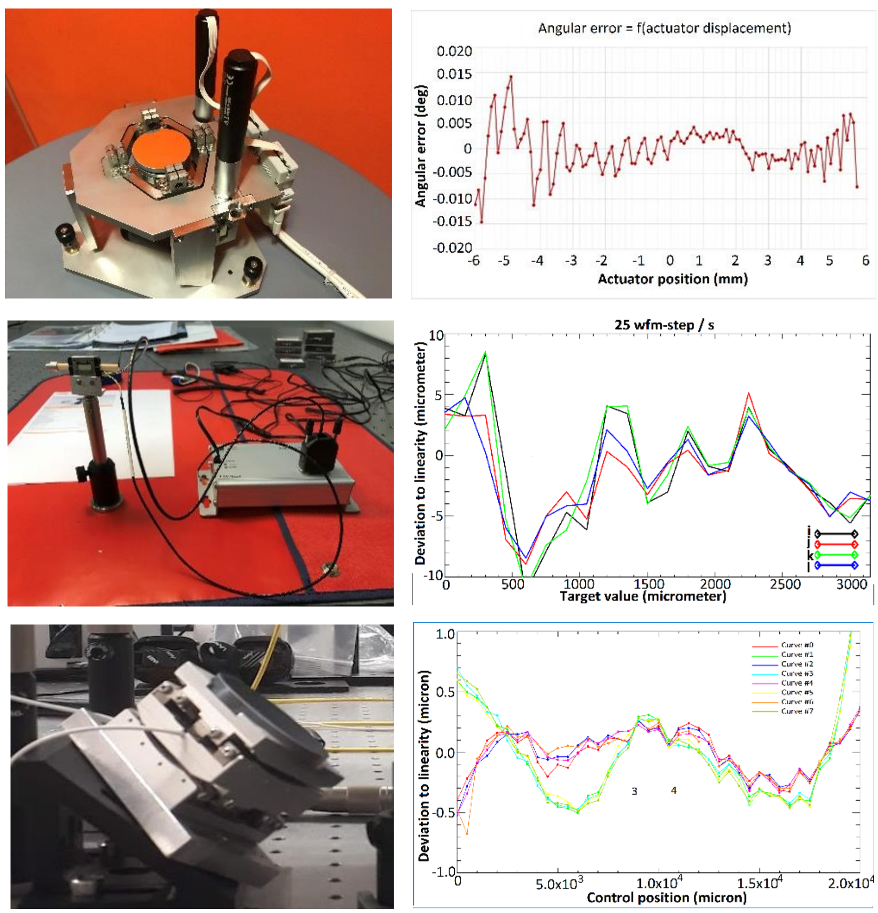

Figure 7. The LAM-made PI-based prototype (top left) developed for the Object Selection Mechanism (OSM) and its insufficient performance in terms of calibration capability (top right). The PiezoMotor-based one (middle left) with better performance (repeatability) but still not in specs (middle right). The SmarAct-based current prototype (bottom left) showing acceptable performance (bottom right) and is still under full characterization.

Using the optical setup bench shown on Figure 8, we tested the SmarAct prototype both at ambient and cold environment.

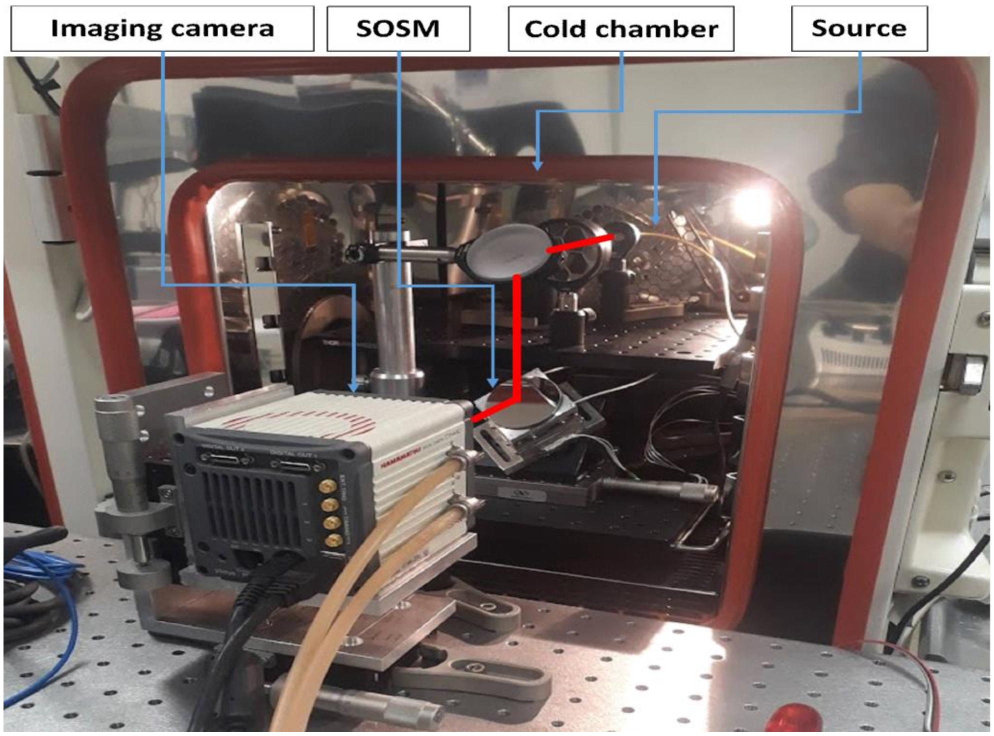

Figure 8. Optical setup test bench showing the SmarAct device inside the cold chamber: the red line illustrates the optical beam coming from the source, reflecting a first time on the fold mirror and a second time on the OSM before entering the camera.

The device is currently under full characterization but the first results seem very good even if work on the optimization of the calibration algorithm remains to be done. Indeed, The SOSM function performance should be an absolute pointing error **< 1mas**. This error includes:

- Device repeatability in command space
  - This represents the precision of repointing for a given couple of (x,y) command sent to the OSM
  - This is estimated on the prototype better than **0.2mas** for both axis and both directions (Figure 9-Left)
- Computation of the correct command (x,y) in order to reach a given sky position (a,b)
  - This computation first requires a calibration of the function: **(x,y)** => **(a,b)** for a subset of points (red dots in Figure 9-Right)
  - Then it requires an interpolation from the calibration data: **(a,b)** => **(x,y)**
  - This procedure is estimated at a **2.5mas** average precision, this is the losange map in Figure 9-Right.

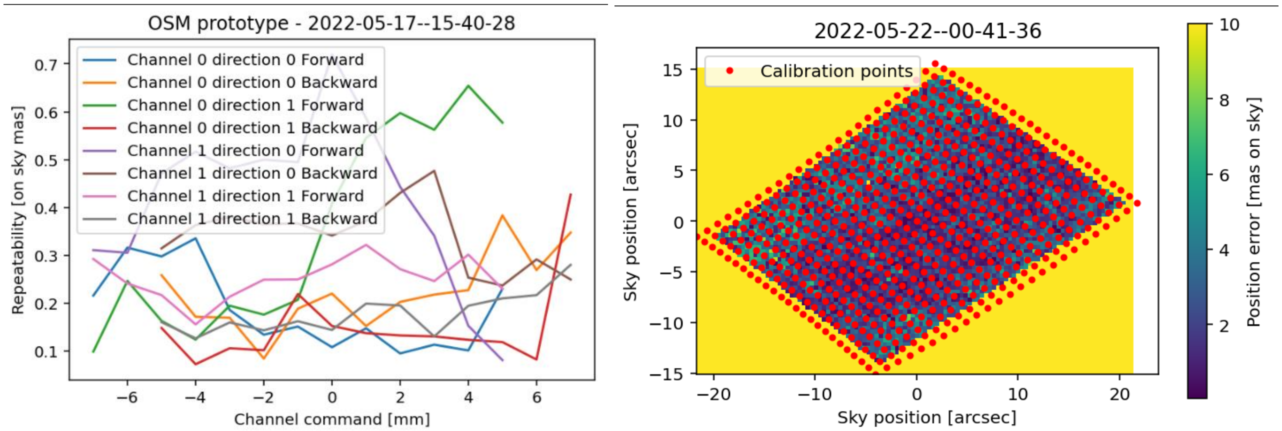

Figure 9. [Left] SmarAct device repeatability in command space. [Right] Calibration grid of the positioning points on Sky.

Finally, the SOSM prototyping activity covered much more than simply testing a component. We have eventually tested three components: PI & PiezoMotor failed while SmarAct is OK. We have implemented and tested the full pointing procedure, after choosing the adequate actuator solution since the final performance will depend on the whole testing setup with an optimized calibration algorithm.

The Table 5 gives a summary the SOSM specifications/measurements compliance. Full characterization at +2°C is planned for very near future.

Table 5: SOSM specifications/measurements compliance.

Specifications	Value	Unit	T° (amb)	T° (cold)
Dynamic	+-4.5	Degree, mechanical angle on component	Measured	Component functional
Precision	5	µrad, on component	Measured on each axis separately Ongoing for whole functionality	Performance still to be done

4-4 CONTROL

Our last need of prototyping concerns the control since we also aspire to demonstrate the device Beckoff standard control compatibility with the idea to demonstrate device functionality and then performance using PLC controllers.

In collaboration with the HARMONI Control System team, we just started with the Pyramid modulator control which requires the development of a "special device", called SMOD:

- We already implemented the Pyramid SMOD controller on the LAM PLC bench (Figure 10).
- Preliminary tests of communication PLC-PI controller are done.
- Functional and performance tests are planned by Q3/Q4-2022

On the other hand, the OSM will use "standard control" with an EtherCat controller, now available from SmarAct. Functional and performance tests will start right after the full pyramid SMOD characterization and then planned by the first quarter of 2023.

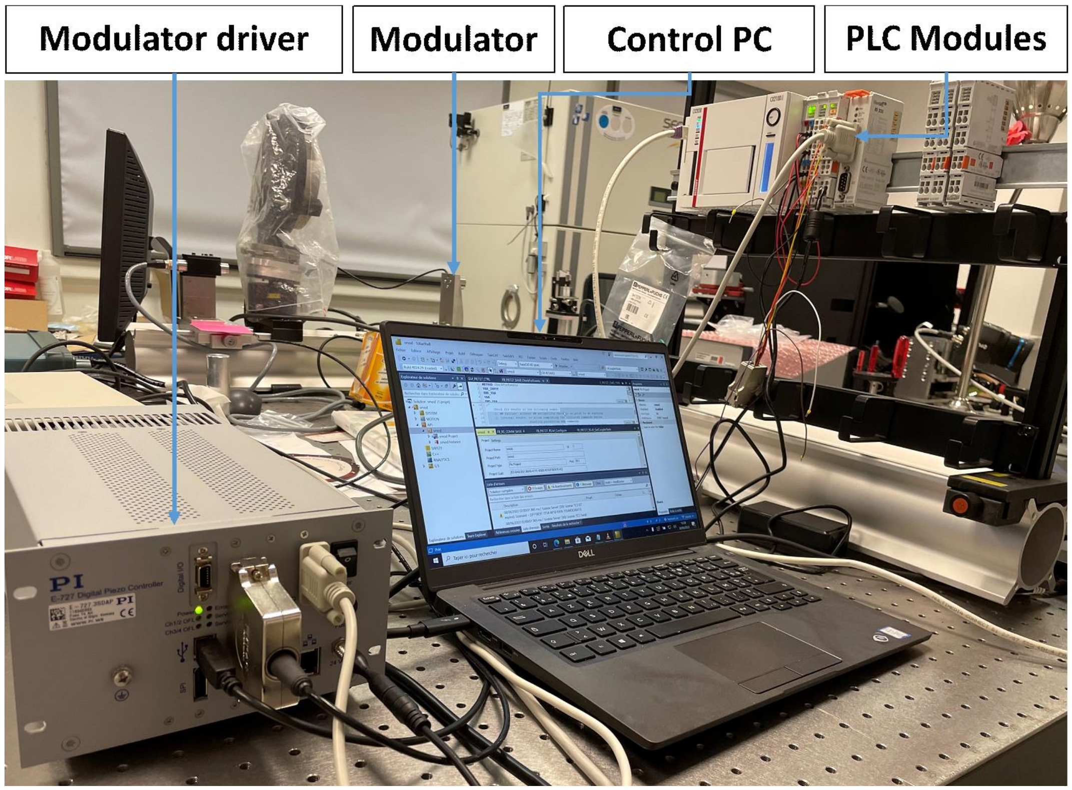

Figure 10. View of PLC control bench under development at LAM.

5. CONCLUSION

In the framework of the HARMONI SCAOS sub-system development, we prototyped two types of tip-tilt devices (Object Selection Mechanism - SOSM and Pyramid Modulator Unit - SPMU) with the idea to work on their performance test and Beckoff electronic control compatibility:

- For the SPMU, the PI system (TT + controller) is fully compliant with the SCAOS requirements. The performance tests both at ambient and cold environment (down to -20°) were confirmed with working different configurations configurations (Frequencies from 500Hz to 1 kHz for various deviations angles ranging from 1 to 15 λ/D). Since now the working temperature of the NGSS has changed, we plan to perform the same tests at +2°C as well as lifetime study starting autumn 2022.
- For the SOSM, and after using different components from PI & PiezoMotor which failed to be in the specifications, we finally (may have) found the right candidate from SmarAct. Indeed, the performance test of the device alone are very good (repeatability average <0.5 mas). However, the final performance depends on the calibration system whose algorithm needs further work and optimization: either we do better interpolation (from linear to cubic or more orders) or we hope that the optical distortion of the final system will be better than the one of the proto setup.
- For the control, the SMOD, special device controller for the pyramid modulator, has already been implemented and will be tested starting this summer (2022). A standard PLC control is foreseen for the SOSM using an EtherCat controller, now available from SmarAct. This work is planed right after the SMO full test, sometimes around first quarter of 2023.

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