GRAAL on-sky performance with the AOF

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1. ABSTRACT

GRAAL is the adaptive optics module feeding the wide-field IR imager HAWK-I at the VLT observatory. As part of the adaptive optics facility, GRAAL is equipped with 4 Laser-guide star wave-front sensors and provides a large field-of-view, ground layer correction system to HAWK-I. GRAAL is installed in Chile and undergoing commissioning. We report on the latest results with the module and the outlook before the operation start in 2018.

Keywords: VLT, AO, GLAO, GRAAL, HAWK-I, AOF, LGS, commissioning, Paranal

2. INTRODUCTION

We started commissioning the Ground layer adaptive optics assisted by Laser (GRAAL) in the Paranal observatory, on the fourth Unit telescope UT4 with its associated instrument, HAWK-I. GRAAL has been used to perform the re-commissioning of the telescope after installation of the deformable secondary mirror (DSM), as well as the verification of the Laser guide star facility (4LGSF). After testing the DSM in adaptive optics mode, we started commissioning activities of the new HAWK-I facility with the adaptive telescope early 2017.

3. GRAAL AND THE AOF

GRAAL feeds HAWK-I, an 8-m class, NIR wide-field instrument (7.5x7.5 arcmin^2). The adaptive module is a part of the Adaptive optics facility project (AOF). This project aims at specializing one of the VLT Unit Telescope (UT4) into a high resolution, versatile adaptive optics tool, serving different instruments matching the capability of the adaptive telescope. Many of its components and operational strategies help ESO foster experience and hands-on before the construction of the ELT reaches its final stages.

The most important changes to the UT architecture are:

- the replacement of the M2-Unit by a new one hosting a 1170 actuators deformable secondary mirror (DSM),
- the addition of 4 Laser guide star units (LGS) to provide artificial sources in any direction on-sky above 30° altitude, and
- the development of GRAAL and GALACSI, two adaptive optics modules able to control the DSM and to improve the image quality for their respective instruments, HAWK-I[i] and MUSE[ii]. While GRAAL is optimised for a large NIR field of view, GALACSI is similarly optimised for a smaller, visible wavelength, field of view.

Key constraints we had in the framework of adaptive telescopes are:

- highly automated operation of the adaptive optics
- outstanding reliability of the components, especially Laser with respect to the previous generations
- decreased maintenance effort with a better monitoring and preventive maintenance

4. GRAAL DESCRIPTION

GRAAL uses 4 LGS and one tip-tilt sensor to perform the corrections required for HAWK-I. It also contains a maintenance and commissioning mode (MCM), where an NGS is used to control the DSM and including a diffraction-limit reimaging optics, avoiding the additional complexity of the Laser, when one wishes to troubleshoot the deformable secondary mirror for instance.

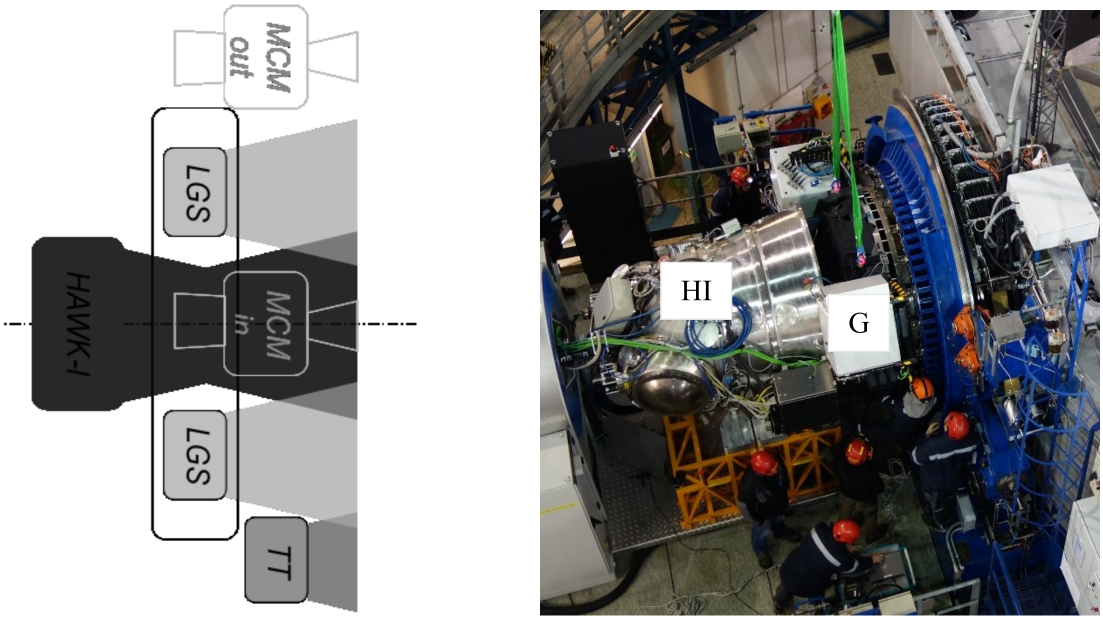

Figure 1: Left: schematic opto-mechanics view of GRAAL. The scientific field is transmitted directly from the telescope to the instrument. LGS and TT pick-up are located such as to avoid shadowing other optics. MCM optics are moved in the field when in use. Right: GRAAL and HAWK-I on the Nasmyth platform. G: GRAAL, during handling, right before being connected to UT4. HI: HAWK-I instrument, in its maintenance position, retracted from the TR.

HAWK-I mode

This is the operational mode of HAWK-I. 4 LGS are projected on a 6 arcmin radius annulus. Ground-layer turbulence is estimated from these guide-stars. The LGS constellation moves with the pupil, while GRAAL is bolted to HAWK-I, and therefore rotates with the sky: LGS beams are running along an annulus around the science target, with 5.6 and 6.7 arcmin internal and external radii.

TT reference is obtained from a pick-up mirror located about 8 arcmin away from the science target. Although located far away from the isoplanetic patch for the whole atmosphere, it provides a very good correction of the ground layer tip-tilt, which dominates the overall TT contents. The TT WFS runs slower than the LGS ones, and we are currently evaluating if an improved telescope guide probe could allow cancelling this component altogether.

The 4 LGS cameras are synchronised such as to provide their frames in parallel to the RTC within a few microseconds. 4 frames are processed in parallel (5 when a TT frame becomes available), allowing performing the overall computation –slopes computation, control matrix multiplication, controller application, delivery of the command to the DSM– in noticeably less than 200 µs. the cameras are based on the e2v low-light technology (now Teledyne e2v), with on-chip electron multiplication. Sub-electron read-out noise is reached above 1 kHz frame rate. For GRAAL, we operate the cameras at a somewhat lower gain of 100, allowing us to operate at about 1 e^- RON. LGS sensors are operated at 1 kHz and TT at 200 Hz.

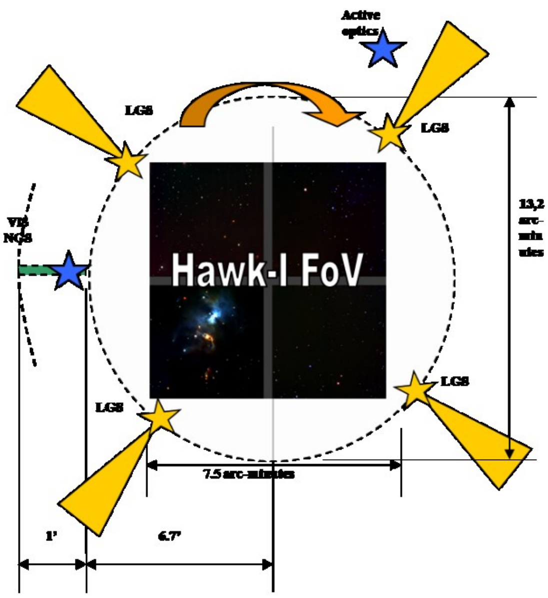

Figure 2: focal plane schematics for the standard Hawk-I mode. The LGS annulus rotates with respect to the instrument and the TT-WFS.

GRAAL real-time computer is based on a standard platform for adaptive optics real-time applications (SPARTA), integrating CPUs, DSPs and FPGAs in a common system:

- FPGA allow managing the communication flow, as well as highly parallelized tasks like slope calculations
- DSPs are used as fast processors for intensive calculations
- CPUs allow processing intensive calculation tasks offline, like calibration or procedures of parameter identification and monitoring a series of relevant parameters:
    - Misregistration
    - Atmospheric parameters on the line of sight (seeing, coherence time) and
    - Profile (Cn2, ground layer, Sodium layer thickness and altitude)
    - Overall performance (estimated correction provided, …)

Maintenance and commissioning mode (MCM)

A natural guide-star, single field of view, AO system is included in GRAAL, allowing the commissioning of the DSM. This system relies on the same WFS as the LGS, to avoid any overhead in terms of maintenance. It is therefore a 40x40 Shack-Hartmann sensor, working in visible light. The light is split with a dichroic, letting available the full wavelength range accessible to HAWK-I going through. An enlarging optics is inserted behind the dichroic, allowing Nyquist-sampling a diffraction-limited PSF down to the H-band.

The enlarging optics being warm, the sky background received in HAWK-I is therefore much larger with the MCM mode (a factor 10 has been measured during a commissioning run, for typical ambient temperature), due to the high background instrumental contribution (HAWK-I does not include a dedicated cold stop to limit the aperture to a f/90 beam).

The MCM uses the same RTC hardware as the normal mode of operation, re-using large parts of the SPHERE RTC software already in operation in Paranal. Few features are not implemented to keep a hardware compatibility with the AOF RTC design (e.g. few loop cycles are lost when updating a control matrix in the AOF systems, whereas SPHERE can update a matrix without frame loss).

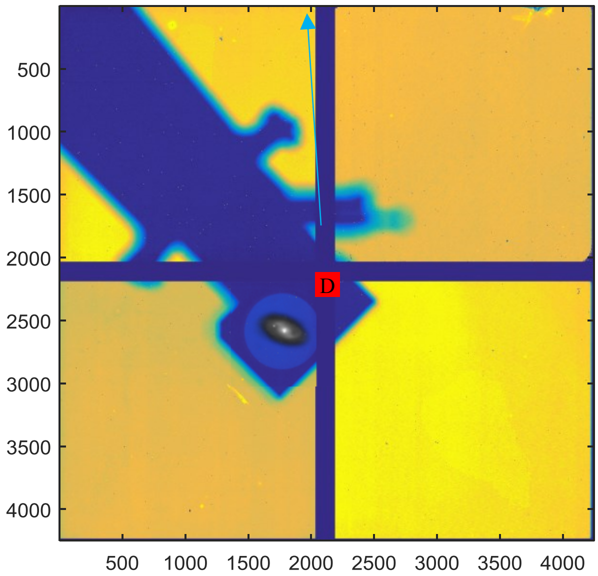

Figure 3: HAWK-I field of view with the MCM arm in place. An important part of the field of view is obscured, only the central part is available with a higher sampling. The gaps between the four detectors is displayed roughly to scale. The MCM enlarged field of view is the blue circle near the middle of the field, while the letter D represents the approximate location of the dichroic entrance. A visible image of Einstein's cross and host galaxy (credit: ESO/F. Courbin et al.) has been added to the field of view at the scale.

5. GRAAL PERFORMANCE

As a ground-layer adaptive optics system GRAAL corrects efficiently atmospheric layers below 300 m altitude. 60% of the time, more than 60% of the turbulence contents is located in this effective correction domain. This allows GRAAL providing a seeing improved by about 20% the vast majority of the time.

GRAAL should therefore enable HAWK-I providing images with an FWHM better than 0.35" over 50% of the observing time in Paranal.

The shape of the PSFs provided by GRAAL are quite similar to images obtained with a better seeing and a smaller outer scale than what the Paranal site offers typically. They exhibit therefore a larger deviation from a Gaussian profile than seeing-limited images, with a more pronounced central peak.

6. GRAAL LATEST TESTS

After a successful installation of GRAAL in August 2015 and a long standby period which we nicknamed hibernation, the first commissioning periods with GRAAL took place in February and October 2017. To maintain the health of the system during hibernation, we proceeded to regular wake-up, alike bears do throughout long subarctic winters. This allowed us maintaining in a working condition the instrument. After 18 months, the instrument had no stuck optomechanism or permanent electrical failure.

We tested on-sky the MCM with its natural guide-star, and the GLAO mode, the main operational mode of GRAAL. By the end of 2107, two more GRAAL commissioning runs will take place and allow us delivering an instrument ready to operate.

On-sky Strehl ratio above 60% could be reached, with a number of modes corrected of up to 700 (out of 1150). The performance was by then limited by the quality of the DSM flat reference on the high spatial frequencies, which aliased into the controlled space. The higher spatial frequency aberrations are the negative footprint of (known) aberrations in the test set-up for the AOF, ASSIST. These aberrations are expected to be corrected once we correct the maximum number of modes from the DSM.

Since then, we have improved the quality of the flat reference. Better images are expected when GRAAL is again used in MCM.

7. ON-SKY MCM TESTS

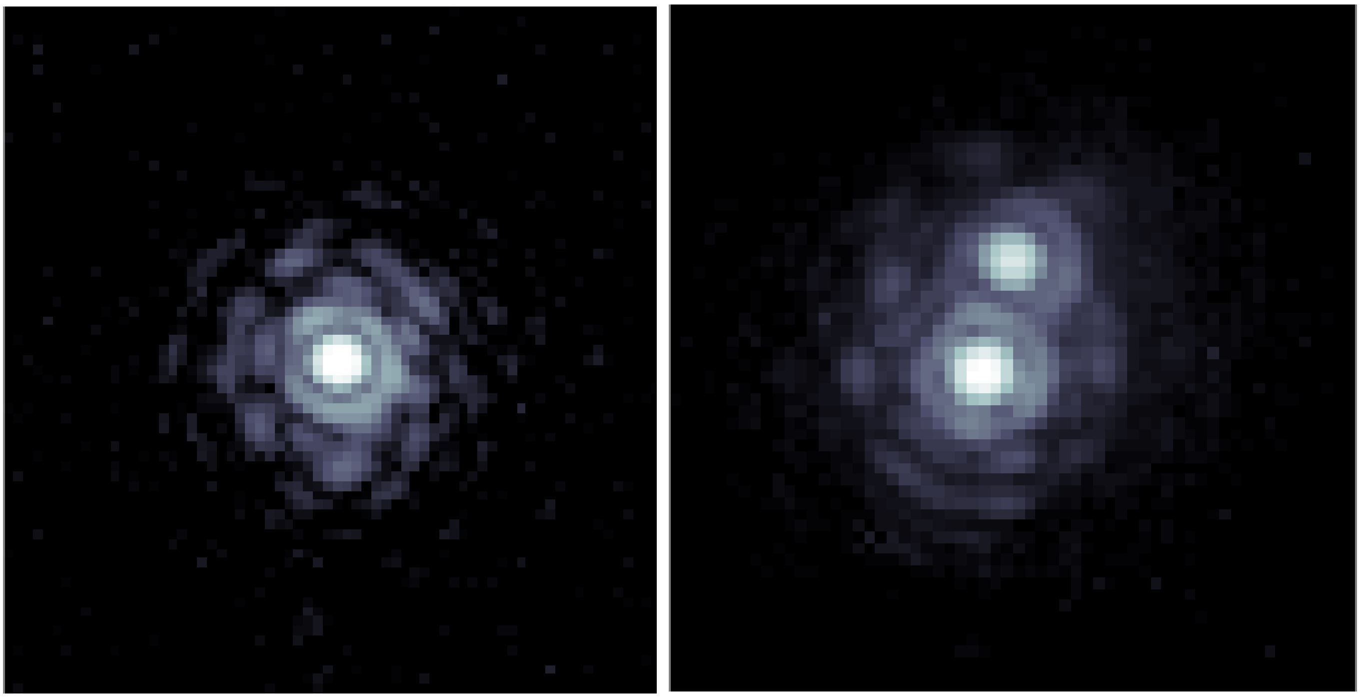

Figure 4: left, an exposure with a SR of 80%, as reached during the single-conjugated commissioning. Right:double-star, with a separation of 0.2”. Images obtained in K-band, loop closed on the star imaged

We verified during these commissioning periods that the DSM is behaving as expected. Number of modes corrected, domain of correction, rejection transfer function (Figure 6 shows TF for the tilt mode as an illustration) are all according to the design of the system.

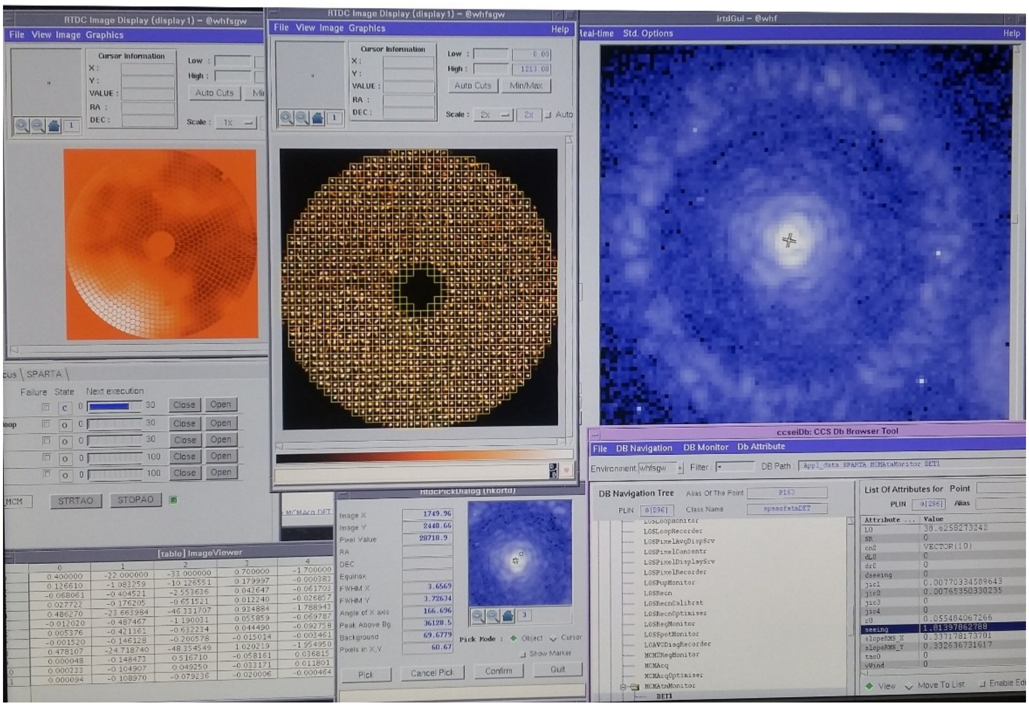

Figure 5:screenshot obtained during preliminary tests with the DSM. The uncorrected speckle ring seen on the right was a static aberration pattern, resulting from at the time uncorrected flat reference aberrations. The limited number of modes corrected in close loop at the time prevented the correction of these calibration errors.

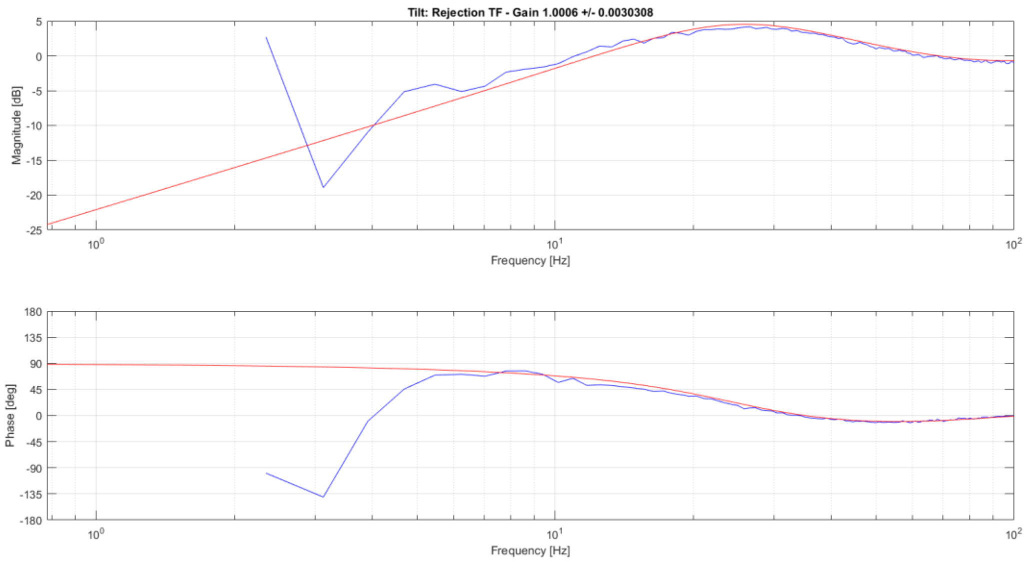

Figure 6: Rejection transfer functions for tilt.

The AOF is equipped with two deformable mirrors within the telescope system: the primary mirror is used for active optics correction and the secondary for adaptive correction at a higher temporal frequency. We tested the coordination between both mirrors, offloading the long-lasting aberrations corrected by the DSM on the primary. This technique which allows us working always with the maximum stroke on the DSM to correct atmospheric disturbances. We validated this technique on-sky, performed the interaction matrix between DSM modes and the elastic modes which are corrected by the M1 active optics supports, as shown in Figure 7. Coma terms can be offloaded onto M1 or corrected for by a lateral displacement of the vertex of M2 with respect to M1. In practice the coma terms observed on-sky are small enough to make this issue not relevant. This is assuming that the telescope M2 lateral position calibration is of course well done for all pointing altitudes on-sky.

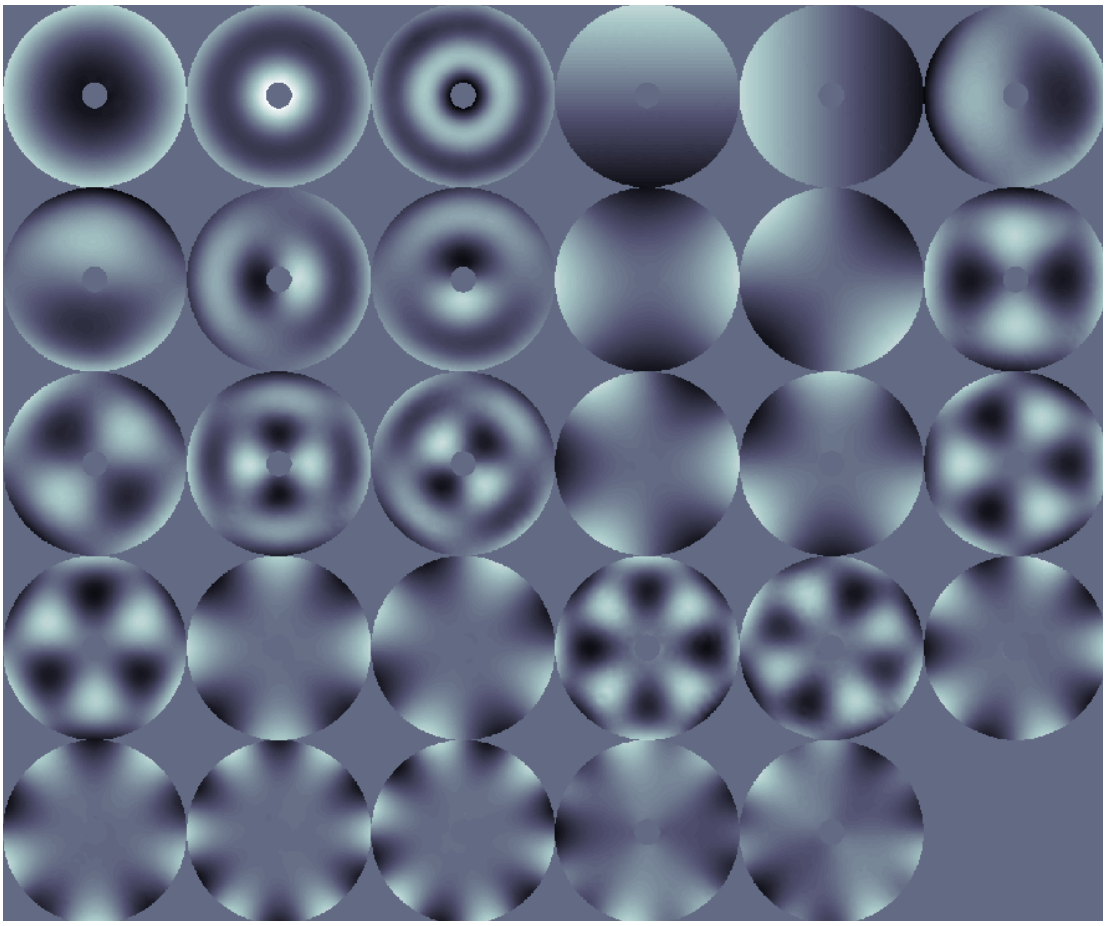

Figure 7:the first elastic modes of the telescope as projected onto the DSM.

During the year 2017, we could start the actual commissioning of the ground layer mode.

8. MONITORING GRAAL PERFORMANCE

Monitoring the actual on-sky performance is particularly important in the case of the AOF, as it is the first project in operation in Paranal where the atmospheric profile has a crucial impact on the added performance from a GLAO system.

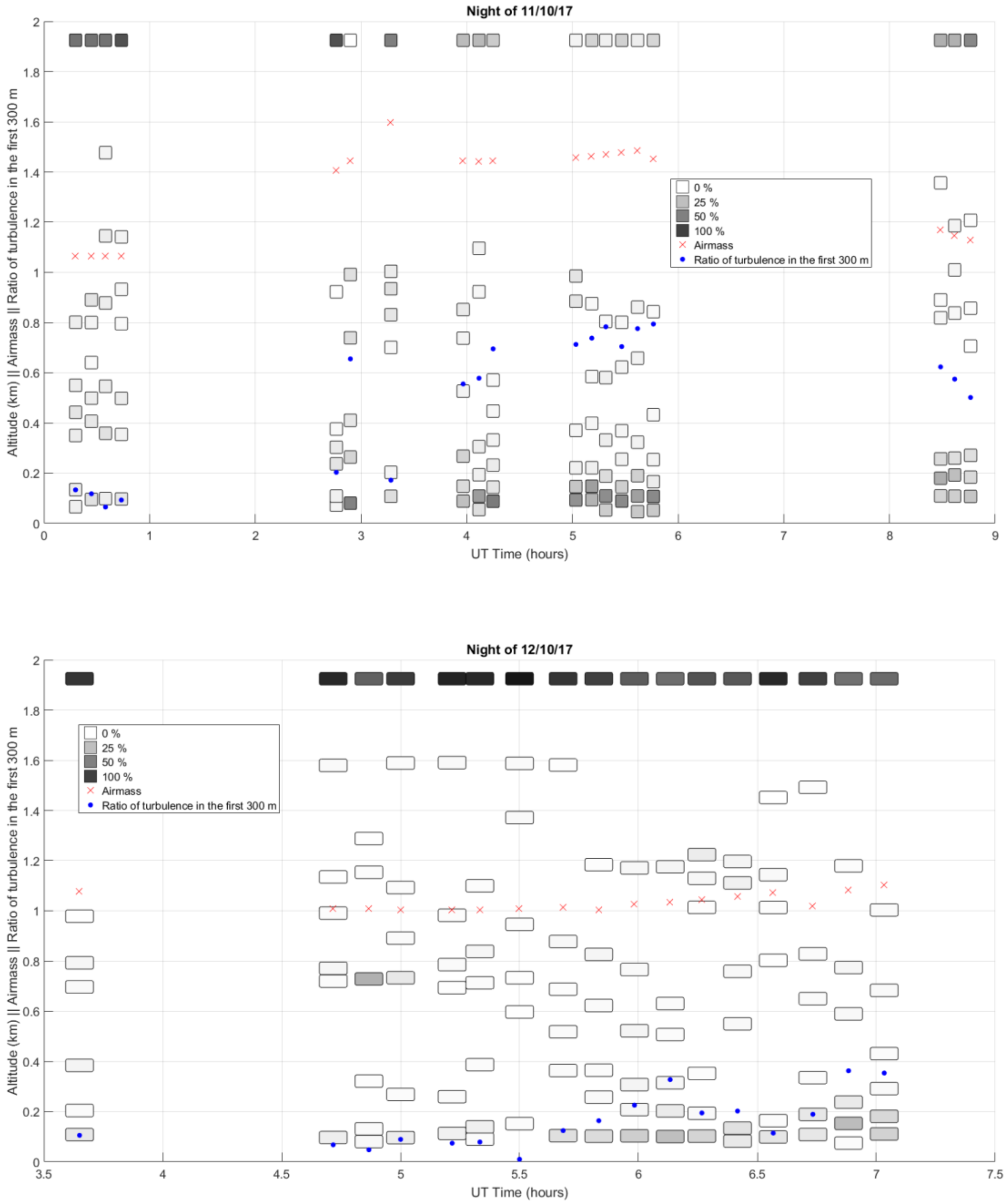

Figure 8:atmospheric profile obtained during two consecutive nights during GRAAL commissioning, obtained by one of us (J. Kolb). Each rounded rectangle represents a turbulent content of one layer; the darker the rectangle, the more turbulent relative content it has. Profiles are estimated at different times (X-axis), whereas the altitude of the layers is represented on the vertical axis.the top row of turbulent contents represent the seeing above the detection limit (typically above 1 or 2 km altitude).

9. GRAAL OPERATION

Using GRAAL in operation relies on a common AOF strategy defined to use a maximum number of commonalities between both Nasmyth AO modules.

The acquisition sequence relies on an acquisition sequence where the LGS acquisition is mostly common to both modules, with the exception of the constellation size (larger for GRAAL), and the way the LGS are roughly acquired, running along a spiral until flux is maximized (with the Laser launch telescopes jitter actuators for GRAAL).

The tip-tilt acquisition sequence is somewhat different; GRAAL TT sensor search area is a large ring, preventing the addition of a bulky and heavy field selector. The selection of the TT star requires therefore rotating HAWK-I instrument to put the TT star at the right location, i.e. the TT-sensro field of view centre. Moreover, HAWK-I performs image jittering to allow estimating the sky background while keeping the target within the instrument field of view: pseudo-random jitters of up to several tens of arcseconds are performed, allowing estimating sky background everywhere on the image with a minimum of 5 jittered images.

This mode requires keeping the same TT-star when we use this so-called auto-jitter mode. The TT-sensor has therefore a large field of view of about 50". We maintain this large available jitter box and perform the acquisition of the AO-TT target always at the centre of the TT-sensor.

The preparation of the observations requires therefore a decicated tool to position properly the TT-sensor with respect to the instrument field of view. This tool has been integrated in the Paranal facility tool GuideCam. The tool allows selecting a TT star in a ring around a science target, which itself can have an offset with respect to the telescope axis. The result allows selecting a TT-star in a search area far bigger than the initial field displayed in

Figure 2. The search area available when the science target is searched in an annulus 16 arcmin diameter and 1 arcmin thick is of 11 arcmin², whereas the actual search are is in practice of around 50 arcmin² (by moving the science target in HAWK-I field of view by up to 2 arcmin). The sky coverage at R=14.5 for such search area is larger than 99%, and stars somewhat fainter can be used to track without noticeable performance loss.

The VLT has been recently equipped with faster telescope guiding probes, allowing as well a TT-free operation with only a minor performance loss (reaching about 95% of the performance improvement obtained with a dedicated TT-star).

10. CONCLUSION

In a summary, GRAAL can be operated with or without TT star, with an improved performance allowing it to improve the image quality by an averaged 20% in K-band. The AO-module makes use of the four Laser guide star facility which can be routinely operated in Paranal. GRAAL enable ESO offering a wide-field IR imager to the community. Early 2018, a science verification is planned allowing offering the improved instrument to the community for the following call for proposal. GLAO instruments will therefore be offered in 2018 to both Nasmyth foci of one of the Unit telescope of the Paranal observatory. This will open up a new, wider window to the adaptive optics world: for the first time, large field of view, high efficiency, AO-corrected instruments will scan the southern sky.

11. ACKNOWLEDGEMENTS

Over the years, our project has accumulated a vast list of contributors. Failing to produce a comprehensive list, we will mostly thank our colleagues in Garching and in Chile for their enduring support. The dedication of the team in Paranal is especially coming straight to our hearts. Their work in a remote desert, maintaining the daily routine of top-science data acquisition in a difficult environment is always a small miracle.

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[i] Kissler-Patig, M. et al., "HAWK-I: the high-acuity wide-field K-band imager for the ESO Very Large Telescope", A&A, 491, Iss 3, 2008, 941-950

[ii] Bacon, R. et al., "Probing Unexplored Territories with MUSE: a Second-Generation Instrument for the VLT", The Messenger, volume 124, 5-10