Third AO4ELT Conference - Adaptive Optics for Extremely Large Telescopes
Florence, Italy. May 2013
ISBN: 978-88-908876-0-4
DOI: 10.12839/AO4ELT3.16254

ESO ADAPTIVE OPTICS FACILITY: UNDER TEST

Robin Arsenault[1], Pierre-Yves Madec, Jerome Paufique, Paolo La Penna, Stefan Stroebele, Elise Vernet, Jean-Francois Pirard, Wolfgang Hackenberg, Harald Kuntschner, Johann Kolb, Nicolas Muller, Aurea Garcia-Rissmann[a], Miska Le Louarn, Paola Amico, Norbert Hubin, Jean-Louis Lizon, Rob Ridings, Jose A. Abad, Gert Fischer, Volker Heinz, Mario Kiekebusch, Javier Argomedo, Ralf Conzelmann, Sebastien Tordo, Rob Donaldson, Christian Soenke, Philippe Duhoux, Enrico Fedrigo, Bernard Delabre, Andrea Jost, Michel Duchateau, Mark Downing, Javier Reyes Moreno, Antonio Manescau, Domenico Bonaccini Calia, Marco Quattri, Christophe Dupuy, Ivan M. Guidolin, Mauro Comin, Ronald Guzman, Bernard Buzzoni, Jutta Quentin, Steffan Lewis, Paul Jolley, Max Kraus, Thomas Pfrommer,
Roberto Biasi[2], Daniele Gallieni[3], Remko Stuik[4],

[1]European Southern Observatory, Karl-Schwarzshild-Str.2, 85748 Garching bei Muenchen, Germany

[2]Microgate, Via Stradivari, 4, I-39100 - BOLZANO-BOZEN, Italy

[3]A.D.S. International S.r.l., via Roma, 87, 23868 Valmadrera (Lc), ITALY

[4]Leiden Observatory, P.O. Box 9513, NL-2300 RA Leiden, The Netherlands

Abstract. The Adaptive Optics Facility project has received most of its subsystems in Garching and the ESO Integration Hall has become the central operation location for the next phase of the project. The main test bench ASSIST and the 2nd Generation M2-Unit (hosting the Deformable Secondary Mirror) have been granted acceptance late 2012. The DSM will now undergo a series of tests on ASSIST to qualify its optical performance which launches the System Test Phase of the AOF. The tests will validate the AO modules operation with the DSM: first the GRAAL adaptive optics module for Hawk-I in natural guide star AO mode on-axis and then its Ground Layer AO mode. This will be followed by the GALACSI (for MUSE) Wide-Field-Mode (GLAO) and then the more challenging Narrow-Field-Mode (LTAO). We will report on the status of the subsystems at the time of the conference but also on the performance of the delivered ASSIST test bench, the DSM and the 20 Watt Sodium fiber Laser pre-production unit which has validated all specifications before final manufacturing of the serial units. We will also present some considerations and tools to ensure an efficient operation of the Facility in Paranal.

1. Introduction

The Adaptive Optics Facility project consists in transforming 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 20 W sodium laser guide stars are being launched from the telescope centerpiece to provide the guide sources for the adaptive optics modules GRAAL, feeding the large IR field of view imager Hawk-I and

---

[a] A.G-R work at ESO has been funded by CNPq (Brasil)

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 delivering a 5 to 10% strehl ratio in the visible. The project started phase B in 2006 and is into final system validation (started in 2013). The system test phase will involve the full fledged ASSIST test bench and will allow full closed loop tests of the AOF modules with the DSM. The first activities to prepare the unit telescope#4 (UT4) to receive the AOF have taken place in April 2012 and have been completed by a second major intervention in September 2013.

The facility has been described previously in various papers; see [1-3], [22]. Several AOF related systems are described in references [4-21].

2. Project Status Overview

The AOF project has completed all phase C reviews in the course of 2010. Most main procurements have also been completed. At the time of this writing the Garching Integration hall contains the GRAAL and GALACSI adaptive optics modules, each on a test stand, the ASSIST test bench and the DSM. The 4LGSF is integrated and tested in a separate laboratory.

ASSIST test bench optical alignment has been validated in stand-alone mode (on-axis, without the DSM) and the system has been granted acceptance in October 2012.

The GRAAL AO module is completely integrated and functional. The system tests are about to start with the DSM for the on-axis natural guide star mode. In early 2014 after the final integration of the WFS cameras, the GLAO mode system tests will start.

The GALACSI AO module is integrated to the exception of the WFS cameras (2 units available) but in a less advanced stage than GRAAL. As optical alignments are completed, sub-systems are being validated. All electronically controlled motion stages are operational and commanded from a preliminary version of the control software. Various sub-systems have being calibrated and validated: the tip-tilt path and field selector pointing model, the commissioning camera and the focus compensating unit versus altitude (one LGS path).

The DSM has been thoroughly tested at the contractor premises in November 2012 and then shipped in Garching ESO headquarters in December 2012. After re-integration and functional verification the system was granted preliminary acceptance. In early 2013 it was installed on ASSIST and the optical tests lasted through summer. A Phasecam interferometer allowed fast acquisition of interferograms and a first optical calibration of the DSM. The optical test report has been delivered and validate all the key specifications [23]. See [28] for a description of the stand-alone electromechanical tests and results.

The 4LGSF facility is being integrated in a specific separate laboratory offering a thermal chamber to test sub-systems in the operational temperature range. Important sub-systems have been outsourced: the Optical Tube Assembly (four units; part of launch telescope) have been delivered and the sodium 20 watt laser pre-production unit has undergone full system tests and complies with all main specifications [17]. The delivery of the first serial unit is scheduled for November 2013. The Optical Tube Assemblies have been designed and manufactured by TNO (the Netherlands) while the Laser has been contracted to TOPTICA (Germany) who is collaborating with MPB (Canada). A first Launch Telescope System has been assembled, mounted on a tilt stand and tested in flexure in Garching. Shortly after, it has been transferred into the cold chamber to perform temperature tests; cold tests and transient.

Early in the project it was realized that the combination of the Laser Facility, DSM, two AO modules and two astronomical instruments leads to a substantial mismatch of the interface between the AOF and the unit telescope. This was identified and quantified by the Interface Control Document and became the requirements for an important upgrade of the telescope unit 4 of the VLT. A first major intervention to prepare the telescope to receive the AOF took place in March-April 2012 and a final one was just completed in September 2013. Both interventions have been a success. Mechanical interfaces were installed on the telescope centerpiece to receive the launch telescopes and electronic cabinets. The fiber, electrical and cooling supplies of the telescope were upgraded as well to accommodate the larger demand. The 4LGSF sub-Nasmyth platform has been installed and cabled and the heat exchanger installed, the Nasmyth B platform has been extended (for MUSE-GALACSI) and the Nasmyth A altitude cable wrap modified to increase its capacity.

The ESO detector department has delivered 6 WFS cameras to the AOF project and 6 more units await the installation and alignment of the lenslets. The cameras fulfill the highly demanding requirements of 1 e- RON at 1 kHz frame rate (see [18,19]). This requires amplification gain but still far from the maximum value. The delivered cameras are integrated in the GRAAL and GALACSI modules and WFS images are read by the SPARTA real-time computers.

The SPARTA real-time computers have also been delivered. They consist of a large electronic cabinet hosting the real-time box (VME rack with commercial boards), the fast Ethernet switches and the CPU workstations for off-line data processing. Software is complete and all the AOF modes can be tested: on-axis natural guide star (GRAAL Maintenance and Commissioning Mode), Ground Layer AO and Laser Tomography AO for the MUSE Narrow Field mode. Note that SPARTA also manages secondary loops for the natural Tip-Tilt star, either visible with the same NGC WFS cameras or IR for the IRLOS of the MUSE narrow-field mode. The laser beam jitter is also controlled by SPARTA using a fast tip-tilt mirror in the launch telescope assembly (GRAAL) or a similar fast tip-tilt mirror in front of the WFS assembly (GALACSI). All functionalities are ready to perform the GRAAL on-axis natural guide star loop closing (subset of SPHERE algorithms) and in September the jitter mirror loop has been closed in GALACSI validating the complete chain of control: WFS cameras – Sparta – jitter mirror actuator.

3. The new Generation Deformable Secondary Mirror

3.1. Delivery in ESO Headquarters

The DSM is hosted in a complete new M2-Unit that will replace the actual Dornier M2 unit of UT4.

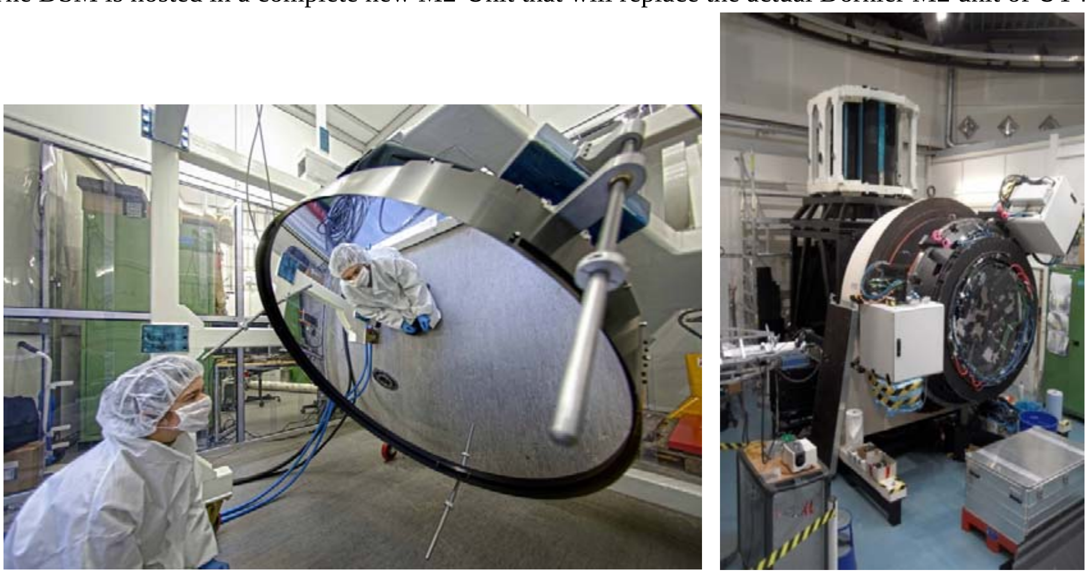

Figure 1: The Deformable secondary Mirror in its test stand at delivery in Dec. 2012. The thin shell mirror in operation is held by the actuators with a gap of 65 μm between the back face and the reference body front face. The right hand side picture shows the DSM mounted on ASSIST, the test bench delivered by NOVA for the testing of the AOF. In the foreground the GRAAL adaptive optics module.

The hub structure implements the same interface as the existing one for the telescope spider and the actual Laser Guide Star Facility launch telescope. The latter will be re-installed on the new M2-Unit. The M2 mirror surface is defined by the thin shell mirror of 1120mm diameter and 2mm thick and the reference body, both made of zerodur, which defines a reference surface for the back (concave side) of the thin shell. The reference body (manufactured by SESO, France) is a thick optical piece, lightweighted, with hole patterns to allow the passage of the 1170 voice coil actuators. These are mounted on the cold plate and apply forces on 1170 corresponding magnets glued on the thin shell back face. Metallic coatings on the shell back face and the front face of the reference body act as capacitive sensors used to measure the gap between both.

A description of the electro-mechanical testing and construction of the DSM can be found in [28].

3.2. Start of the DSM Optical Tests

The optical validation of the DSM took place on the ASSIST test bench delivered to ESO by the NOVA (Univ. of Leiden) consortium. The DSM has been installed on ASSIST in late January 2013. After a rough alignment, interferograms were obtained using a Phasecam 4020 (4D Technology) interferometer in an on-axis configuration. This triggered the start of the optical tests of the DSM.

Quickly the optical quality of the DSM was improved down to 56 nm RMS surface.

Although the Phasecam interferometer allowed msec acquisition time, the calibration was made difficult by convection within the ASSIST tower, and temperature variations. Sophisticated algorithms were implemented to try mitigating these perturbations. Note as well that several actuators were not visible from the interferometer as being either behind the central obstruction or behind the spider holding the ASSIST secondary mirror. These features required more time to clearly understand the impact and implement solutions.

To summarize the optical tests and main specification of the system, it was demonstrated that the RMS surface error of the DSM after corrections with its 1170 own actuators can reach a 18 nm RMS figure. Note that a 31 nm RMS value had to be removed from the measurements to take into account the ASSIST 1.7 m mirror surface error.

The remaining issues still being assessed are that forces needed on the actuators to reach this value exceeds the specification of less than 0.1 N (~0.25N). The other concern is a strong trefoil term being introduced by temperature variations of the cooling fluid. This term constitutes a substantial fraction of the operating gap and a solution needs to be identified to control this effect.

Final results of the optical calibration campaign are described in [27].

3.3. The Spare Thin Shell Mirror

The first thin shell has been manufactured by REOSC (France). The convex face is polished to the nominal M2 optical prescription and then the optical piece is thinned to the 2mm nominal thickness. The defects on the convex shape can be easily corrected if they represent low order deformations. A computer program has been developed by Osservatorio Astrofisico di Arcetri in order to assess the forces required to obtain the M2 nominal prescription figure from the actual convex shape. The specification to be fulfilled by the optical supplier is then to provide a convex face that requires less than 0.1 Newton (10% of full range) to bring the shell to the 8 nm RMS surface error.

The first science shell reached the specified quality requirement: the convex shape could be brought to 8 nm RMS surface error by correcting ~800 modes and this required ~0.1 Newton. If all the 1170 modes are corrected, the surface error is reduced further but higher forces are required.

The first science shell has been realized in specification and delivered to ADS in January 2012. The second science shell is nearing completion with an expected delivery of end 2013. The results of the convex shape figuring are at hand and are spectacular. The full PV error amounts to 1.1 μm and the simulated shape after correction show outstanding results. The right hand side shows a simulation of the surface error after correction by “n” modes; one can see that 10 nm RMS surface can be reached by correcting ~50 modes while the ultimate surface quality goes down to a mere 3 nm RMS. Note that even at this extreme value, the forces used are still below the limit of 0.1 N (10% of full stroke).

The thinning process of this second shell is progressing well the shell being now at the nominal 2.00mm thickness and efforts are now concentrating on reducing residual focus and wedge term with smaller tool. When done the final polishing will conclude the manufacturing. Acceptance is planned for November 2013.

4. The GRAAL and GALACSI Adaptive Optics Modules

The integration of the GRAAL adaptive optics module in the integration hall at ESO is nearly completed. After finalizing the alignment of the module with ASSIST and the DSM the system test of the on-axis natural guide star mode will start.

The module has received all its opto-mechanical components and is populated with the final WFS cameras. The last ones will be integrated in the course of 2014 but 3 are integrated and allow the start of the system tests. The co-rotator to follow the LGS rotation has been fully validated. The control software is operational and the technical templates to perform calibration or tests are routinely used; they will be finalized to provide tools for the needed calibration at the observatory.

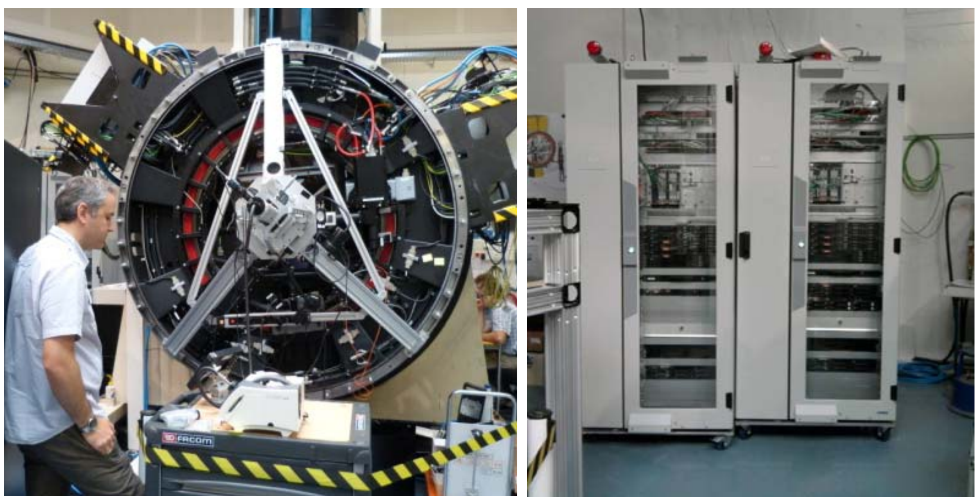

Figure 2: GRAAL module in alignment configuration on the left; that is with the tripod rig defining the Nasmyth optical axis. On the right, the two SPARTA real time computer cabinets for GRAAL and GALACSI. They contain the fast internet switches, the real time box (VME rack with COTS) and the CPU’s (DELL servers) for off-line processing. Both hardware are identical (but running different SW’s developed for GALACSI and GRAAL.

The SPARTA real-time computer cabinet is also completed. All functionalities have been implemented for the on-axis natural guide star mode and the adaptive optics loop can be closed when needed. The SPARTA real-time computer already provides reading of the WFS camera images and has been used to finalized optical alignment. See [5] for a description of the GRAAL adaptive optics module.

GALACSI integration is progressing slightly slower since efforts focus on GRAAL. One LGS WFS camera and one tip-tilt camera have been integrated in GALACSI’s module. These allowed the calibration of the pointing model of the visible field selector and of the focus compensating unit (for LGS paths).

Note that the laser jitter loop mirror loop has been closed on GALACSI which validate the whole chain of control by SPARTA: WFS camera image readout, slopes calculation, command matrix multiply, modes extraction (high order to DM and tip-tilt to jitter mirror).

5. The Four Laser Guide Star Facility

5.1. The Sodium Fiber Laser

The AOF will use four 20 Watt fiber lasers to create artificial guide stars for the adaptive optics modules. TOPTICA (Germany) is the main contractor and collaborate with MPB (Canada) in charge of developing the infrared high power fiber laser. The power delivered by the laser amounts to 22.2 Watt distributed in 18 Watt in the main NaD2a line and 2.1 Watt in the NaD2b line (note that 2.1 Watts is also distributed in the counterpart of the NaD2b line, symmetrical in wavelength with respect to the D2a line).

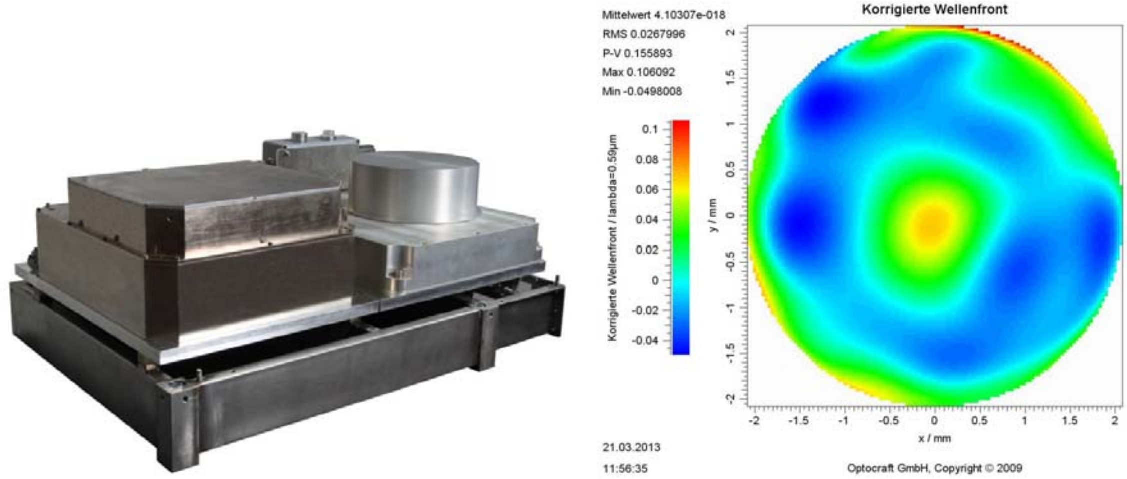

Figure 3: Left, the laser head pre-production unit; with the insulation cover (not shown here) the full size is 900 mm x 700 mm x 385 mm and the assembly weighs 80 kg. Right: the laser serial unit#1 output beam optical quality. The color scheme ranges from -0.04 to +0.1 lamba (@ 0.59 μm). The beam quality amounts to 26.7 nm RMS well below the specified 70 nm RMS, close to the goal set at 25 nm.

The first laser unit, an improved version of the pre-production unit, underwent detailed tests and results meet the specifications. The delivery of this unit to Garching is scheduled for November 2013 where the unit will be tested by ESO staff and interfaced with the launched telescope. Figure 3 shows the spectacular beam quality obtained on this unit. Note that all key specifications have been tested at relevant environmental conditions.

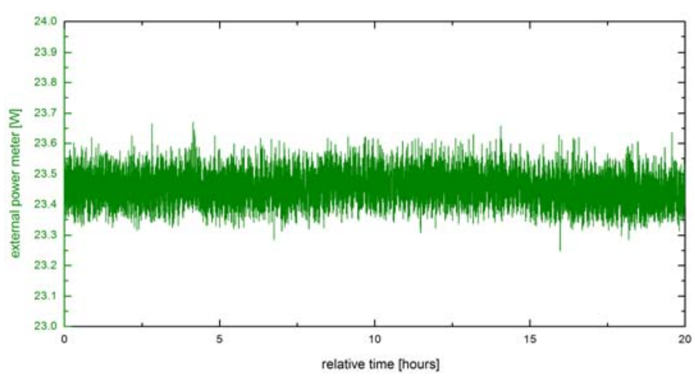

Figure 4: The output power stability tested over some 20 hours; < 1.5% PtP variations.

5.2. The Launch Telescope System

The Launch Telescope Assembly has been put together in Garching and is ready to receive the first laser unit. A dummy laser simulator has been installed having same CoG and weight and providing an alignment beam for the Beam Control Diagnostic System and Optical Tube Assembly. The setup is mounted on a tilt table allowing measurements of optical beam quality and flexures (beam deflection) with inclination angle.

The complete rig is compact enough to be inserted into Garching cold chamber to perform temperature tests and transients. It is shown on Figure 5.

Preliminary results are encouraging and show an excellent behavior of the complete system. These tests revealed a small change of focus versus temperature which will be used as calibration for the Beam Expander Unit inside the Beam Control Diagnostic System to compensate this effect.

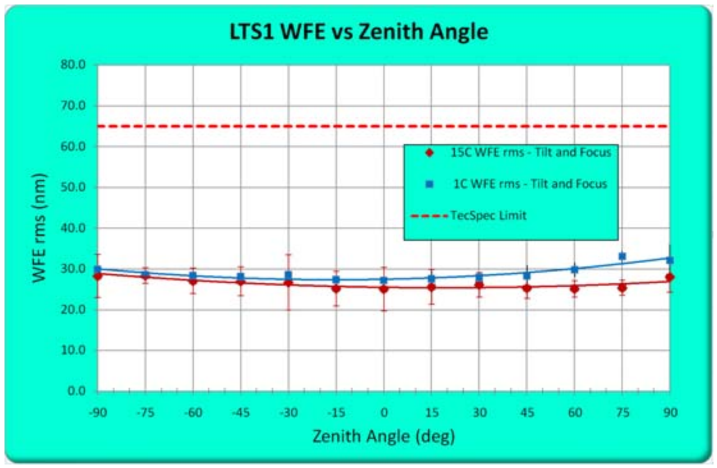

Figure 5: The Launch Telescope Assembly being tested in ESO cold chamber. The system is in horizon pointing inclination and fed with a “dummy” Laser to define the optical axis and characterize optical quality of the beam versus inclination and temperature. Right: The WFE RMS of the launch telescope system (including Beam Control Diagnosis System and Optical Tube Assembly) versus temperature and inclination. The quality remains well below the specified 65 nm RMS in all conditions.

6. The Preparation of the VLT Unit#4 Telescope

A first intervention on UT4 took place in March-April 2012 to install all the mechanical interfaces for the 4LGSF, upgrade the cooling capacity of the telescope for the AOF and other modifications (altitude cable wrap increased capacity on on Nasmyth focus, complete network fiber connections, accommodations for receiving the SPARTA cabinets in the bodega (basement) and others. The telescope has been recommissioned following this intervention and the results of the tests conducted showed an adequate behavior, comparable to the status before the intervention.

A second intervention is conducted as these lines are written and aims at completing the installation: an additional platform under Nasmyth B has been installed to receive the 4LGSF heat exchanger and electronic cabinets, an extension to the Nasmyth B platform has been implemented to allow more space for MUSE-GALACSI electronic cabinets, cooling implementation (started in first intervention) is being completed and the altitude cable wrap of the Nasmyth A is being upgraded to increase its capacity as was done for the opposite one.

Following completion a test will be conducted to ensure that the telescope unit 4 performs as well as previously. Note that we don’t expect any issue since the mass added to the telescope for this second intervention is negligible in comparison to the first intervention.

7. On-Line Parameters

The AOF real-time computers of GRAAL and GALACSI will allow some on-line processing to be carried on the recorded parameters namely the mirror commands and WFS residual signals. Algorithms have been developed or adapted to deliver useful information to the astronomer while observations are being acquired. For the selection of GRAAL or GALACSI a relevant parameter is the C_n^2 profile or distribution of turbulence in the atmosphere. It turns out that systems like GRAAL or GALACSI, designed to probe the atmospheric turbulence in several directions are ideal tool to reconstruct the turbulence profile by tomography.

In Open Loop, the slopes measured in the 4 directions of observation (on the 4 LGS WFSs) can be used to feed a turbulence profiler algorithm. Similarly in Closed Loop, the DM commands can be multiplied by the Interaction Matrix and added to the slopes residuals to provide the Pseudo-Open Loop slopes, which can then be used in the same fashion.

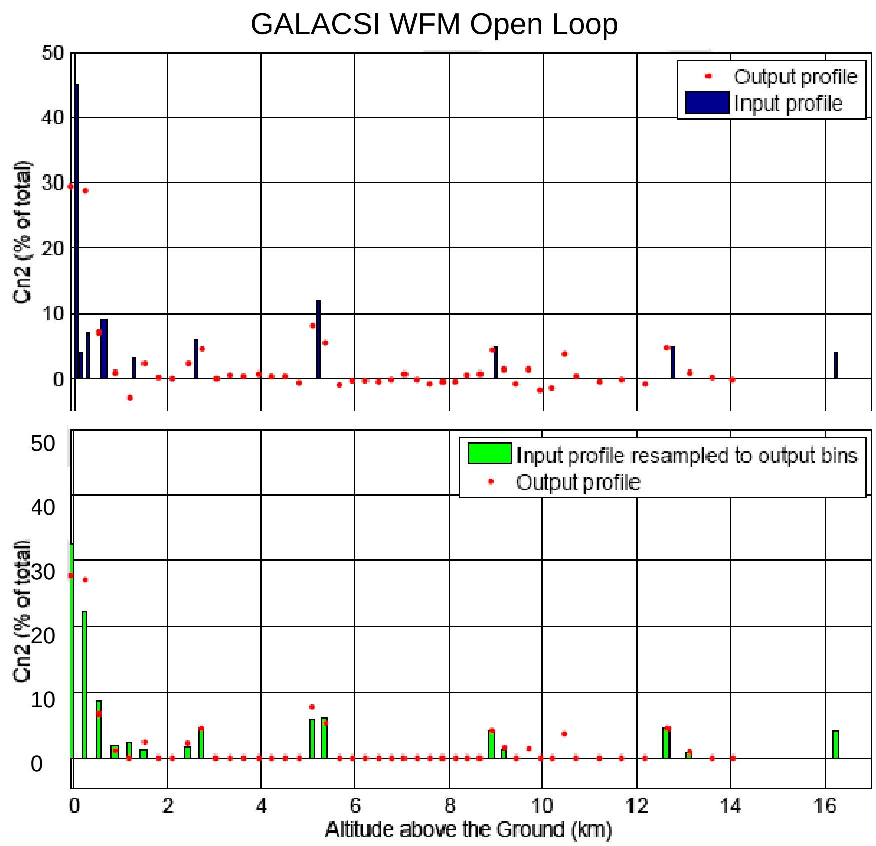

Figure 6: Example profile reconstructed from GALACSI WFM Open Loop data. Top: Raw input and output profiles. Bottom: Input profile resampled to the output bins and ouput profile filtered for 1 sigma of the noise.

Two Cn2 profiler algorithms have been developed in the framework of the GeMS MCAO instrument for the Gemini South telescope. Their concept is based on [23], they are presented in detail in [24]. The algorithm has been kindly provided to ESO by Gemini and PUC (Pontificia Universidad Católica de Chile) teams. After a phase of analysis, only the so-called “wind-profiler” algorithm was retained. The reason for this choice was the better robustness of the algorithm especially with respect to probing high altitude bins. The code has been adapted to the AOF case to account for its geometry and to provide the desired outputs in a Matlab structure.
The algorithm has then been tested on AO telemetry data produced by the ESO AO simulation tool Octopus in AOF configuration. The most important conclusion is that the profiler manages to identify the turbulent layers with an excellent accuracy in Open Loop whether there is only one layer, several in groups, or a real profile. The amount of turbulence at a given altitude is reconstructed with an accuracy better than 0.5% rms of the absolute value.

In Closed Loop, the profiler is applied to Pseudo Open Loop data: due to the reconstruction mechanism (addition of the DM contribution to the residual WFSs measurements), the contribution of the First layer is overestimated. This overestimation increases when the Guide Stars get closer (from GRAAL to GALACSI WFM and then to GALACSI NFM).
Tests of calibration strategy and algorithms have been conducted on the MAD test bench in Garching and results are presented in [26].

8. Conclusions

The AOF project is finalizing its integration and entering into a phase of system tests.

Several major milestones have been reached in the course of 2012 with the acceptance of the ASSIST test bench and the delivery of the DSM to ESO. The laser pre-production unit validated the expected performances for the laser and the first unit will be delivered to ESO in the fall 2013. The UT4 infrastructure upgrade is completed and thus the telescope interfaces are fully compatible with the AOF. The only exception to this is the back focal length increase for MUSE and GALACSI which will be done in October 2013.

The year 2014 will be dedicated to the system tests phase in Garching of the adaptive optics modules and DSM installed on the ASSIST bench.

End of 2014 the first AOF sub-systems will be shipped to Paranal for installation on the telescope. It is only in the course of 2015 that the system test phase will be completed in Garching and that the commissioning in Paranal will get into full swing. This effort is expected to last throughout 2016.

9. References

1. Arsenault, R., Madec, P.-Y., Hubin, N., et al., “Manufacturing of the ESO Adaptive Optics Facility”, Proc. SPIE 7736, 20 (2010).

2. Arsenault, R., Madec, P.-Y., Hubin, N., et al., “ESO Adaptive Optics Facility”, Proc. SPIE 7015, 75 (2008).

3. Arsenault, R., Biasi, R., Gallieni, D., et al., “A Deformable Secondary Mirror for the VLT”, Proc. SPIE 6272, 29 (2006).

4. Stroebele, S., La Penna, P., Arsenault, R., et al.,”GALACSI System Design”, Proc. SPIE 8447, 115 (2012)

5. Paufique, J., Arsenault, R., Madec, P.-Y., et al., “Status of the GRAAL system development: very wide-field correction with 4 laser guide-stars”, Proc. SPIE 8447, 116 (2012).

6. Catalan, A., Casalta Escuer, J.M., Paufique, J., “VLT GRAAL main assembly instrument design, manufacturing, integration, and test”, Proc. SPIE 8447, 117 (2012).

7. Stuik, R., La Penna, P., Dupuy, C., et al., “Deploying the testbed for the VLT adaptive optics facility: ASSIST”, Proc. SPIE 8447, 118 (2012).

8. Biasi, R., Andrighettoni, M., Angerer, G., et al., “VLT deformable secondary mirror: integration and electromechanical tests results”, Proc. SPIE 8447, 88 (2012).

9. Kuntschner, H., Amico, P., Kolb, J., et al., “Operational concept of the VLT’s adaptive optics facility and its instruments”, Proc. SPIE 8448, 07 (2012).

10. Kolb, J., Martinez, P., Girard, J.H.V, “What can be retrieved from adaptive optics real-time data?”, Proc. SPIE 8447, 219 (2012).

11. Kolb, J., Le Louarn, M., Muller, N., et al., “Calibration strategy of the AOF”, Proc. SPIE 8447, 85 (2012)

12. Villecroze, R., Fusco, T., Bacon, R.M., et al., “PSF reconstruction for wide field AO systems: application to the GALACSIMUSE instrument on the VLT”, Proc. SPIE 8447, 221 (2012).

13. Holzlöhner, R., Rochester, S.M., Bonaccini Calia, D., et al., “Simulations of pulsed sodium laser guide stars: an overview”, Proc. SPIE 8447, 17 (2012).

14. Bonaccini Calia, D., Guidolin, I.M., Friedenauer, A., et al., “The ESO transportable laser guide star unit for on sky measurementsof LGS photon return and other experiments”, Proc. SPIE 8447, 61 (2012).

15. Dupuy, C., Pfrommer, T., Bonaccini Calia, D., “4DAD, a device to align angularly and laterally a high-power laser using a conventional sighting telescope as metrology”, Proc. SPIE 8450, 196 (2012).

16. Poutriquet, F., Rinchet, A., Carel, J.-L., et al., “Manufacturing of glassy thin shell for adaptive optics: results achieved”, Proc. SPIE 8447, 89 (2012).

17. Friedenauer, A., Ernstberger, B., Kaenders, W.G., et al., “RFA-based 589-nm guide star lasers for ESO VLT: a paradigm shift in performance, operational simplicity, reliability and maintenance“, Proc. SPIE 8447, 15 (2012).

18. Reyes Moreno, J., Downing, M., Conzelmann, M.D., et al., ” An overview of the ESO adaptive optics wavefront sensing camera” , Proc. SPIE 8447, 237 (2012)

19. Feautrier, P., Gach, J.-L., Downing, M., et al., “Advances in detector technologies for visible and infrared wavefront sensing”, Proc. SPIE 8447, 26 (2012)

20. Arsenault, R., Madec, P.-Y., Hubin, N., et al., “Manufacturing of the ESO Adaptive Optics Facility”, Proc. SPIE 7736, 20 (2010).

21. Arsenault, R., Madec, P.-Y., Paufique, J., et al., “ESO Adaptivve Optics Facility Progress Report”, Proc. SPIE 8447, 0J (2012).

22. Arsenault, R., Vernet, E., Madec, P.-Y. , et al., “Delivery of the Second Generation VLT Secondary Mirror (M2) Unit to ESO“, ESO Messenger No.151 – March 2013, p.14-19

23. Briguglio, R., Xompero, M., Riccardi, A., et al., “Optical calibration and test of the VLT Deformable Secondary Mirror”, AO4ELT 3rd Conference No. 13507, May 2013

24. Wang, Schöck, Chanan, “Atmospheric turbulence profiling with slodar using ultiple adaptive optics wavefront sensors”, Applied Optics, Vol. 47, Issue 11, pp. 1880-1892, (2008)

25. Cortes, A., “Atmospheric turbulence profiling using multiple laser star wavefront sensors”, MNRAS, 427: 2089-2099, (2012)

26. Muller, N., Kolb, J., Tordo, S., et al., “Validation of the AOF calibration strategy on the MAD bench”, This Conference, Poster N:13215, (2013)

27. Briguglio, R., Xompero, M., Riccardi, A., et al., “Optical calibration and test of the VLT Deformable Secondary Mirror”, This Conference, Oral N:13507, (2013)

28. Gallieni, D., Biasi, R., “The new VLT-DSM M2 unit: construction and electro-mechanical testing”, This Conference, Oral N:17883, (2013)