Adaptive Optics Facility Status Report: When First Light Is Produced Rather Than Captured

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First light for the 4 Laser Guide Star Facility (4LGSF) took place in Paranal on 26 April 2016 with four laser units in operation for the first time. A combined test with the first laser guide star unit and the Ground Layer Adaptive optics Assisted by Lasers (GRAAL) instrument in October 2015 demonstrated the whole acquisition sequence of the Adaptive Optics Facility (AOF). Many tools that will support the operation of the AOF for science observations have meanwhile been implemented. GALACSI was granted Provisional Acceptance in Europe in April 2016, completing the system tests and qualification in Garching of the adaptive optics modules GRAAL and GALACSI (Ground Atmospheric Layer Adaptive Optics for Spectroscopic Imaging), their real-time computers and the deformable secondary mirror (DSM). Results of tests both in the laboratory and on sky are presented. The installation of the DSM and GALACSI will be completed by early 2017, to be followed by commissioning of all AOF systems.

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Chronicle of recent AOF activities

The Adaptive Optics Facility (Arsenault et al., 2010; 2014) is a long-term project on the Very Large Telescope, Unit 4 (UT4) to provide the adaptive optics systems for the two UT4 instruments MUSE (the Multi Unit Spectroscopic Explorer), fed by GALACSI, and the High Acuity Wide field *K*-band Imager (HAWK-I), fed by GRAAL with a four sodium laser guide star system. After years of planning, construction and testing, with the completion of reviews for Provisional Acceptance Europe (PAE) of AOF modules in the course of 2015, activities are now shifting to Paranal.

The first laser guide star unit (LGSU#1) was installed and tested on UT4 in 2015, with first light in April 2015, and the three other units were then completed. The LGSU#1 commissioning was completed in August 2015 and the unit showed excellent performance. It confirmed the good design choices and validated all the interfaces with UT4. PAE for the 4LGSF system was granted at the end of 2015 and in January 2016 the three remaining LGSUs were re-integrated in Paranal and installed on UT4. On 26 April 2016 first light for the 4LGSF took place (see cover image and Release eso1613) and the commissioning of the 4LGSF in stand-alone mode could begin.

In the meantime, a two-year-long system testing phase was concluded in Garching (February 2016). The adaptive optics (AO) modules GRAAL and GALACSI were mounted in that order on the ASSIST (Adaptive Secondary Setup and Instrument Simulator) test bench and tested in realistic conditions. GRAAL tests were completed in early 2015 and GRAAL's PAE was granted in April 2015. Then the system was prepared for shipment and re-integrated in Paranal in June. This provided a unique opportunity in October 2015 to undertake a combined commissioning run with LGSU#1 and GRAAL, allowing many aspects of the acquisition sequence of the AOF on the telescope to be debugged and tested under real conditions. This evaluation was very instructive and useful to the project and again validated many design choices.

Then the GALACSI module was installed on ASSIST and tests continued. By autumn 2015, the tests in the MUSE wide-field mode configuration were completed and a start could be made with tests of the MUSE narrow-field mode. These were completed in February 2016 and the PAE for GALACSI was granted in April.

In parallel, many tools required to optimise the operation of the AOF have been developed, ranging from new versions of the GuideCam tool and the observing tool to the delivery of the laser traffic control software and the complete refurbishment of the astronomical site monitor. Most of these tools are now operational. The commissioning period of the AOF itself will ensure a final integration of these tools into the operational scheme of the AOF. All these tests have

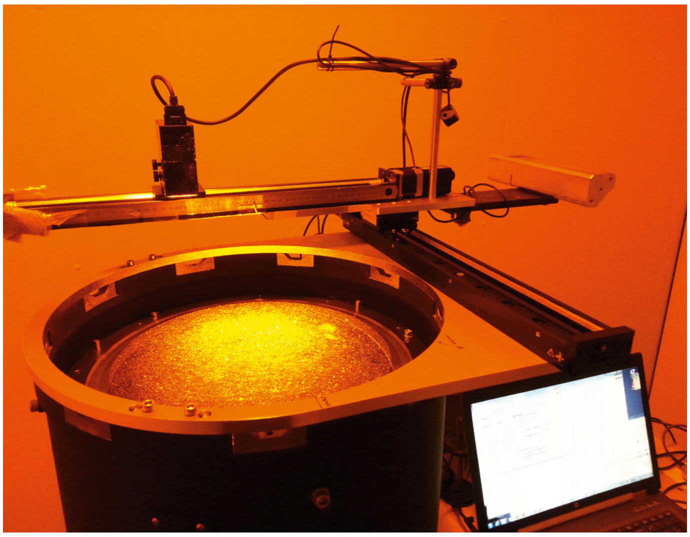

Figure 1. Characterisation of the beam profile from the optical tube assembly shown in the Garching cold chamber, after integration with the beam control diagnostic system and the laser.

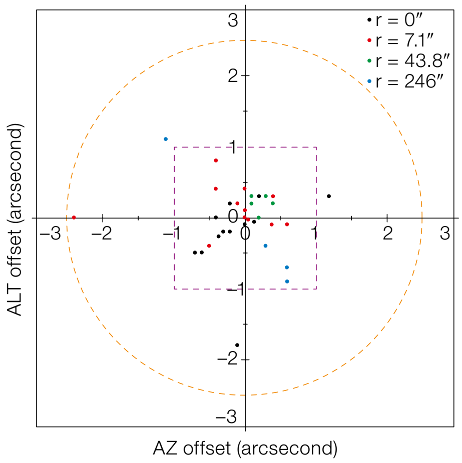

Figure 2. Accuracy of the pointing of the laser guide stars (LGSU#1). The red circle is the requirement. The final performance is better than the requirements by a factor of two, ensuring a short acquisition time for the AOF and a small overhead with respect to observation without laser guide star. Symbol colour indicates pointing angle from telescope optical axis.

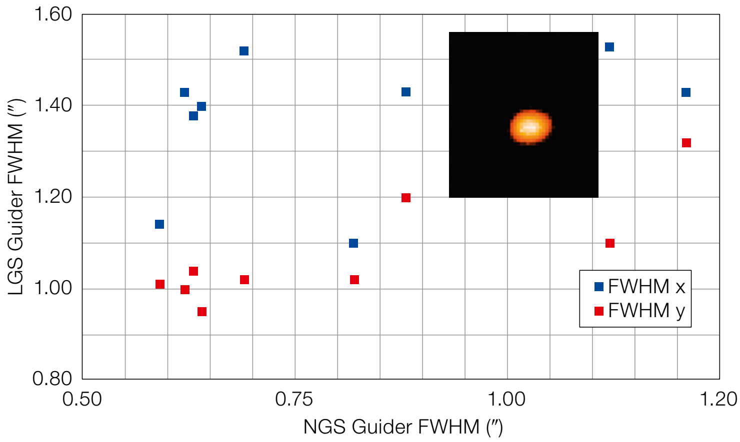

Figure 3. The laser guide star spot size versus the natural guide star (NGS) image full width half maximum (FWHM) measured by the telescope guider. The two values of FWHM are plotted separately.

demonstrated full compliance of the AOF systems with their specification and the desired performance has been reached and clearly demonstrated.

Throughout the AOF review process, and the system testing and installations in Paranal, the project has placed strong emphasis on training our Chilean colleagues. Many trips and exchanges took place between Garching and Paranal. This spirit of collaboration and enthusiasm will no doubt ensure that the astronomical community receives expert support for the AOF systems and effective maintenance and optimisation of its performance will take place.

4LGSF highlights

The 4LGSF subsystem of the AOF has demanded a substantial effort in terms of manpower, finance and contract supervision. The engineering systems expertise within the AOF/4LGSF project has ensured an efficient overview of the numerous state-of-the-art components composing this facility (Hackenberg et al., 2014).

There are five key specifications of the lasers that represented real challenges in the early years of the AOF project. These were:

1. High power output: 22 watt;
2. Pointing accuracy of the laser spot: < 5 arcseconds peak-to-valley;
3. Laser spot size: < 1.35 arcseconds for 1-arcsecond seeing (30° from zenith);
4. Return flux of 5×10^6 photons m^{-2} sec^{-1} at the UT4 Nasmyth focus (for average sodium density of 4×10^{13} m^{-2});
5. Reliability and robustness.

The power figure was reached early in the development phase and did not represent a major issue for the TOPTICA/MPB consortium in charge of delivering the five laser units (four plus one spare). The robust and simple laser design ensured the stable behaviour of the laser output power during its development and all the test phases in Garching, and today at the telescope. The most impressive demonstration was the reception of the first laser unit in Garching; after unloading from the truck transport (TOPTICA headquarters are 35 kilometres from Garching), rolling off into the ESO laboratory, making the connections and switching on, the power meter unflinchingly showed a remarkable and stable dead-on 22-watt output! This speaks for the laser's robustness, which was always considered an important feature for a system that was to be operated in an observatory environment. Also the numerous systems in operation on the AOF require a long mean time between failure in order to fulfil the requirement of high night-time availability.

The pointing accuracy was also a difficult requirement; one must remember that the operational optical quality for all 4LGSF optics is in the diffraction regime. This demands high optical quality from the components, careful alignment, stable and rigid systems to maintain alignment and careful engineering to control the pointing. The system met the specification in the laboratory in Garching with no margin. At this stage the project decided to implement a laser pointing camera (Bonaccini Calia et al., 2014), which would relieve this specification somewhat. The laser pointing camera is a small unit mounted on the telescope top ring that identifies the laser star, determines its position with respect to the telescope axis and updates the laser pointing if it is too far off. This system was delivered by the Rome Observatory and its implementation has been very successful (see Figure 2).

The laser spot size is also within specification and is evidence for the stable and excellent image quality of both the laser beam control diagnostic system and the optical telescope assembly. Figure 1 shows the characterisation of the beam profile in the Garching cold chamber after integration with the beam control diagnostic system and the laser.

In early 2008, when the laser call for tender was launched, the interaction between the laser beam and the atomic fine structure of the sodium atoms was not so well understood, strange as this may seem in hindsight. Coordinated efforts between the ESO laser and atomic physics community helped to improve this situation (Holzlöhner et al., 2008; 2010; 2012). These efforts have been largely successful as the spectral format prescribed has delivered the desired outcome. It was decided to specify to the laser supplier to inject 20 watts into the main Na D_{2a} line and 10 % of this power

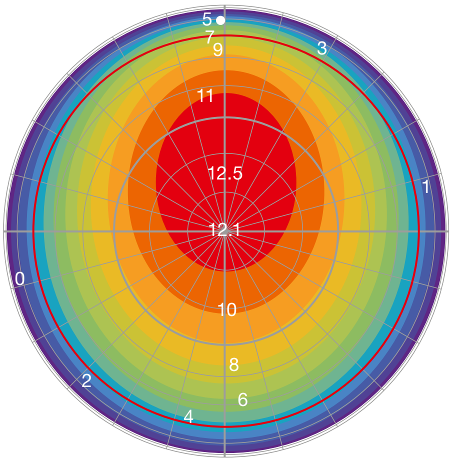

Figure 4. Simulation of the expected return flux (for a simulated laser flux of 16 watt) plotted over the sky. The variation across the hemisphere is due to the interaction between the beam polarisation and the Earth's magnetic field; the maximum occurs towards the south magnetic pole. Measured values range between about 10 and 20 × 10^6 photon m^{-2} s^{-1} (laser is actually 22 watt not 16) and follow well the distribution simulated across the hemisphere.

in the Na D_{2b} line. This should prevent the sodium atoms from recombining in a state where the main Na D_{2a} laser line can no longer excite the atoms. The result is an improved return flux.

The first on-sky results of return flux are very encouraging, but the final assessment will only be made after a complete year of monitoring to cover the full range of seasonal variations of the density of the atmospheric sodium layer (Figure 4).

GRAAL-LGSU#1 combined tests

The GRAAL module (Arsenault et al., 2014; Paufique et al., 2012) serves the HAWK-I imager and provides a ground layer correction over the 7.5 × 7.5 arcminute field of view of HAWK-I. It also provides an option called maintenance and commissioning mode, featuring on-axis natural guide star adaptive optics. This mode allows the 1170 degrees of freedom of the DSM to be fully exploited and aims at testing and validating the correction capability of the mirror.

The installation of GRAAL on UT4 took place in June 2015 (Figure 6) and the combined commissioning with LGSU#1 in October 2015. Obviously, no adaptive optics verification could be done in October 2015 without the DSM. However, many loops and offload schemes could be tested and the LGSU#1 could be acquired on one wavefront sensor and the tip-tilt star selection tested. This allowed many steps to be executed under real conditions and offered reassurance as to the estimated acquisition overhead, which had already been tested on ASSIST in Garching. With all the loops closing (except the main adaptive optics loop with the DSM), the overhead was always found to be less than four minutes (requirement five minutes). The jitter loop on one laser was closed on this occasion: the jitter mirror in the LGSU#1 was controlled by the GRAAL laser guide star wavefront sensor to reduce the tip-tilt of the laser spot caused by telescope shake.

The pupil alignment on the wavefront sensor was, however, found to become decentred by more than we had predicted. This misalignment arises from a combination of factors including telescope misalignment, but also from the co-rotator (inside GRAAL) and the Nasmyth co-rotator. However, simulations and tests on ASSIST (with GALACSI, see Figure 7) convinced us that this could be handled by the scheme of regular command matrix updates.

The GuideCam tool was used for tip-tilt star selection, and the laser traffic control software proved very useful to predict and prevent laser collisions with other telescope beams. The most frequent collisions were experienced with the Visible and Infrared Survey Telescope for Astronomy (VISTA), the VLT Survey Telescope (VST) and the Auxiliary Telescopes (ATs).

GALACSI performance

As for the GRAAL module, the tests of the GALACSI module (La Penna et al., 2014) on ASSIST clearly demonstrated that it fulfils the system specifications. The performance requirements for the GALACSI wide-field mode is to increase the received energy per pixel by a factor of two, over the 60 × 60 arcsecond MUSE field of view at 750 nm wavelength and for 1.1-arcsecond seeing. This is defined for a given atmospheric refractive index structure parameter (C_n^2) distribution. This parameterisation was assumed

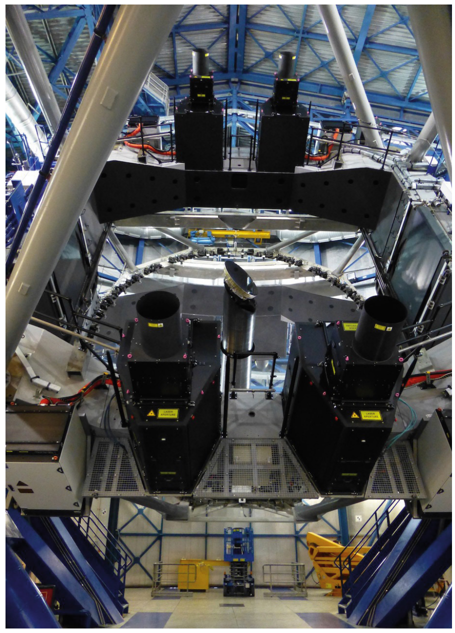

Figure 5. The four laser guide star units mounted on the UT4 centrepiece with their respective laser and instrument control cabinets.

early on in the GALACSI system simulations and the design concept was expected to provide the desired correction. This can clearly be seen in Figure 8.

The ASSIST test bench comprises only three discrete phase screens to simulate the continuous distribution of turbulence in the atmosphere. This number of phase screens and their relative importance are not fully representative of the specified C_n^2 profile. However, when the ASSIST distribution was simulated, we could reproduce the measured values of ensquared energy (dashed line on Figure 8) well. This convinced us that on sky with the specified C_n^2 profile, the GALACSI module would provide the required correction. With the specified atmosphere, simulations predict a factor of two in improvement in ensquared energy (EE) with 55 % turbulence in the first 500 metres above ground.

These tests were carried out relatively quickly as they implemented a similar algorithm to the GRAAL ground layer adaptive optics correction (Arsenault et al., 2013) and little surprise was expected. However, the GALACSI–MUSE narrow-field mode involved a new, complex algorithm for laser tomography. The complete

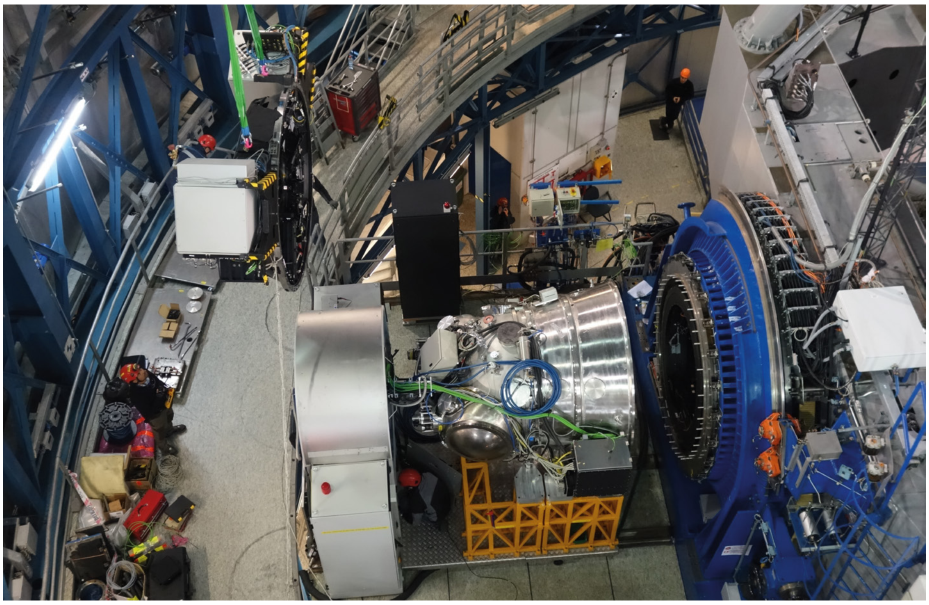

Figure 6. The GRAAL module being handled above the Nasmyth A platform of UT4 (top left of picture) before being sandwiched between HAWK-I and the Nasmyth flange.

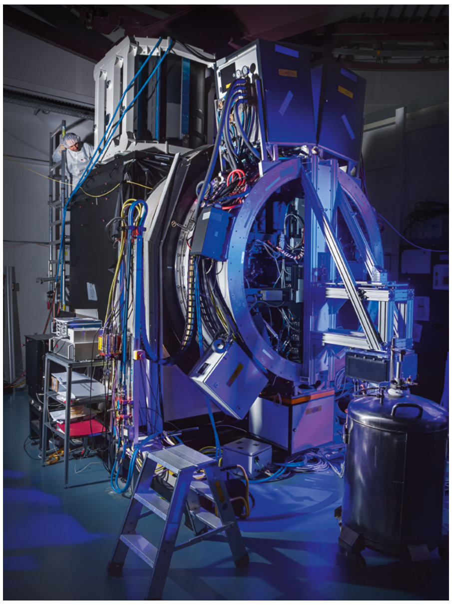

Figure 7. The GALACSI module mounted on the ASSIST test bench. A special rig has been produced to interface the IRLOS (InfraRed Low Order Sensor) used for tip-tilt and focus sensing with the MUSE narrow-field mode.

definition of the command matrix for this algorithm was defined by the ESO Adaptive Optics Group and performed beyond expectations. The main difficulty arose with the measurement of the Strehl ratio values in the visible. The specification called for a Strehl ratio of 5 % (goal 10 %) at 650 nm in a 5-arcsecond field of view and for 0.6-arcsecond seeing. One should not be misled by such "low" values of the Strehl ratio! This is a true challenge for adaptive optics due to the short wavelength (visible, 650 nm); it corresponds to a 77 % Strehl ratio at 2.2 μm and starts to approach planet-finder performance if the goal value is considered (82 % Strehl ratio at 2.2 μm).

Despite the challenges, the image improvement is indeed spectacular (see Figure 9) and measurements of the Strehl ratio confirm this impression. The tests performed on ASSIST also revealed a very robust algorithm. The correction also worked well in worse seeing conditions (using the 1.1-arcsecond seeing simulation) and was found to be stable. Besides, the correction appeared to be robust enough that the control matrix does not have to be modified when the turbulence profile evolves, which will certainly simplify operations.

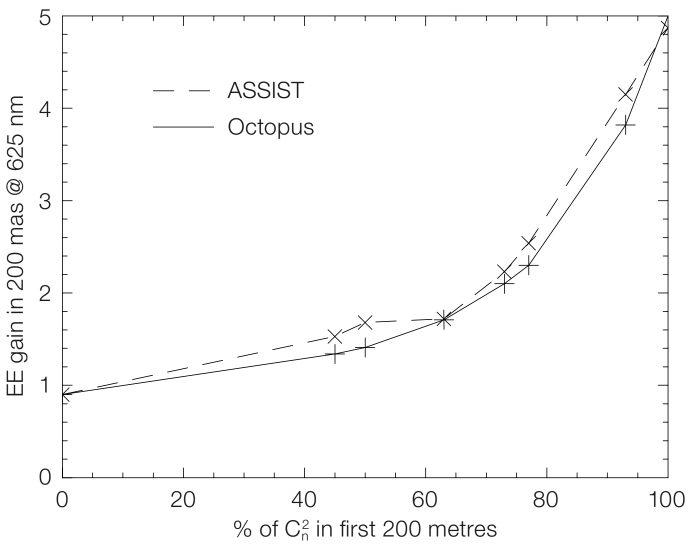

Figure 8. The evolution of the correction on ASSIST at 625 nm as a function of the fraction of turbulence in the ground layer (first 200 metres). The improvement starts getting substantial when more than 60 % of the turbulence lies below 200 metres altitude. Good agreement is seen between the simulation (solid line, Octopus) and the ASSIST measurements.

Benefits of the system tests

The choices for the design and construction of the ASSIST test bench (Stuik et al., 2012) were initially guided by the need to provide Microgate and ADS (the two companies in charge of delivering the new secondary mirror unit to ESO) with a tool allowing the final optical calibration of the DSM (Arsenault et al., 2013; Manetti et al., 2014 and Briguglio et al., 2014). At the end of the manufacturing process, each DSM capacitive sensor has to be optically calibrated, and the optical shell flattened to within 7.5 nm root mean square error. This requires an interferometric setup. Due to the convex shape of the DSM, this set-up ended up in a cumbersome 2 × 2 × 3 metre tower made of a 1.7-metre diameter aspherical primary mirror and a much smaller aspherical secondary mirror (see Figure 10).

It was thus decided to add, at the input of this tower, a simple source simulator and turbulence generator, and to design

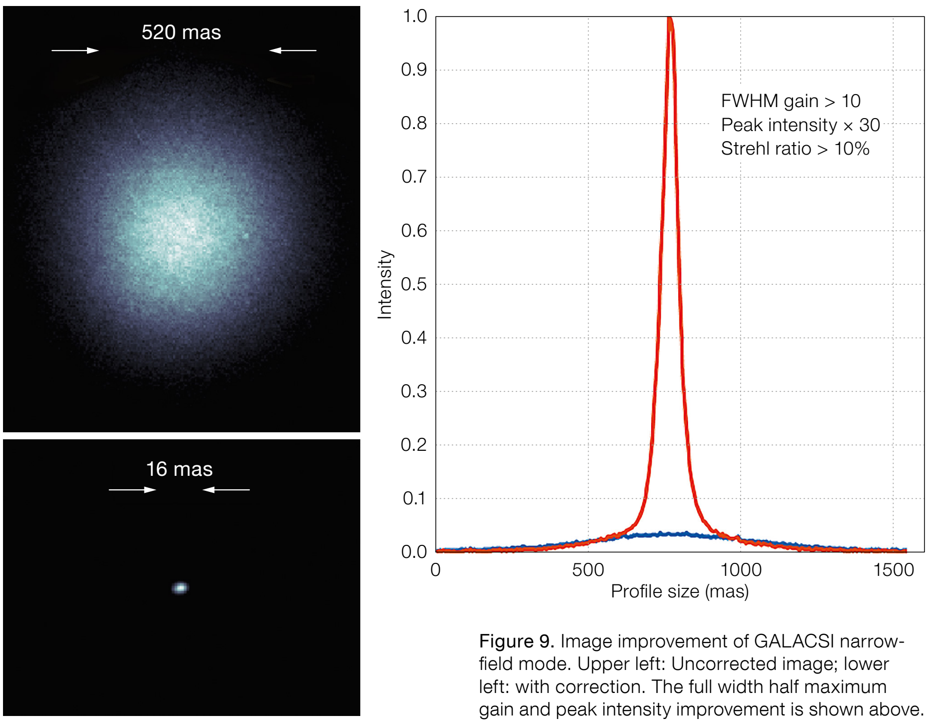

Figure 9. Image improvement of GALACSI narrow-field mode. Upper left: Uncorrected image; lower left: with correction. The full width half maximum gain and peak intensity improvement is shown above.

a VLT focus simulator to be located at the output of ASSIST. The complete ASSIST would then not only be able to achieve the last step of the DSM optical calibration but also to fully characterise GRAAL and GALACSI before going to Paranal. The nice optical design was provided by Bernard Delabre, and NOVA (University of Leiden) supplied the system and covered most of the costs and effort.

More than four months were necessary to complete the critical optical calibration of the DSM. During the two years of tests on ASSIST, several "birth defects" in the subsystems have been identified and corrected. Four months were spent on fixing two major failures of the new secondary mirror unit, time much more fruitfully and efficiently spent in the laboratory than on the telescope!

The ASSIST setup with the VLT control model allowed a configuration that was very close to that of the final telescope to be achieved. Therefore, substantial progress could be made on template coding and testing and on the software infrastructure. The complete acquisition sequence could be tested and optimised. Finally, ASSIST has offered a comfortable work environment with calibrated atmospheric turbulence, a situation much more stable and reproducible than on the telescope.

The AOF staff who have operated the system for these past two years in the laboratory have gained a superb knowledge and understanding of the system. No doubt unknowns, new issues and problems will surface once the system is operating on UT4, but the experience gained in Garching will prove invaluable in solving these efficiently. A number of Paranal staff have travelled to Garching and have been using the system to prepare them for the future operation and maintenance work at the observatory.

AOF operation tools and infrastructure

At the instigation of the AOF Scientist, many tools were put in place to optimise the AOF's operation. Many of them have been mentioned already. The GuideCam tool has been developed for GRAAL/HAWK-I to allow tip-tilt natural guide star selection. A similar version with some additional functionalities is being developed for GALACSI/MUSE as well.

The laser traffic control system (Amico et al., 2105) is a piece of software used to predict optical collisions between the powerful laser beams of the 4LGSF and the lines of sight of other telescopes on the mountain. It has been in operation for two observing periods and we have received very positive feedback from Science Operations in Paranal. A web interface displays the situation of all the telescopes on Cerro Paranal and predicts any collision with the AOF lasers. Priority rules are implemented and recommendations are made to the telescope operator. Alarms are triggered when a collision is imminent. The observing tool has also been updated by implementing a query system to the laser traffic control system to check whether an observing block risks a collision. This will serve observers during the night and help in the preparation and scheduling of observing blocks.

The AOF observing mode to select will depend on atmospheric conditions. To this end the astronomical site monitor went through three major improvements:

1. New atmospheric tools have been implemented; a multi-aperture scintillation sensor and a differential image motion monitor have been installed on a higher structure (7 metres above ground) so that they are less sensitive to the near-ground surface layer, which can cause a systematically more pessimistic reading of the seeing than the telescope guider. A new SLOpe Detection And Ranging instrument (SLODAR) has also been Paranalised and integrated into the astronomical site monitor infrastructure.
2. The database to store the readings of these new tools has been upgraded to include additional parameters. This database is also automatically replicated in Garching.
3. Finally, a new display tool has been developed and implemented. The standard setup has been chosen to faithfully replicate the previous look and feel, so that many users may not yet have noticed the difference. But this new display tool is very powerful and allows any user, through a login, to define his/her own preferred setting and parameters.

The astronomical site monitor will provide the turbulence distribution in the atmosphere, which will be a critical criterion for

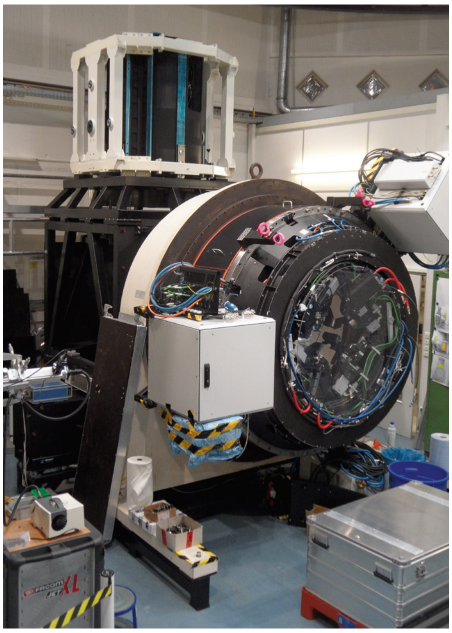

Figure 10. The GRAAL module on ASSIST with the DSM at the top during system tests in Garching.

observation mode scheduling (Kuntschner et al., 2012). The simple rule is:
- Good seeing 0.6 arcseconds and better implies GALACSI laser tomography adaptive optics and MUSE narrow-field mode;
- Worse seeing ~ 1 arcsecond and strong ground layer, 70 % below 500 metres, implies GALACSI ground larger adaptive optics and MUSE wide-field mode;
- Even worse seeing ~ 1 arcsecond and strong and very low ground layer (below 300 metres) implies GRAAL/HAWK-I;
- In all other conditions, seeing-limited operation (about 30 % of the time).

Science outlook

It is planned to first use the AOF in MUSE wide-field mode for science from mid-2017 onward. Other modes such as the narrow-field mode of MUSE and HAWK-I ground layer adaptive optics will follow in 2018. With the adaptive secondary mirror, all foci at UT4 can be provided with turbulence-corrected images, without the addition of adaptive modules and supplementary optics in front of the instruments. The concept is more far-reaching than only a deformable secondary mirror, since the instrument park is optimised to benefit from this upgrade. In 2020 a new instrument at the Cassegrain focus will follow (ERIS — Enhanced Resolution Imager and Spectrograph), which combines the use of the near-infrared integral field unit SINFONI and a diffraction-limited camera sensitive up to 5 µm. All UT4 instruments can make use of natural guide stars as well as up to four laser guide stars for wavefront sensing.

For MUSE's wide-field mode, the adaptive optics module GALACSI will concentrate the energy of the point spread function across the field of view, enabling more occasions with excellent seeing conditions in regular observing time to be available. MUSE's narrow-field mode opens up a new domain with Strehl conditions of > 5 % in the visible (650 nm), which facilitates science cases for very crowded field integral field spectroscopy, such as for the centres of galaxies and globular clusters.

HAWK-I with GRAAL is expected to provide about a factor of two improvement in the occurrence of good *J*-, *H*- and *K*-band images (< 0.4 arcseconds). Improvement is also expected for all seeing conditions, promising almost space-based observatory quality images in the near-infrared.

Next phases and milestones

Two main systems remain to be installed on the telescope. In October 2016 there will be a UT4 shutdown until December to install the new secondary mirror unit with the deformable secondary mirror. Then, the telescope will be re-validated in non-adaptive optics mode. In early January 2017, the GRAAL maintenance and commissioning mode will be used to validate the adaptive optics correction capability of the DSM, while GALACSI will be re-integrated and installed on UT4. This operation should be completed by March 2017.

The AOF team will then conduct regular commissioning runs throughout 2017 with the goal of delivering the GALACSI–MUSE wide-field mode for Observing Period 100. After this the project will focus on commissioning the GRAAL ground layer adaptive optics and GALACSI laser tomography adaptive optics modes.

Conclusions

The AOF has completed its activities in Garching and now the focus is shifting ever more to Paranal, completing the stand-alone 4LGSF commissioning and then moving on to the installation of the deformable secondary mirror on UT4 in the fourth quarter of this year. With this facility in place commissioning of GALACSI in wide-field mode can start, yielding the first science by mid-2017. HAWK-I/GRAAL narrow-field mode and MUSE's ground layer adaptive optics will follow in 2018. The suite of instruments is accompanied by a full set of operation tools and an upgrade of the astronomical site monitor, which will all support efficient operation of the AOF. The current progress and laboratory measurements within specification of the adaptive optics models for HAWK-I and MUSE establish high expectations for the onset of science observations from mid-2017.

Acknowledgements

The AOF project started at ESO in 2006; we thus celebrate its tenth anniversary this year! We are very grateful to all the team members who have been dedicated to this project since its beginning and for their hard work even in the difficult times of technical failures and challenges. Also, a great many people have contributed to the AOF for temporary support activities, or a review board panel; they are also warmly thanked for their contributions. We also very much appreciate all the functional managers and group leaders who have been helping to solve resource issues and conflicts during this long effort. The AOF has also greatly benefited from the expert support of its industrial partners, and we wish to thank here especially Microgate, ADS Intl., TOPTICA, MPB and SAFRAN Reosc.

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