Status of the GRAAL system development: very wide-field correction with 4 laser guide-stars

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ABSTRACT

We recall the design and present the development status of GRAAL, the Ground-layer adaptive optics assisted by Laser, which will deliver wide-field (10 arcmin), enhanced images to the HAWK-I instrument on the VLT, with an improved seeing. GRAAL is an adaptive optics module, part of the Adaptive optics facility (AOF), using four Laser- and one natural guide-stars to measure the turbulence, and correcting for it by deforming the adaptive secondary mirror of a Unit telescope in the Paranal observatory.

GRAAL is in the laboratory in Europe and the integration of its laser guide-star optics is completed. The first wave-front sensor camera will be ready for its integration in the coming weeks, allowing the first system tests to start.

Keywords: GRAAL, HAWK-I, VLT, Paranal, AO, GLAO, LGS, L3-CCD

1. INTRODUCTION

GRAAL, the Ground layer adaptive optics assisted by Laser, provides improved seeing images to the wide-field, infrared imager HAWK-I. Using 4 Laser guide stars (LGS) wave-front sensors, it corrects the atmospheric wavefront perturbations by a deformable secondary mirror, replacing the current mirror of a Unit telescope in the Paranal observatory. This allows an improved image quality, especially in the long-range of the near-IR instrument HAWK-I.

GRAAL is an ESO project, in the framework of the Adaptive optics facility (AOF). It uses the deformable mirror replacing the M2 of YEPUN, the fourth of the Paranal observatory's 8-m telescopes. The corrections applied to the mirror are estimated from the aberrations measured on the images of 4 Laser guide-stars launched from the side of the telescope on the meso- and thermospheric Sodium layer.

1.1 Ground layer adaptive optics

Ground layer adaptive optics (GLAO) corrects the lowest layers of the atmospheric turbulence, improving the image quality delivered to astronomical observations. GLAO mostly uses Laser guide-stars [2], [3], [4], [5]. GRAAL's performance rationales have already been described [1] and will be only briefly recalled.

1.2 GRAAL and HAWK-I

Very-wide field ground-layer adaptive optics is a recent development. Although even larger field-of-view systems are in design [7], GRAAL is the widest field-of-view GLAO system developed for an 8-m class telescope, with a free-from-optics scientific field of view of over 10.5 arcmin. It will be installed in the Paranal observatory in 2014 feeding an infrared imager with a 7.5 arcmin square field of view, HAWK-I. Its sky coverage exceeds 95%, and allows 100% sky coverage with a slightly limited performance.

GRAAL offers an improvement of about 40% on the K-band FWHM, allowing routine observations with 0.3" FWHM (50% of the time with a seeing in the line of sight of 0.95"). This represents a factor 2 with respect to the current situation, where worse seeing conditions are used more often by HAWK-I than by the adaptive optics instruments NACAO and SINFONI, located on other foci of the same telescope. It also allows using the full potential of HAWK-I and its sampling of 0.1" per pixel.

The Unit telescopes of the Paranal observatory have been designed such as to minimize the non-atmospheric sources of image degradation, with for instance a closed-loop active optics during science observations. GRAAL will therefore only correct further these disturbances at higher temporal frequencies, excepted in the case of very good seeing, where the telescope and enclosure residual seeing contributions might become significant in the PSF formation.

1.3 GRAAL concept

In a nutshell, GRAAL uses 4 LGS wave-front sensor and one tip-tilt sensor. In addition, a natural guide-star mode is available for maintenance and commissioning purposes. The LGS are located on the corners of a 8.4' side square and rotate with the pupil. The tip-tilt star is selected outside of the HAWK-I field of view. The system introduces therefore no additional optics within the HAWK-I field of view.

The wave-front sensors are 40x40 Shack-Hartmann sensors. Their design is fully identical to the design of the GALACSI wave-front sensors: the AOF uses 9 identical versions of a wave-front sensor, probably the largest series of AO systems built so far. The tip-tilt sensor is based on the same camera design, without lenslet assembled. The 1 arcmin field of view of the tip-tilt sensor is used to perform "jittering" operations with HAWK-I, to estimate the background for the wide-field images provided by HAWK-I.

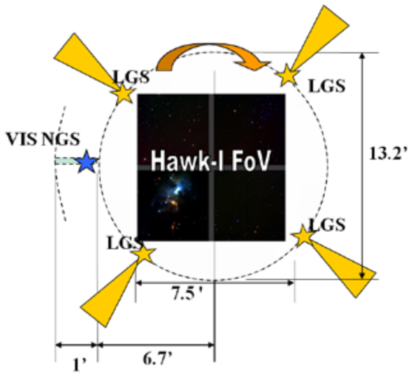

Figure 1: GRAAL focal plane illustration. The 4 LGS rotate with respect to the field of view. The visible tip-tilt star is selected outside of the LGS ring. The cones represent the Rayleigh scattering areas from the upward propagation of the Laser beams (Lasers are side-launched).

GRAAL hardware configuration is described in detail in [1]. One noticeable change occurred since then: the SPARTA cabinet will be located far away from the instrument, and linked (as before) through fibres to the rest of the infrastructure. The change will minimize the vibration transferred by the instrument to the telescope structure, which will be beneficial to both high-Strehl instruments and VLTI systems.

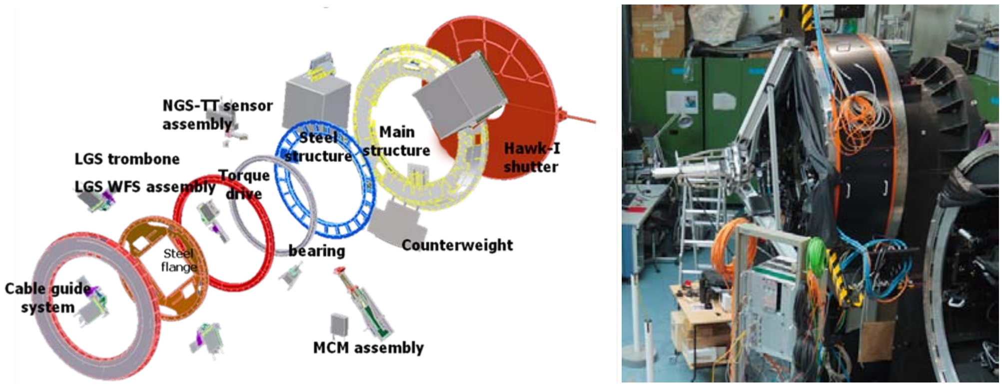

Figure 2: Left: GRAAL design exploded view. The light comes from the upper-right, and the shutter of HAWK-I protects the AO module from incoming dust and wind. Two electronics cabinets are attached to the main structure. Right: GRAAL in the laboratory early 2012. A VLT alignment simulator is connected to the module on the left. A movable chassis holds the electronics racks controlling GRAAL motion. To the right, a part of the other Nasmyth module –GALACSI– is visible.

GRAAL system is highly relying on the AOF systems and shares common features with GALACSI. Therefore we simply recall briefly the system of GRAAL in Figure 3. Both modes in open and closed-loop are represented, illustrating the number of interactions that the system will have to manage in operation. All actions involving M! or 4LGSF will have to be tested on-sky, with only limited tests performed in Europe, given the absence of a representative hardware for test.

We plan the calibration of the AO system to take place in a semi-synthetic manner. Based on physical data acquired from WFS measurements of internal calibration sources moved by known quantities, and on a laboratory calibration of the DSM, we derive interaction and control matrices to be used on-sky.

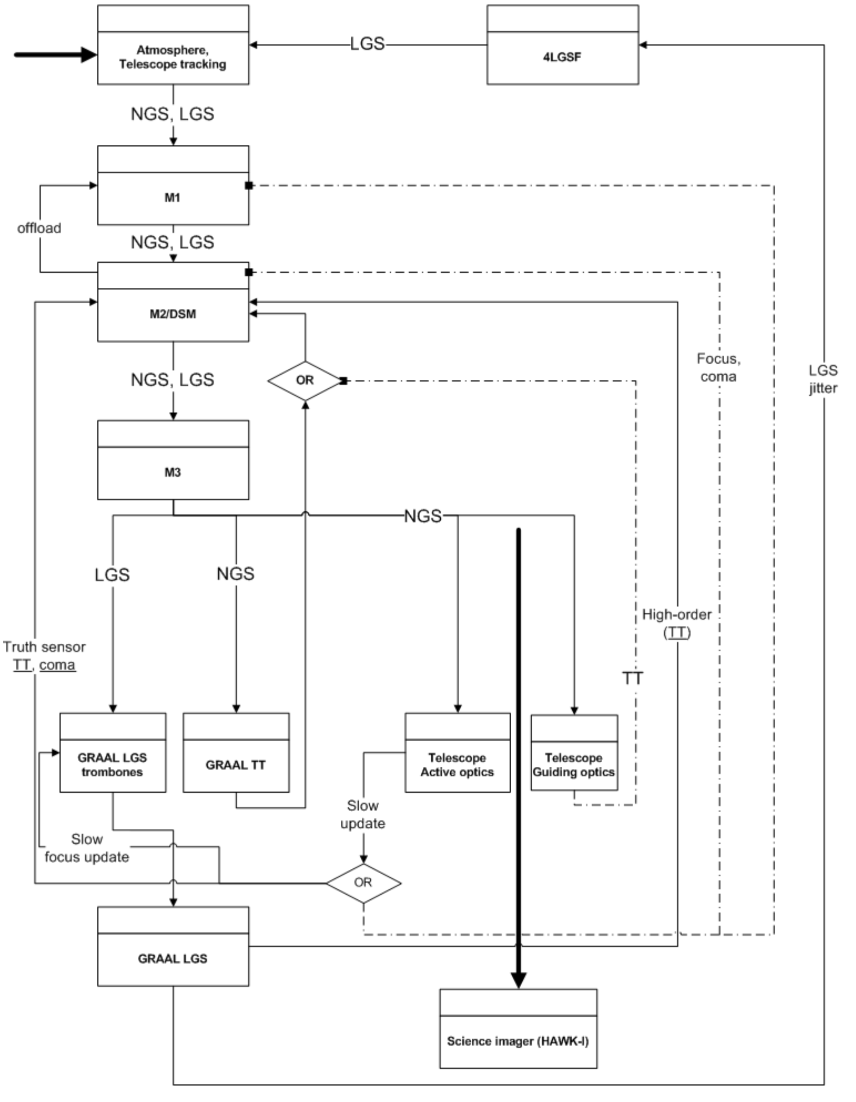

Figure 3: simplified system model for GRAAL. Open-loop functions are ensured by the telescope (dash-dotted lines), most of the closed-loop functions are performed by the real-time computer (solid lines control limks). The scheme is more complex than with classical AO systems, given the location of the deformable mirror, affecting most telescope control systems.

1.4 Observation modes

HAWK-I will use GRAAL in a ground-layer correction mode. In this configuration we use:

- 4 LGS wave-front sensor (WFS) for high order correction, on a fixed annular configuration 12 arcmin diameter,
- one natural guide-star WFS for the tip-tilt correction, taken outside of the LGS-ring, and
- the active optics of the Unit telescope for the focus low-speed variations, coming from Sodium layer altitude variations. The active optics of the telescope allows as well the monitoring of ill-controlled modes and ensures that only atmospheric disturbances are corrected.

We control actively 300 modes in operation. The AOF allows up to 1170 modes to be controlled. Modes beyond the 300th have spatial frequencies too high to provide an improvement over the large field of view of HAWK-I. The deformable mirror is conjugated at a negative altitude of 90 m (below the primary mirror altitude).

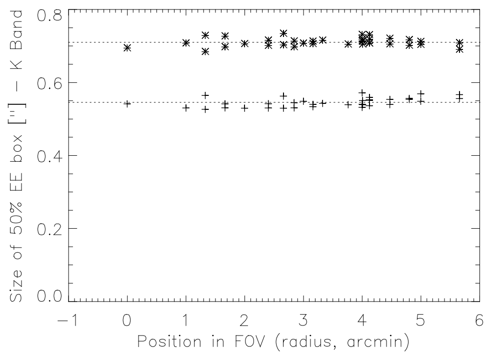

Figure 4: performance of GRAAL with/without AO. The diameter encompassing 50% of the energy is drawn against the position in the field.

In K-band, the gain G (ratio of seeing disk diameter in open loop over closed loop) is typically larger than 1.25.

UT seeing on the line of sight (@500 nm, arcsec)		0.74	0.87	1	1.1
Profile		K-band gain			
averaged case	G ($Ø_{50\%}$)	1.55	1.40	1.24	1.13
averaged case	PSSn (normalised to seeing case)	2.37	2.01	1.60	1.32

Table 1: GRAAL performance for different seeing conditions. Each performance actually results from the average of simulations performed for different vertical profiles.

GRAAL will therefore use the deformable secondary mirror (DSM) with relaxed constraints in terms of registration between the DSM and the WFS. Optical aberration which would be poorly seen and might accumulate in the commands sent to the DSM, can still be observed on the (natural-star) telescope guide-probe as needed, using it as a truth sensor (with 21x21 subapertures).

A maintenance mode exists also, based on a single 40x40 subapertures Shack-Hartmann sensor. It will provide a way to calibrate and regularly check the performance of the DSM. Based on the use of a natural guide-star, it provides a Strehl ratio >60% in H-band, and provides a correction using the full potential of the DSM with 1170 actuators. The mode will be used also for the commissioning of the AOF, especially the deformable secondary mirror.

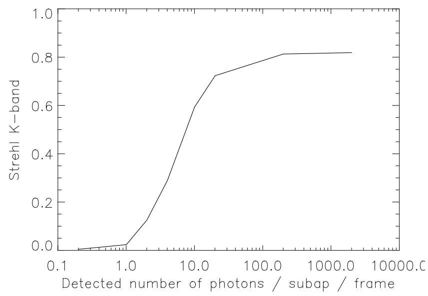

Figure 5: Maintenance and commissioning mode performance. 1170 modes are controlled.

2. STATUS

We are currently integrating GRAAL in the ESO assembly hall in Europe. We have received all parts required for the integration of the GRAAL, and the first wave-front sensor cameras are under the final stages of assembly and are being delivered in a short series starting when these lines are written. In the coming months, GRAAL will be tested functionally for all its sub-assemblies and stand-alone system tests. Closed-loop tests will have nevertheless to wait until the DSM is delivered and accepted at ESO.

GRAAL is a project led and developed by ESO. Nevertheless, most motors and many assemblies have been developed, manufactured, assembled and tested throughout Europe. Besides, the AOF makes use of products developed overseas. Figure 6 shows the approximate geographical source of GRAAL components, for the contracts passed for GRAAL. Off-the-shelf products are not represented here.

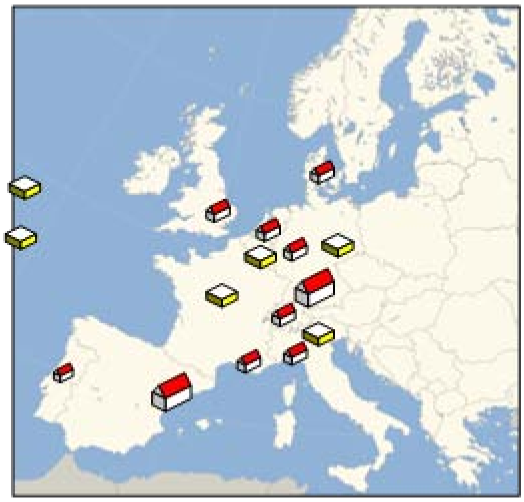

Figure 6: Sources localization for GRAAL development, per cost origin. Houses represent parts or products directly delivered for GRAAL, e.g. assemblies or detectors; flat-roof buildings represent AOF products, e.g. DSM, Laser, test-bench. Background map from wikipedia.org.

2.1 Main structure

The GRAAL main assembly has been delivered by the Spanish company NTE, assembled and tested to the point that guarantees that the system can perform its duty at ESO [8]. The assembly is a 660 kg hollow cone, equipped with a 1.1 m diameter bearing (built by the company Rothe Erde), a direct-drive motor from Phase motion control. The position is measured with a 4 scanning-heads incremental tape from Heidenhain. The tracking accuracy of the system ensures adds virtually no jitter to the LGS images (less than 30 mas). The jitter is therefore mostly atmospheric, and compensated by a closed-loop system on the launch telescope jitter actuator. We evaluated the jitter influence to be negligible for the residual obtained of 120 mas in a worst-case scenario of high zenithal distance.

Mechanical interfaces to the optics have been tested in dimension and flexures, the main instrument rotator has been verified in movement accuracy, with and without the SW used by the instrument. The main structure provides a stiff structure for the optical interfaces. The flexures under gravity while rotating GRAAL are smaller than 20”for mirror supports and typically less than 20 µm lateral displacement for most interfaces. The run-out of the LGS co-rotator is less than 50” and around 200 µm, providing the wave-front sensors with the required accuracy in tracking the deformable mirror rotation during an observation. Overall, the mis-registration of the wave-front sensors in operation will be better than 15% of a subaperture. Figure 7 shows the performance variation associated with a pupil misregistration. No adverse effect is observed up to 0.05 m misregistration, corresponding to 25% of a subaperture for our 40x40 system. This result deviates from the rule of thumb of 10% commonly used for AO-system dimensioning. Less than 300 modes being corrected by GRAAL (1/4 of the total number of subapertures), the same number of modes could therefore be controlled by a system with 20x20 subapertures and 300 actuators. The corresponding pupil misregistration would in this case be equivalent to 12% of a subaperture size.

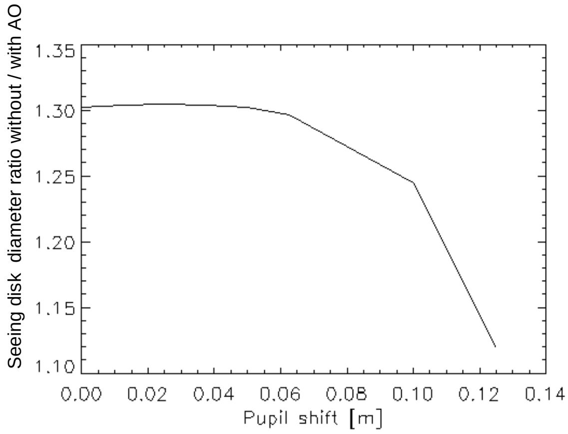

Figure 7: effect of a pupil misregistration on the performance. The pupil displacement is computed for an 8 m pupil, for 281 modes corrected.

2.2 Wave-front sensors

The main structure provides the environment for a tip-tilt sensor with optics, pick-up carriage and calibration unit. It holds as well a maintenance and commissioning unit, with a 40x40 Shack-Hartmann sensor for natural guide-star.
4 copies of a laser guide-star wave-front sensor (40x40 Shack-Hartmann) with optics and a focusing mechanism track the LGS both in position and in distance.

2.3 Optics

The company SESO, France, has manufactured the main optics for GRAAL. All the optics of GRAAL have been delivered in 2010 already, and their integration has been made partially. 4 LGS paths have been aligned, and co-aligned together. The alignment allows so far the positioning of the telescope pupil such that no subaperture is misaligned by more than 5% of its dimension.
The tip-tilt optics assembly will be completed this summer, after the reception of the third wave-front sensor camera.
Süss micro-optics, Switzerland, has manufactured the lenslet arrays of GRAAL (used also for GALACSI, the other AOF module). The lenslet have shown an excellent performance, with a wave-front error of typically 35 nm rms on each lenslet, and a homogeneity in the focal length at a 0.1 mm level (defined as the distance of optimal energy concentration). Overall, the lenslet arrays allow a loss of less than 4% of light for coatings, fill factor and scattering. This ensures an energy concentrated in the diffraction central spot higher than 70%

2.4 Wave-front sensor cameras

We have selected e2V L3-CCD chips for our cameras. We have reached sub-electron RON for frame rates of up to 1200 Hz, with on-chip amplification gains of about 200 on a prototype. The general design of the cameras is based on developments reported in [6] and [9]. The first camera is being delivered this summer.
The wave-front sensors include a field stop, re-imaging optics and pupil-conjugated lenslet arrays.

Besides, the cameras are designed as line-replaceable units, and as such exhibit exceptional accuracy and stability of the optical alignment. Specific tools have been designed to reach a position of the sensor at the level of a few micrometers, and maintain a precision of lateral alignment better than 12 µm during operation. This allows:

- Using the cameras without loss of field of view
- Maintaining a pupil registration compatible with adaptive optics requirements of GRAAL and the other AOF
- In addition, the parallelism between CCD and lenslet is also controlled to a negligible level (<5 arcmin).

The alignment of the cameras with respect to its optical interface is performed in the laboratory thanks to a dedicated set-up and fiducial marks on the lenslet array, matching the ones on the CCD chip.

2.5 Real-time computer

SPARTA for GRAAL is already physically available [10]. Part of its modules are already developed and tested: the NGS part is essentially available as a variation of SPHERE RTC. All communication links have been tested, especially with the WFS camera, and have been largely debugged, enabling an efficient system test phase to start in 2013.

The large data throughput expected for commissioning data will require a specific data storage concept to allow an efficient storage of data as well as an efficient transfer of the data (about 1TB/night) to Europe for offline analysis. This point remains to be clarified.

2.6 Software

The instrument software is well developed. It will take over the current HAWK-I software functionalities embedding as well all the AO modules. All functions can be operated from SW, and templates started to be used, coordinating several functions.

2.7 Electronics

All electronics cabinets are developed and most functions are ready for system verification. All motions have been tested and integrated in the SW, allowing the control of the module from a high level. The control of the motion is based on an old ESO-standard (MACCON), for which sufficient spares have been procured for maintenance. The control of the cabinets is on the opposite based on PLC controllers, allowing also the implementation of safety aspects in a dedicated architecture.

2.8 Calibration

A calibration plan is drafted, allowing all critical parameters (essentially on the WFS) to be monitored on a regular basis. Identification of the AO parameters is also a working project, with the goal of identifying interaction matrices from closed-loop data [11].

2.9 Operation

The operation concept of GRAAL with HAWK-I is already largely developed [12]. Modifications to the exposure time calculator are foreseen, but also the inclusion of a tip-tilt selection tool to enable the astronomer to select an appropriate target, real-time diagnostics for the AO performance before and during observation.

2.10Commissioning

The installation in Paranal in foreseen early 2014, but the commissioning with the complete AOF will have to wait for the delivery of the DSM, and will therefore take place at the very end of 2014.

3. CONCLUSION

GRAAL, the Ground layer adaptive optics assisted by Laser, will provide a large improvement on the image quality currently delivered by the IR wide-field instrument HAWK-I. The AO module is now delivered in Europe for final assembly with the WFS cameras foreseen this summer. The system offers routinely an image quality delivered only exceptionally in Paranal, increasing further the efficiency of HAWK-I observations. Tests of the system including the DSM will take place in 2013, shipment to Paranal beginning of 2014 and operation will start in 2015.

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