ESO Adaptive Optics Facility Progress and First Laboratory Test Results

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ABSTRACT

The Adaptive Optics Facility project is completing the integration of its systems at ESO Headquarters in Garching. The main test bench ASSIST and the 2nd Generation M2-Unit (hosting the Deformable Secondary Mirror) have been granted acceptance late 2012. The DSM has undergone a series of tests on ASSIST in 2013 which have validated its optical performance and launched the System Test Phase of the AOF. This has been followed by the performance evaluation of the GRAAL natural guide star mode on-axis and will continue in 2014 with its Ground Layer AO mode. The GALACSI module (for MUSE) Wide-Field-Mode (GLAO) and the more challenging Narrow-Field-Mode (LTAO) will then be tested. The AOF has also taken delivery of the second scientific thin shell mirror and the first 22 Watt Sodium laser Unit. We will report on the system tests status, the performances evaluated on the ASSIST bench and advancement of the 4Laser Guide Star Facility. We will also present the near future plans for commissioning on the telescope and some considerations on tools to ensure an efficient operation of the Facility in Paranal.

Keywords: Adaptive Optics, Ground Layer Correction, Adaptive Secondary, Sodium Laser

1. INTRODUCTION

The Adaptive Optics Facility project consists in transforming Yepun, the fourth unit telescope of the VLT into an adaptive telescope. To this purpose a new M2-Unit is implemented with a deformable mirror hosting 1170 voice coil actuators. Four 22 W sodium laser guide stars are being launched from the telescope centerpiece to provide the guide

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sources for the adaptive optics modules GRAAL, feeding the large infrared field of view imager Hawk-I and GALACSI, feeding the integral field spectrograph MUSE. The two AO modules provide a Ground Layer Adaptive Optics correction while GALACSI also provides MUSE with a Laser Tomography mode providing diffraction limited images in the visible. The project started phase B in 2006 and most systems integration are nearing completion. The DSM optical tests have been completed and the GRAAL system test phase has started in early 2014. Yepun has been made fully compatible to receive the AOF in term of interfaces: mechanical, electrical, cooling and space requirements are conform and ready.

The facility has been described previously in various papers [1], [2], [3].

Several papers relating to the AOF are being presented in the scope of the present conference; see references [4] to [6].

2. PROJECT STATUS

2.1 The main AOF Sub-Systems: DSM, GRAAL, GALACSI, 4LGSF and ASSIST

The AOF systems are at different phase; some completed and delivered in Garching others in the last stages of integration. The ASSIST test bench has been completed and delivered in October 2012. It has been operational and used during 2013 for the optical tests of the DSM. The latter has been delivered to ESO in December 2012 (see Figure 1) and installed on the ASSIST test bench in order to perform the optical tests, the last stage of validation of the unit.

Figure 1: The Deformable Secondary Mirror as delivered to ESO Garching in December 2012. The assembly was mounted in the integration hall inside a clean tent and reconnected to validate the functionalities of the system after transport from Italy.

A final test report was delivered to ESO in September 2013 and final acceptance was granted a few months later. The high precision optical measurements and delicate calibrations to be performed raised several technical challenges that took longer than initially planned. However, all main specifications have been validated and useful experience toward the installation on the telescope is being gained during these tests [7], [9].

The validation of the DSM on ASSIST inaugurated the beginning of the system test phase; the next step in the sequence is the validation of the GRAAL adaptive optics module. The GRAAL module serves the large 7.5'x7.5' field of view infrared imager Hawk-I. The GRAAL system tests have started in February 2014 for the on-axis natural guide star mode. This has already delivered a number of interesting results and again contributed to a better understanding of the whole control chain. For these tests the complete control loop is being tested. The ASSIST test bench feeds the GRAAL wavefront sensor with an on-axis natural source after reflection on the DSM (see Figure 2). The optical beam is altered by calibrated turbulence generated by a set of phase screens inserted into the optical beam. The DSM is controlled by the

SPARTA real time computer developed in-house at ESO. The complete adaptive optics loop has been closed and activities focus on improving the correction and calibration of the system. In August 2014 we intend to start the tests of the Ground Layer Correction of GRAAL. For a description of the GRAAL module see [12] and the ASSIST test bench see [13].

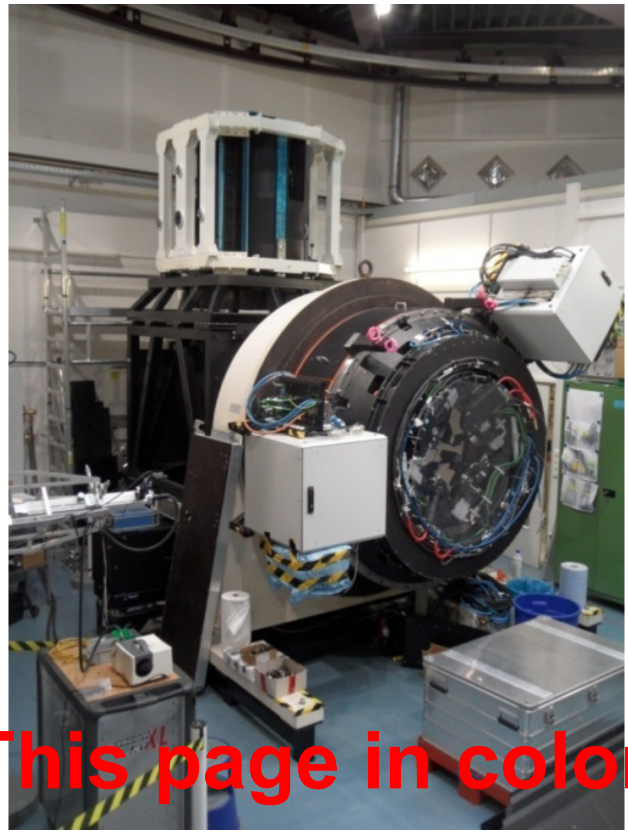


Figure 2: The configuration of the AOF systems being tested in the Integration Hall in Garching. It consists of the ASSIST test bench, hosting a 1.7m aspherical mirror to feed the DSM. The latter is sitting on top of the assembly within the white steel beams "cage". In the forground, the GRAAL adaptive optics module being fed by the ASSIST bench and DSM. In this configuration the wavefront sensors measure an optical beam as they will on the telescope thanks to the source modules inside ASSIST and phase screens which simulate a calibrated turbulence. Tests have started and the first adaptive optics loop has been closed in April 2014.

The GALACSI adaptive optics module, serving the MUSE integral field spectrograph, is still being integrated. The principal remaining integration activity is the installation of the laser guide star wavefront cameras and alignment of their feed optics. This should be completed by the end of 2014 and a milestone validating the module in stand-alone mode is planned at this time. However, many subsystems of GALASI have already been calibrated and validated like a commissioning camera (to evaluate corrected image strehl ratio), a visible star tip-tilt camera including a very accurate field selector system and one LGS WFS camera associated to a fast steering mirror to correct laser beam jitter. GALACSI will take the place of GRAAL on ASSIST when the latter will have completed the GLAO system tests. We expect to have validated GALACSI on ASSIST in the summer 2015. See [8] for more details.

The 4LGSF project took delivery of the first 22W Sodium Laser unit delivered by TOPTICA in November 2013. The Laser has been integrated with the other 4LGSF systems to compose the first complete Laser Guide Star Unit (see Figure 3); one of four. The Laser unit 1 has been granted PAE and the 4LGSF proceed with further system tests. The delivery of the Laser Unit 2 and 3 and 4 is expected this summer. The 4LGSF project is expected to proceed with the facility system tests this summer and fall, leading to a final acceptance in Garching in early 2015. See [5] and [10] for more details on the 4LGSF facility.

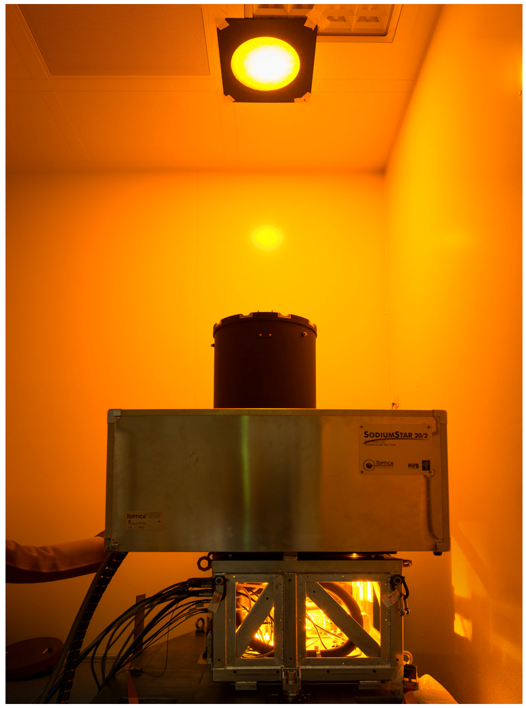


Figure 3: The first delivered Laser Unit from TOPTICA shooting 22 W of sodium light through the Launch Telescope System. The rectangular box is the laser inside its thermally insulated cover. It sits on the Beam Control Diagnostic Systems which contains optics to feed the Optical Tube Assembly (black tube behind). These tests are carried out inside ESO's cold chamber where the system is validated in the operational temperature range.

2.2 The Heart and Lungs of the AOF: The SPARTA real-time computers and the wavefront sensor cameras

The AOF project had under its wing two important technological developments that have delivered the expected performance.

The SPARTA real-time computer hardware is identical for GRAAL and GALACSI (see Figure 3), which allowed a development on either system during the integration. The software development benefited from synergies between the versions being developed at ESO. For instance the GRAAL and GALACSI GLAO corrections algorithms are essentially identical for their real-time operation. The natural guide star, on-axis mode of GRAAL is an additional instance of the version of SPARTA built for the SPHERE instrument. Several high-level features have been implemented to accommodate the calibrations scheme envisioned. The tests conducted so far demonstrated that the FPGA/DSP/CPU architecture does deliver the expected short latency; a value of 81 µs has been measured (from last WFS camera pixel arrival to the application of the DSM command).

The AOF takes delivery of 15 standard cameras that are used as laser guide star wavefront sensor cameras or natural guide star tip-tilt cameras (see Figure 4). They are identical in GALACSI and GRAAL, allowing serial production and common management of spares. They are based on the e2v L3 CCD220 controlled by the ESO New General Controller. Note that the Ocam prototype design has been adopted by ESO for the analog electronic with improvements provided by First Light Advanced Imagery, while the digital design was made at ESO. Deep depletion cameras are used for the natural guide star tip-tilt version while standard ones are used for the Laser wavefront sensor. A 40x40 lenslet array defines the Shack-Hartmann sub-apertures using 6 pixels across each with scale of 0.83" per pixel and a reasonable 5" field of view. These e2v detectors use electron gain amplification in order to reduce the read-out noise (RON) of the CCDs. Although the RON is nominally high (70 e-) the gain amplification mechanism reduces its effective value to below one photoelectron. The gain in question can be selected from 1 to 1000 and the AOF cameras are used at a gain value of ~100 which reduces the RON to acceptable level (1e-) to reach the system performance, while protecting the camera from quick aging (a risk at high gains). Last, but not least, this extraordinary performance is reached at 1 kHz frame rate to match the AOF closed-loop frequency.

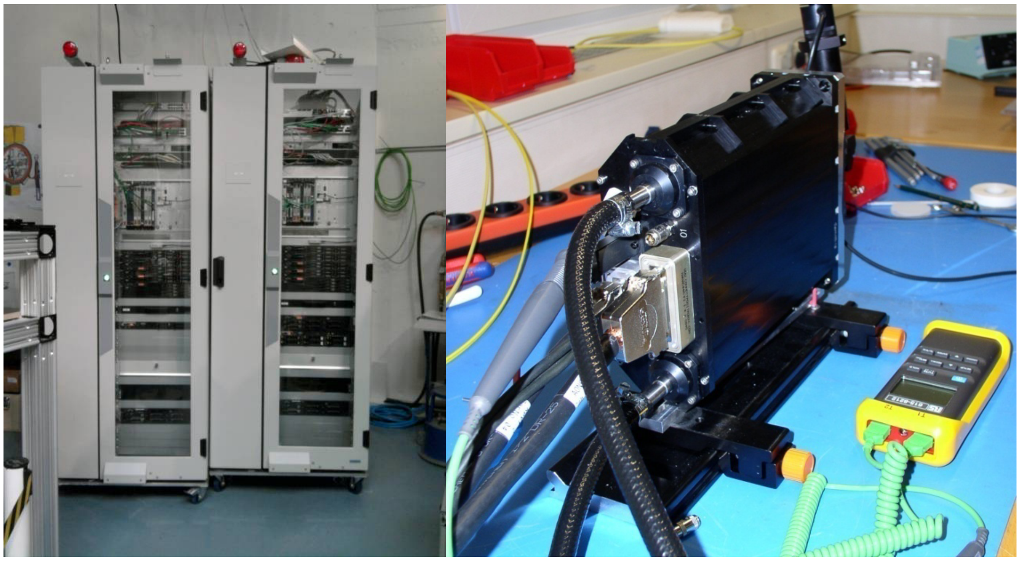


Figure 4: The left picture shows the two cabinets hosting the GRAAL and GALACSI SPARTA real time computers as well as the servers required to control the tip-tilt and WFS cameras. These host the real time box, servers for off-line processing and switches for fast communication and connection to the networks. The right side picture shows one instance of the wavefront sensor camera in its compact housing. The latter is sealed and flushed with dry nitrogen. The detector cooling is ensured via a Peltier cooler (see water pipes connecting at the back).

2.3 The Upgrade of Yepun, the VLT Unit 4 Telescope and Science Operation Tools

In 2013 the upgrade of the Yepun was completed. The basis for the work was identified by the non-conformances of the AOF with the standard VLT interfaces. This allowed the identification of several work packages that defined the work to be performed. Two major interventions were conducted taking advantage of the scheduled M1 coating operations which gave better access to the telescope structure. The first one took place in March-April 2012 and the second one in September 2013.

The electrical power and network was upgraded to take into account the higher demands. A complete recabling of the centerpiece took place and the two Nasmyth altitude cable wraps were upgraded to increase their capacity. Additional pumps were installed to increase the cooling capacity of the UT4 to take into account the increased demands especially from the DSM and the 4LGSF. The Nasmyth A platform was extended to allow more space for the electronic cabinets of MUSE and GALACSI. The Bodega (telescope basement) room was prepared to accommodate the home of the SPARTA real-time computers for GRAAL and GALACSI (electrical, network, cooling). A platform was added under the Nasmyth B platform to install two 4LGSF electronic cabinets and the Laser heat exchanger. More spectacular, the centerpiece was equipped with all mechanical interfaces to install the 4LGSF: interfaces to 4 Laser Guide Star Units and a pair of cabinets (one for the laser and one for the Laser Guide Star Unit control) for each system. Dummy weights have been installed before the arrival of the final systems allowing testing the behavior of the telescope tracking in real load configuration. The Figure 5 illustrates some of the modifications brought to the telescope.

The operation of the AOF is deemed to be a complex process and care is taken to ensure that the observatory staff have the tools needed for this. The Astronomical Site Monitoring of Paranal is extended and the displays updated; these shall indicate not only seeing but also the distribution of the turbulence with height. This is a key parameter in order to decide whether GRAAL is best suited (300 meters important ground layer) GALACSI GLAO (500 meters important ground layer) or GALACSI Laser Tomography mode (best seeing < 0.6”). A tool to identify natural tip-tilt star is being coordinated at ESO for use with all new instruments and the AOF has provided inputs to the requirements of this tool. A Laser Traffic Control Software has been adopted and slightly adapted to the Paranal observatory. A so-called “publisher software” has been developed in-house to feed the Laser Traffic Control Software with the Paranal telescope positions (four 8m telescope, VISTA, VST and VLTI Auxiliary telescopes) and whether their instruments are influenced by the laser beam. The future release of the Observing Tool will allow observers to query the LTCS to see the impact of scheduling a given observing block and potential laser collisions. We intend to test these tools during the early phase of the AOF commissioning in order to be able to use them for the later phases which should streamline the sky tests.

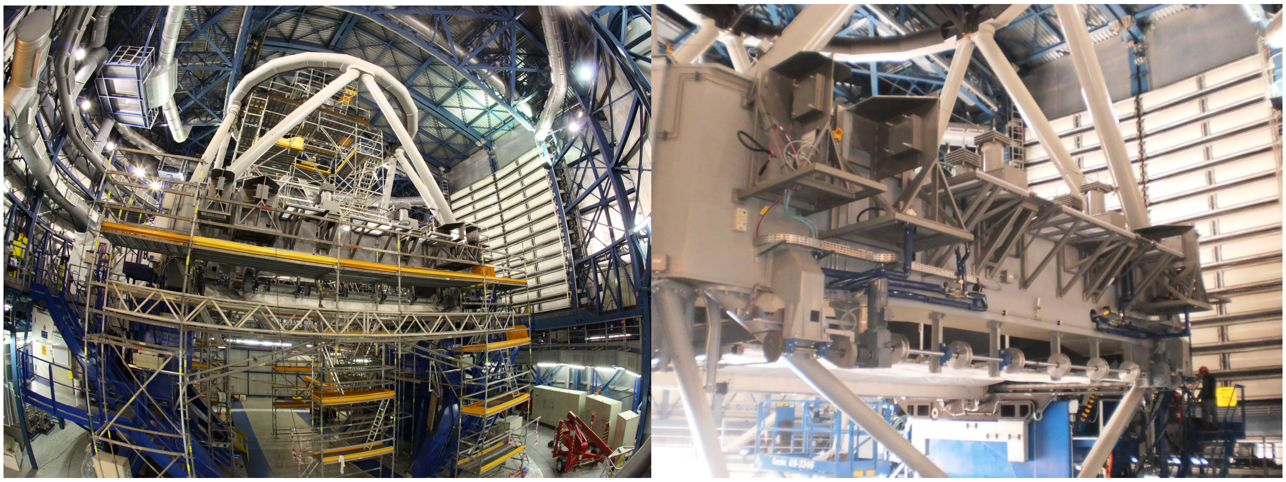


Figure 5: The VLT unit 4 telescope (left) in April 2012 surrounded by scaffolding to provide access to the centerpiece. One can see the mechanical interfaces mounted on the side of the centerpiece to accommodate the Launch Telescope Systems for the Laser and their electronic cabinets. The dummy weights mounted (see right hand picture) allowed a full characterization of the telescope azimuth and altitude loops after the implementation of the additional load brought in by the AOF.

2.4 Status and Next phases

The following list of milestones illustrates the technological challenges associated with the project and provides an accurate idea of the project advancement.

- The WFS cameras have been tested and used for the AO module alignment. They provide a pixel stream via FPDP link to the SPARTA real time computer. The goal of sub-electron read out noise at 1 kHz frame rate has been validated.
- The Real-Time-Computer SPARTA
- The DSM optical tests have been performed on ASSIST and validated the main specifications and in particular a 18 nm WFE with 1170 applied to “flatten” the shell
- SAFRAN-REOSC has delivered a spare thin shell to ESO in December 2013
- The GRAAL adaptive optics module has been installed on ASSIST and aligned with the DSM and a complete control loop has been closed involving the high order wavefront sensor camera (40x40 subaperture Schack-Hartman sensor), the DSM and the SPARTA real time computer
- Two 22W sodium Lasers developed by TOPTICA have been delivered to ESO and the first complete Laser Guide Star Unit has been validated in cold and in flexure
- The GRAAL system tests have started using the natural guide star, on-axis wavefront sensor.

In the summer of 2014 the GRAAL module will be equipped with all Laser Guide star wavefront sensor cameras and the tests aiming at validating the GLAO correction algorithm will start. This phase will last until the end of 2014, at which time a formal review will verify all system specification and authorize shipment to Paranal for the start of the commissioning activities.

The GALACSI AO module will replace GRAAL on ASSIST and the GALACSI tests are expected to last until the end of the summer 2015. Again a formal review will precede shipment to Paranal to start the commissioning activities.

Note that DSM and ASSIST will remain in Europe a few more months, time needed to fully calibrate the spare thin shell and make it a valid, operational spare.

The year 2016 will see the installation of the new M2-Unit on the VLT unit 4 telescope and the core commissioning activities of the AO modules GRAAL and GALACSI with the DSM and the Four Laser Guide Star Facility. This phase will be completed by a full validation with the instruments: the Hawk-I infrared imager with GRAAL and the MUSE integral field spectrograph with GALACSI.

Note that in 2015 while GALACSI will be tested on ASSIST in Europe, a substantial level of activities will take place on UT4 as the GRAAL module will be installed on the Nasmyth platform while the 4LGSF will be installed and validated in stand-alone mode. We intend to ship the first Laser Guide Start Unit in advance in order to be able to conduct some laser guide star acquisition tests with GRAAL. This will allow an early start of commissioning activities and reduce the scope of tasks to be done after the DSM installation.

Commissioning activities will start in 2015 and last into 2017 with an intense peak in 2016.

3. START OF SYSTEM TEST PHASE; FIRST RESULTS

The first issue of the AOF System Test Plan dates back to May 2009; needless to say that this phase has received attention early on in the life of the project. Following the Test Readiness Review of February 2013 a detailed test procedure document was prepared for GRAAL. For each tests a quick description is given, expected duration, pre-requisites or inputs, detailed procedure and Pass/Fail criteria, outputs. This has allowed the AOF to proceed swiftly with these tests when the GRAAL module alignment on ASSIST was completed.

The preliminary tests focused on establishing the basic characteristics of the setup:

- calibrating the wavefront sensor detectors: background versus gain, noise versus gain etc.
- pupil illumination on the detectors,
- measurement of slopes with various centroiding methods
- estimation of optical aberrations
- calibration of the flux received from the ASSIST source
- IR camera image quality

3.1 Wavefront Sensor response

The first tests have been about the apparently simple task of measuring the pixel scale of the Wavefront Sensor (how many arseconds of motion on the sky correspond to one pixel on the detector), but a crucial task since it allows checking the good behavior of many hardware and software components of the system, before closing the Adaptive Optics loop. The measurement procedure is simple: sending small tilt offsets to the DSM hexapod and recording simultaneous images on the Wavefront Sensor. The knowledge acquired thanks to this measurement covers:

- The Software ability to run a template communicating with all available AOF components: DSM, Hexapod, SPARTA, WFS cameras, Instrument Workstation
- The Hexapod control accuracy (indeed we pushed it to its limits by sending commands much smaller than the specified minimum value)
- The recording of Real-Time Data using SPARTA
- The slopes computation process
- The linearity range of the WFS
- Estimation of the source size and detector PSF (charge diffusion)
- The possible presence of ghost images on the WFS
- The alignment of the Hexapod axes w.r.t. the WFS ones
- The alignment of the field-stop in front of the WFS (this field-stop avoids light from one sub-aperture to leak into its neighbor)

- The response of the WFS sub-apertures to a tilt. This response is different for the fully-illuminated sub-apertures than for the ones at the edge of the pupil, and can be used to calibrate the WFS model that will serve when generating the Pseudo-Synthetic Interaction Matrix of the system (see Figure 6).
- And obviously the pixel scale which average value can be compared to the design one to indicate the alignment quality, and which map per sub-apertures indicated pupil aberrations and lenslet array defects (see Figure 7).

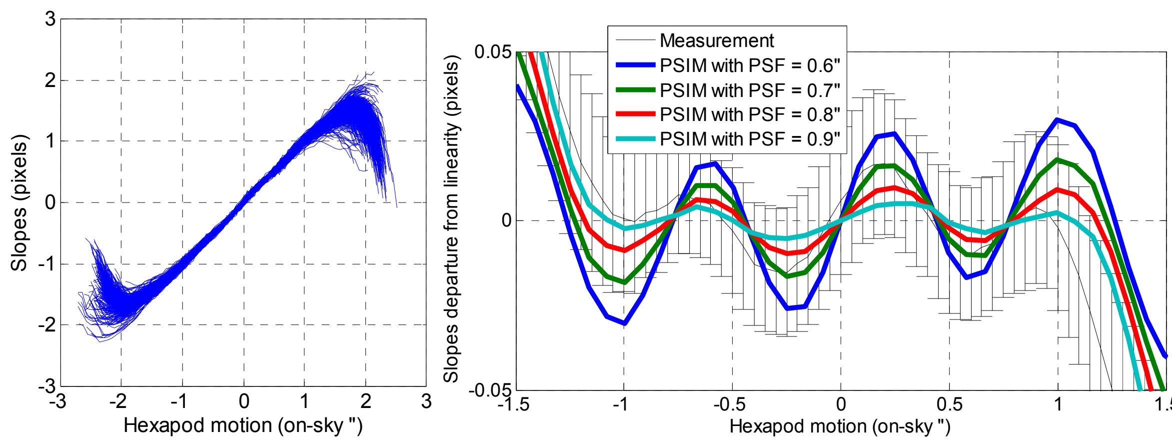


Figure 6 On the left, the slopes measurement for the fully-illuminated sub-apertures are represented as a function of the tilt angle sent to the hexapod. On the right, their measured departure from linearity is represented as the black error bars. They are compared with the response provided by a model (PSIM) for different assumptions of detector PSF values (from 0.6 to 0.9 arcsec) around the one that has been measured on the detector.

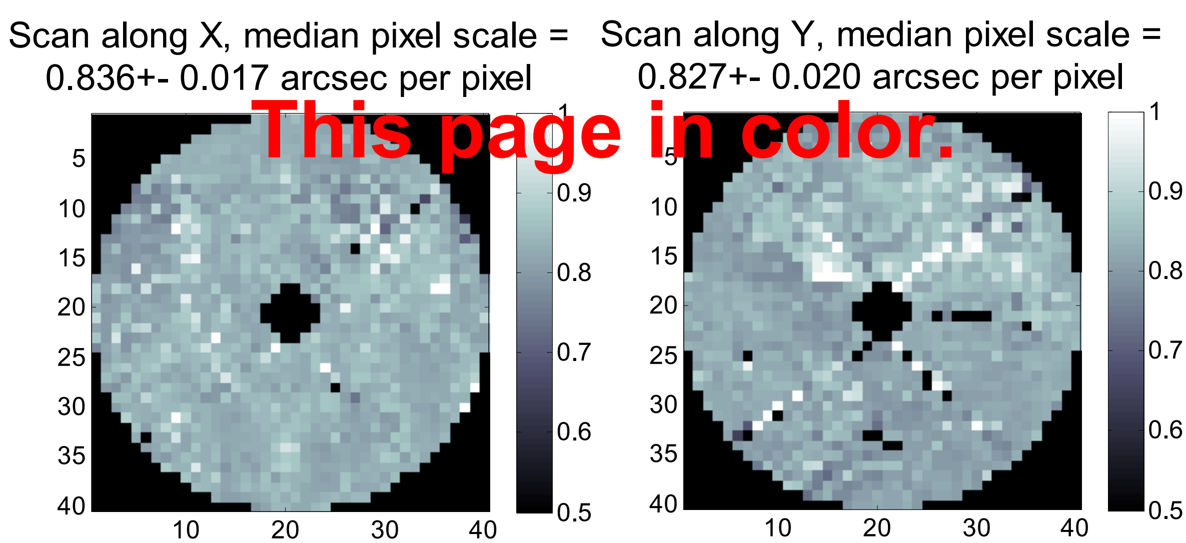


Figure 7 Map of X and Y pixel scale (respectively left and right images) measured per sub-aperture. The measurement failed for a few sub-apertures, especially near the spider's shadow. The median values are very close to the design one: 0.83 arcsec / pixel.

3.2 Interaction Matrix measurement

The next major task of the system tests concerns the generation of the AO Interaction Matrix (IM). It contains the response of the WFS to the DSM deformations and will allow, after inversion, computing the DSM commands correcting for the measured turbulence at 1 kHz. In the case of the DSM, this matrix is composed of 1156 rows (DSM valid actuators) and 2480 columns (40x40 apertures in a circular area, each with 2 slopes one in X and one in Y).

In classical post-focal AO systems like NAOS, the IM can be re-measured at will by placing an artificial source at the entrance focal plane of the instrument. But this is not possible on an adaptive telescope like the VLT equipped with the AOF, as the deformable mirror is part of the telescope optical train.
Hence the baseline for the AOF is to use a Pseudo-Synthetic Interaction Matrix (PSIM), based on a computer model of the DSM and WFS, fine-tuned by matching it with measured characteristics of those same components: WFS response and DSM influence functions.
As it is quite a novel concept to be implemented in a scientific AO instrument, it is important for it to be tested in the laboratory and ASSIST offers this possibility. Indeed the atmosphere emulated by optical turbulent Phase Screens can be removed, and an IM can be measured like on a post-focal AO system.
IMs have been measured using several different methods and their performance will be compared with the one of the PSIM. For each method several parameters like the amplitude and number of the cycles can be varied to maximize the IM Signal-to-Noise Ratio. Those methods are:

- Zonal IM: actuators are pushed one by one and the WFS response is recorded
- Hadamard IM: all actuators are controlled at the same time following a Hadamard pattern (see some examples on Figure 8), theoretically maximizing the SNR for a given measurement duration [11]
- Modal IM: Hadamard IM may be optimal for a piezo-electric mirror, it is not anymore for a force-controlled one like the DSM because of the very high spatial frequencies in the Hadamard modes make the mirror saturate (in force) already for small amplitudes. Thus other sets of modes to study are ones closer to the ones of the atmosphere (Karhuenen-Loeve modes) and/or to the ones the DSM can reproduce with weak forces (stiffness modes). Their amplitude can me optimized mode by mode to produce the maximal response on the WFS while not exceeding the maximum force allowed
- IM on turbulence: the three methods above can be used as well to record an IM not on the artificial source alone, but on this source seen through the turbulence, similarly to recording an IM on-sky. Fast push-pull actuations (at 250 Hz) allow freezing the constantly evolving effect of the turbulence. This is the back-up method for the AOF that will permit recording a reference IM at the VLT before even the PSIM is tuned. This method has shown to provide excellent results on the ESO MCAO Demonstrator MAD.

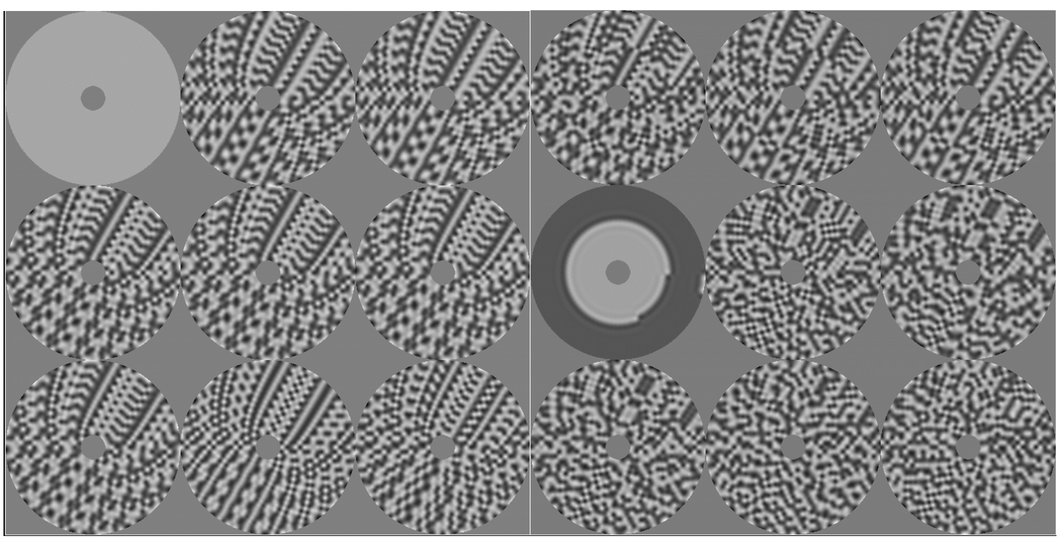


Figure 8: The first 9 Hadamard modes (left) and the last 9 Hadamard modes (right).

3.3 Pseudo-synthetic IM

An AOF Interaction Matrix (2480x1156 elements) is composed in majority of zeros because the influence of one actuator is seen by a few sub-apertures only. Thus the display of such matrix in full is pointless and barely resolved by a computer screen or a printer. Instead we have been using a display of the 40 largest signals along X and Y in the sub-apertures for each actuator. This reduces the matrix to 80x1156 elements which we have then folded four times to get a squarer and easier to display matrix of 289*320 elements (Figure 9).

Some parameters of the PSIM have to be tuned in order to match the real IM of the system. Those parameters describe the pupil mismatch between the DSM and the WFS and are the X and Y shifts, the rotation and the X and Y magnification. A method developed at ESO [14] allows identifying those parameters after iterative comparison of the PSIM with a measured one. Hence the importance of being able to measure an IM even on-sky.

This method has been applied and a PSIM could be generated very close to the measured one (see Figure 9). It has even been used to close the AO loop and the first tests show that it delivers the same performance as the measured one.

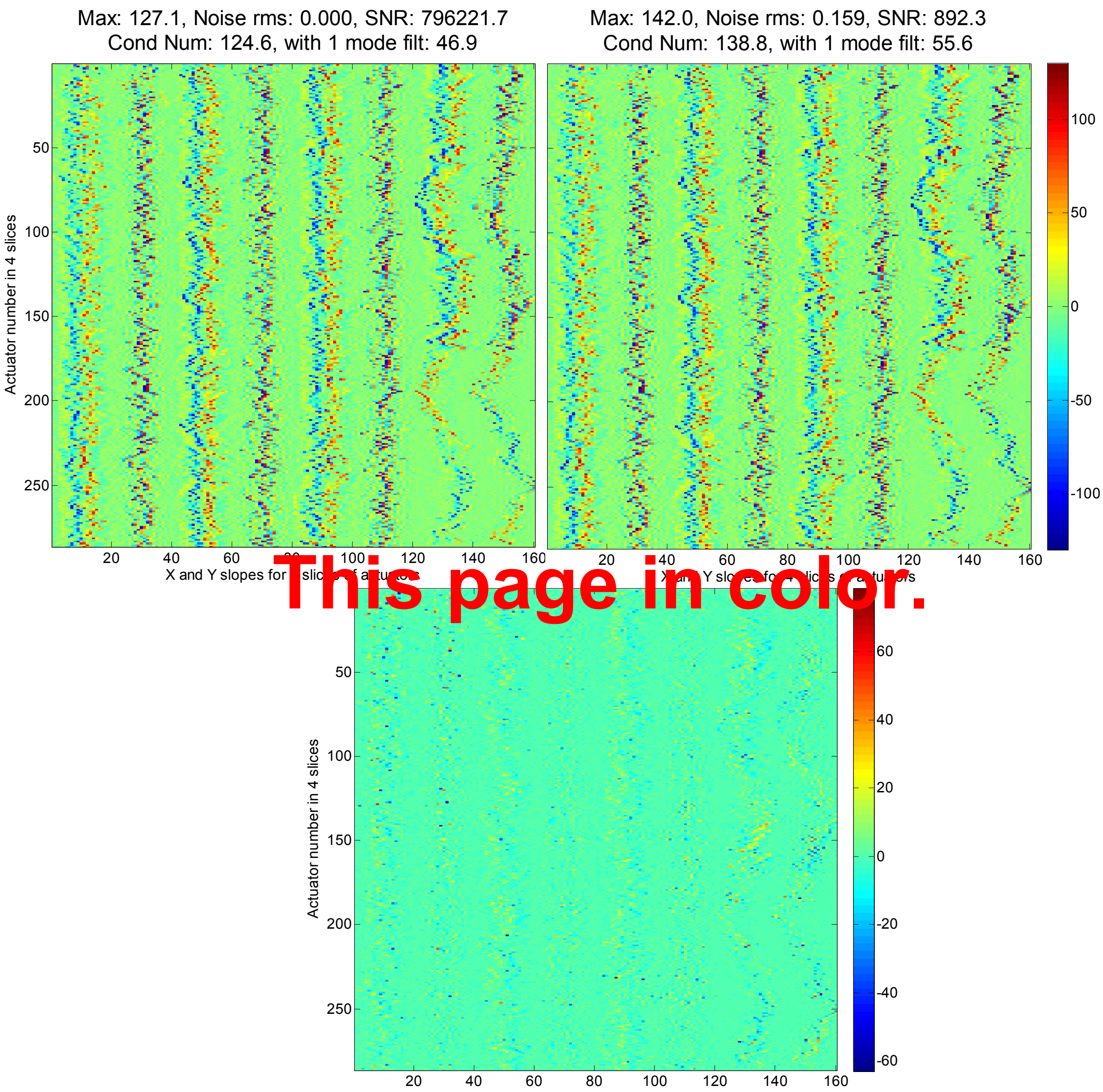


Figure 9 Pseudo-Synthetic IM (top-left) vs. Measured IM (top-right) in condensed display. The 8 vertical stripes that compose them are side by side the X and Y slopes for the actuators 1-289, 290-578, 579-867 and 868-1156. The two matrices seem to differ only for their SNR: ~900 for the measured IM against almost infinite for the PSIM. At the bottom is shown the difference between the two, exhibiting only few discrepancies for some particular sub-apertures.

3.4 Mis-registration estimation

As the DSM and the WFS are separated by tens of meters, it is expected that their alignment mismatch evolves with time. The AOF at the VLT has no means to correct a possible mis-registration (the lateral shifts of the DSM are already used to correct coma, and there are no pupil alignment mirrors in ASSIST), so the baseline strategy consists in updating the Control Matrix based on a PSIM recomputed for the estimated values of mis-registration.
The AOF performance can start to be affected if this mismatch (in particular lateral shifts) is larger than 10% of a sub-aperture (3 mm at the level of the DSM). To have the possibility to measure the actual DSM/WFS mis-registration during observation, we have developed a method that allows estimating the mis-registration while in AO closed loop using solely real-time data (DSM commands and WFS residuals) without applying any disturbance [14].
The first step of this method consists in reconstructing a rough IM by post-processing of the real-time data. The second step is identical to the one described previously in which a PSIM is matched to a measured IM in order to retrieve the mis-registration parameters. Indeed the reconstructed rough IM is certainly too noisy to be used to close the AO loop but contains enough signal to identify 5 parameters.
The validity of this method has been shown theoretically, in simulations and on data recorded on a test bench (MAD at ESO Headquarters) as well as on the sky (NAOS). It has now also been validated with AOF on ASSIST with turbulence generated by Phase Screens. The procedure consisted in closing the MCM AO loop on turbulence reproducing a seeing of 0.65 arcsec and the wind profile typical of Paranal, and recording 30 seconds of data at 1 kHz. This data is then post-processed, decimated (1 frame kept every 1, 3, 6, 15 or 30) and used to reconstruct the rough IM (for a given loop delay), the SNR of which is around 30. The mis-registration parameters can then be estimated by matching a PSIM to this rough IM. As can be seen on Figure 10, several loop delays have been tested, knowing that the actual one of the system is close to 2 frames. Figure 10 shows that the estimation of X and Y shifts converges for a number of frames as low as 2000. The same goes for rotation and magnification.

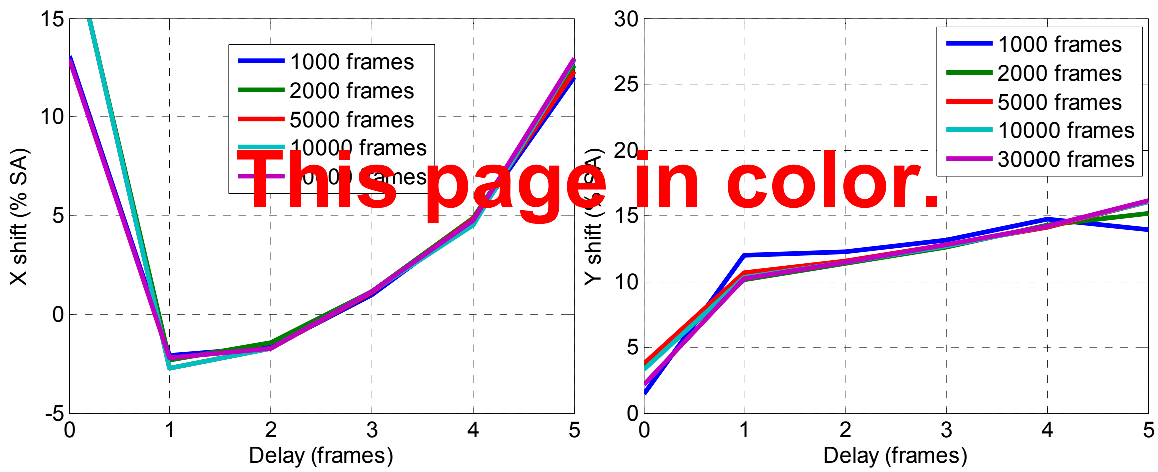


Figure 10 Evolution of the estimated X and Y shifts vs. assumed delay for the IMs reconstructed with different dataset decimation.

3.5 AOF rejection transfer function

The temporal behavior of the AOF servo loop has been characterized by measuring the rejection transfer function of the complete loop. This has been done by adding white noise to the control signal of the DSM in the modal space, while the system was in closed loop and was made possible thanks to a nice feature of SPARTA allowing adding any kind of signal to the control vector of the DSM in real time. By adding perturbations to one single control mode and recording at the same time, while in closed loop, the telemetry data of the AO loop it is possible measuring directly the open loop, closed loop and rejection transfer function of the servo.

Measurements have been taken in high flux conditions, with a simple integrator as IIR filter. The integrator gain was set at 0.4. The modal basis considered is the Karhuenen-Loeve one; modes number 4, 10, 50, 100, 250, 500 and 900 have been sequentially used to excite the system, and associated transfer functions have been measured.

The rejection transfer function of the KL mode 500 is presented in Figure 11. The solid line corresponds to the measured transfer function while the dashed line is the theoretical one, assuming a settling time of 0.7 ms for the DSM (as measured by the DSM manufacturer) and an overall 200 µs latency (80 µs for SPARTA and 110 µs for the DSM – measured values). The rejection cut-off frequency is larger than 50Hz, as expected.

The accordance between the measurements and the theoretical prediction is excellent demonstrating the very good behavior of the overall loop. It is worth noting that the measured rejection transfer functions of all the modes considered are exactly the same, making the complete system sane and easy to control.

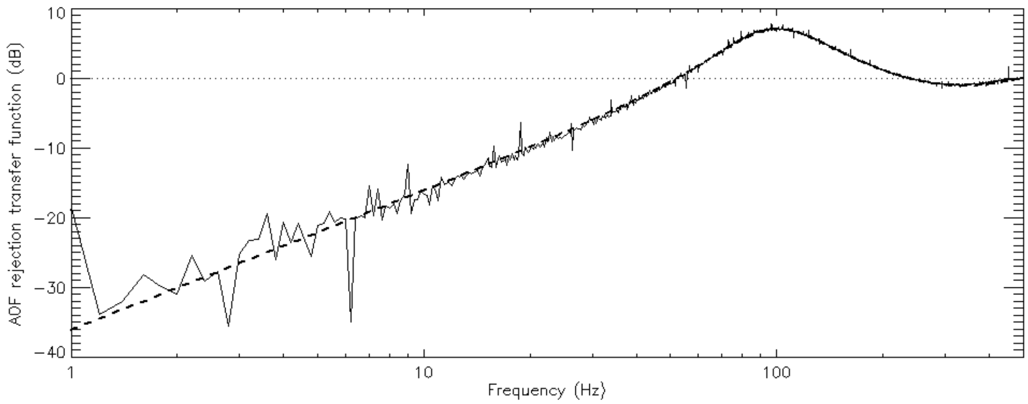
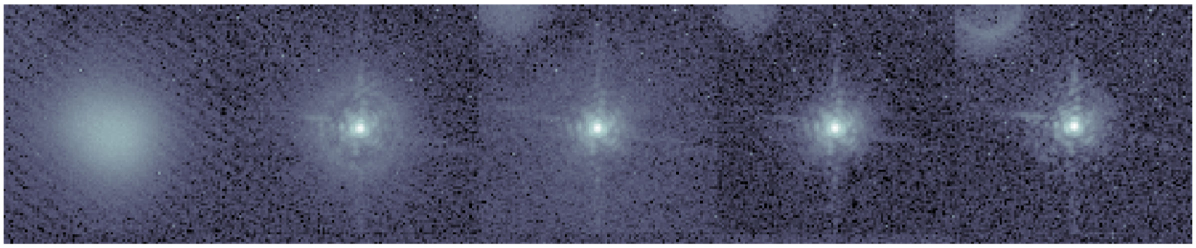


Figure 11 GRAAL rejection transfer function
Solid line: measurement done on KL mode #500 – K_i = 0.4
Dashed line: theoretical – K_i = 0.4 – DSM settling time: 0.7 ms – latency: 200 µs

3.6 Performance of the DSM in Closed loop

Closing the AO loop at 1 kHz between the WFS and the DSM via SPARTA revealed no major issue. The optical Phase Screens that emulate a turbulence with seeing of 0.65 arcsec were introduced and rotated to reproduce the characteristic Paranal wind profile. The AO loop could be closed with an integral gain of 0.4 and three different number of controlled modes: 150, 550 and 950 (see Figure 12). We can notice that the major part of the turbulence is corrected and the GRAAL Maintenance and Commissioning Mode delivers very sharp images close to the one recorded on the calibration source (rightmost image). Preliminary results provide a reference Strehl Ratio measured on the calibration fiber of 76% and on the closed loop images of 65%, i.e. a relative correction of 85% at 1.65 µm.



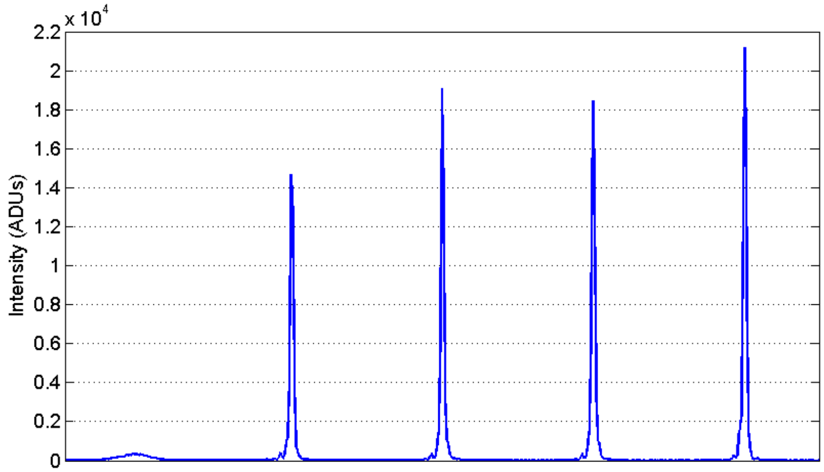


Figure 12 Long-exposure H band images (top) and their horizontal cuts (bottom) recorded (from left to right): in open loop turbulence, in closed loop on turbulence with 150, 550 and 950 modes controlled, and in closed loop on the calibration fiber (rightmost image).

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