GRAAL: a seeing enhancer for the NIR wide-field imager Hawk-I

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ABSTRACT

We describe the design and development status of GRAAL, the Ground-layer adaptive optics assisted by Laser, which will deliver enhanced images to the Hawk-I instrument on the VLT. GRAAL is an adaptive optics module, part of AOF, the Adaptive optics facility, 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.

The outstanding feature of GRAAL is the extremely wide field of view correction, over 10 arcmin diameter, with an image enhancement of about 20% in average in K band. When observing GRAAL will provide FWHM better than 0.3" 40% of the time. Besides the Adaptive optics facility deformable mirror and Laser guide stars, the system uses sub-electron L3-CCD and a real-time computing platform, SPARTA.

GRAAL completed early this year a final design phase shared internally and outsourced for its mechanical part by the Spanish company NTE. It is now in manufacturing, with a first light in the laboratory planned in 2011.

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

1. INTRODUCTION

GRAAL is an adaptive optics module developed in the frame of the Adaptive optics facility (AOF), it offers an improved seeing quality to its client instrument, Hawk-I. In the introduction, we present the concept of ground layer adaptive optics, the instrument and the AOF. The following sections provide the simulated performance, a description of the design of the module, and some management aspects of the project and schedule.

1.1 Ground layer adaptive optics

Ground layer adaptive optics (GLAO) relies on the correction of the lowest layers of the atmospheric turbulence to improve the image quality delivered to astronomical observations. A practical implementation of this type of adaptive optics faces numerous difficulties:

In contrast with classical on-axis adaptive optics, this type of AO requires excluding the highest layers of the atmosphere from the correction brought by the system. This can be done by using a Rayleigh guide-star [1] for limited telescope diameters, or with multiple Sodium Laser guide-stars, for larger telescopes [2],[3]. The combination of powerful Laser sources at the Sodium wavelength and low noise fast detectors makes it possible today to implement GLAO system on 8–m class telescopes [5].

1.2 GRAAL and Hawk-I

The ground-layer adaptive optics assisted by Laser (GRAAL) is the widest-field GLAO system in development or foreseen to our knowledge, with a free-from-optics scientific field of view of over 10.5 arcmin. It will be in operation in the Paranal observatory in 2014 and will feed an infrared imager with a 7.5 arcmin square field of view, Hawk-I. It has an outstanding sky coverage (95%, and up to 100% with a slightly limited performance), and reduces the size of the stars by 20% (diameter including 50% of the energy) and keep the emissivity of the science images as low as possible (less than 10% increase in emissivity), up to a seeing of 1". In optimal conditions, GRAAL allows the instrument sampling optimally its FoV with 0.2" FWHM.

The high-acuity, wide-field K-band imager is already in operation since three years, and will benefit of a second life with improved capabilities once equipped with its adaptive optics. It is equipped with 4 Hawaii RG-II detectors, providing an exquisite sampling of 0.1"/pixel over the full field of view, from 0.9 up to 2.4 µm. The 4 detectors cover nearly the whole unvignetted field of view of a Unit telescope of the VLT, hence optimizing the surveying capability of the telescope. It complements efficiently the other large IR survey telescope of the Paranal observatory (VISTA), with a finer sampling, lesser FoV but a fainter practical observing limit than given by the 4–m class telescope.

It is currently limited by the seeing of the site in all conditions, as has been shown during excellent seeing conditions (FWHM<0.3" on some images, uniform over the FoV). 50% of the images reach an imaging quality better than 0.5 arcsec in Ks; best periods of seeing are mostly dedicated to the two other AO instruments located on the same telescope, which prevents Hawk-I from delivering even better performances. To benefit from GRAAL image improvement and reach the expected performance for Hawk-I, the observation criteria for Hawk-I have to evolve by the installation of the AO-module.

GRAAL will allow Hawk-I to operate more often with a better apparent seeing.

1.3 The Adaptive optics facility

For an efficient correction, at least three Laser guide-stars are required in the case of GRAAL. The upgrade of one Unit telescope (UT) of the Paranal observatory to a full adaptive telescope is called Adaptive optics facility (AOF). It includes four Laser guide stars, which can be launched up to 6 arcmin off-axis, fixed with respect to the telescope pupil. It includes as well a deformable secondary mirror replacing the secondary of the UT, 1.2 m diameter with 1170 actuators over the mirror surface. Refer to [5] for a full description of the AOF and its current status.

Two adaptive optics modules are currently in development to take advantage of this facility, GALACSI [4] and GRAAL. A third one could be implemented in the Cassegrain focus [6].

GRAAL is an adaptive optics system, using 4 LGS, 1 NGS for tip-tilt sensing, the active optics Shack-Hartmann sensor for truth sensing. The LGS are equidistant on a 12 arcmin diameter ring.

2. PERFORMANCE SIMULATIONS

Extensive simulations were performed in the course of the project, to assess the behavior of the system, taking into account numerous conditions and error terms, including pupil alignment mismatch, LGS flux variations, number of corrected modes, turbulence strength and profile, NGS magnitude.

2.1 The right metrics

A metrics was defined and used from very early on during the project: the diameter enclosing 50% of the energy collected from a point-source through the system (including the atmosphere). The ratio G without/with adaptive optics is used as a criterion of performance for GRAAL:

$$G = \frac{\emptyset_{50\%}^{noAO}}{\emptyset_{50\%}^{AO}} \quad (1)$$

The metrics was used as an approximation for determining the gain in exposure time or limiting magnitude for observations in background-limited science cases.
A metrics more optimal for this type of observation is the point-source sensitivity (PSS), which shows when normalized with respect to the seeing-limited case the gain given by the adaptive optics in terms of SNR [7] [8]. The normalized PSS (PSSn) is defined for the whole system atmosphere-telescope-adaptive optics, as the ratio of the square of the PSF with AO to the square of the PSF without AO.

$$\mathrm{PSSn} = \frac{\int \mathrm{PSF}_{\mathrm{AO}}^2}{\int \mathrm{PSF}_{\mathrm{noAO}}^2} \propto \mathrm{SNR}^2 \quad (2)$$

2.2 Seeing improvement

In contrast with [8], the PSSn in the context of GRAAL is always greater than 1. A PSSn of 1 corresponds to the seeing-limited case (no AO). For diffraction imaging, PSSn of 30 to 300 would be reached: the SNR for a point-source image is two orders of magnitude greater with diffraction-limited imaging than with seeing-limited observation (for an 8 m telescope in K-band in a background-limited imaging).

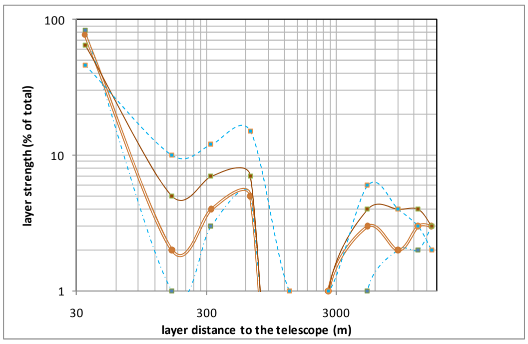
Given the field of view corrected by GRAAL with only one deformable mirror, diffraction limit is never reached in practice, but as we will see later, the PSSn delivered by GRAAL are larger than 2 in half of the cases (K-band). For faint source survey detection (which is a primary science goal of Hawk-I), the efficiency of an observation can be estimated as the product of the area by the PSSn.
For seeing-limited observations as Hawk-I does today, the efficiency is therefore of 7.5x7.5, or 56 arcmin².
For observations performed with GRAAL, the efficiency is approximately doubled, i.e. 110 arcmin²
Observations performed with a single conjugated adaptive optics would provide an efficiency of about 80 arcmin², with a lesser sky coverage in NGS and unacceptable field-dependent PSF, diffraction-limited around the guide-star, seeing-limited away from it.

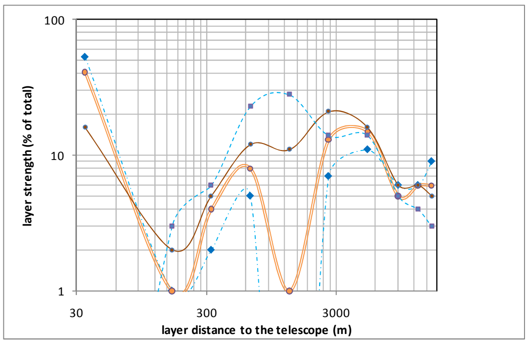
2.3 Paranal site characteristics

For any wide-field adaptive optics, the turbulence profile is an essential component to assess the performance of the system. In practice, the further away guide-stars are brought, the more the system performance depends on the seeing profile.

GLAO systems have nevertheless an advantage with respect to other wide-field adaptive optics: it does not require an estimation of the turbulence profile for the free atmosphere to perform its correction. Only the lowest layers can be corrected, therefore the variations of turbulence in altitude can be considered as a single component.

The Cerro Paranal atmosphere has been thoroughly studied, and especially in view of the coming wide-field AO instruments, the vertical profile of turbulence strength has been the object of thorough investigations. We used the best model available at the time to evaluate properly the performances of the system under representative configurations. The model was established considering differences between the seeing monitor of the Paranal observatory and the telescope actual measurements to account for differences in altitude and in location, using MASS data as well as SLODAR campaigns performed over months on the mountain.





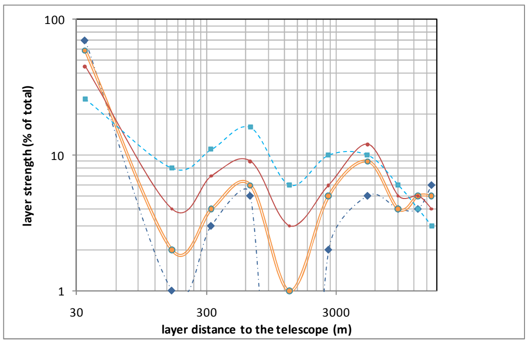


Figure 1: atmospheric vertical profiles used for the GRAAL study.
Top: best 25% (left) and worst 25% (right) vertical profiles, for the ground layer contribution
Bottom: median vertical profile case. For each graph:
500 nm seeing on the line of sight: dash-dotted for 0.74", solid for 0.87", doubled line for 1", dotted line for 1.13"

In the case of GRAAL, the LGSs are separated by 8 and 12 arcmin (opposite edge or corner). In addition, the telescope M2 image through M1 entrance pupil is located 90 m below M1. All turbulence located in the atmosphere above the telescope is therefore seen and corrected with some parallax, meaning that the highest spatial frequencies are poorly corrected. In practice, a simple geometric model shows that a maximum of 250-500 modes can be efficiently corrected by the M2 over such a field of view: the decorrelation between the WFS subapertures and the atmosphere on one side, and between atmosphere and deformable mirror on the other side, shows that beyond this value of 500 modes, the modes are averaged out from one sensor to the other.

Atmospheric layers which can be corrected can be estimated with a similar geometric law. Beyond 1 to 3 km altitude, no more than a 2 to 10 modes can be seen and corrected. Besides, the intensity of the turbulence in these altitudes is typically much lesser than at the ground level in Paranal, making useless any correction at all for these layers.

Numerical simulations were performed, which confirmed this relative limitation of the number of modes which are corrected efficiently. In practice, the number of modes is a free parameter between 200 and 600, whereas the DSM offers more than 1100: GRAAL is a very tolerant customer for the DSM (Figure 2) and a good choice for first-light of the AOF as is planned today.

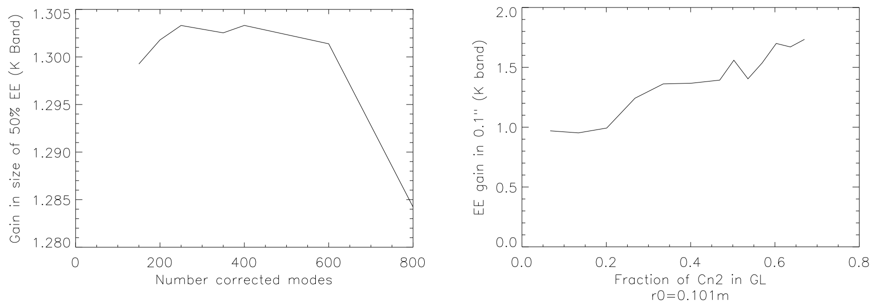


Figure 2: Left: performance against number of modes. The averaged performance weakly depends on the number of modes. The loss beyond 600 modes is due to a slight pupil misalignment introduced as part of the error budget. Right: performance as a function of ground layer strength. The correlation is large; the metrics used in this last graph differs from the rest of the document, it is the gain of energy enclosed in one pixel centered on a star.

2.4 How many laser guide stars

The AOF offers four LGSs. An analysis of GRAAL performances shows that the use of three LGS instead of four affects only marginally the performance of the instrument. Given the number of sub-systems involved in GRAAL, we decided to keep the use of the 4 LGS, such as to increase the overall reliability of the system in operation: in case of failure of one of the four LGS channels, the AO-module can be reconfigured in a matter of minutes to operate with the three remaining channels without important impact, as the performance G –defined in equation (2)– drops by 1% while going from 4 to 3 LGSs.

2.5 Tip-tilt sensing

Tip-tilt sensing has been evaluated for two configurations, with a visible, off-axis TT sensor, and with the science detectors, which offer the possibility of on-chip fast-readout (specific to the Hawaii RG II detectors). The latter was discarded, due to the added complexity in terms of operation, the limited performance gain in wide-band, and the decrease of sky coverage for narrowband observations.

The loop rate is weakly affecting the performance beyond 200 Hz. In GRAAL, tip-tilt and high order correction commands are combined before being sent to the deformable mirror. We could therefore choose 200, 250 or 333 Hz for the TT loop frequency and doing so avoids a variable jitter between TT image read-out and correction sent to the system. Our baseline is 250 Hz.

2.6 Estimated performance

Four seeing cases were considered, each case being split in 3 sub-cases depending on the ground layer strength (Figure 1), i.e. a total of 12 individual simulations. All sub-cases PSFs were weighted according to their frequency of occurrence and averaged out to account for site atmospheric variability.

Each simulation case included a mis-registration between DM and WFS, photon, background and detector noise for the WFS, the transmission of all optics, LGS jitter, loop delays for integration, read-out time, RTC latency, DSM settling time. Other error terms were included by convolving each PSF with a 2D-gaussian profile estimated from the error budget (0.11”FWHM).

GRAAL performance has then been estimated in 30 positions spread over the whole 7.5x7.5 arcmin² FoV. The resulting average performance and uniformity have been estimated in several bands from Y to K. All error terms not included in the simulations are covered by the convolution of each resulting AO PSF with a conservative gaussian distribution, 0.11” FWHM). Non-AO PSF are left without convolution, providing a conservative performance estimation for the best cases, as instrument effects will affect the performance in the best conditions.

In K-band, the gain G 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	Gain ($Ø_{50\%}$)	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.

The uniformity of the correction is excellent, as is expected from a GLAO system. It is actually limited by the accuracy of the simulations, and is smaller than 5% (the relative variation of the $Ø_{50\%}$ has a standard deviation smaller than 3% over the FoV, and is not related to the location with respect to any guide-star).

PSSn are limited by Hawk-I spatial sampling for the good seeing cases. In 50% of the cases, the FWHM delivered by GRAAL is better than 0.3”, and 25% of the time it is better than 0.25”. This outstanding imaging quality will open several fields which cannot be studied as of today due to the lack of resolution of Hawk-I without AO.

2.7 Availability

Based on the simulation results mentioned in the previous section, we evaluated the availability of GRAAL within its specifications not only for the reference seeing case, but as well in a range of conditions covering most of the actual observation cases in Paranal, taking into account the occurrence of atmospheric conditions for each case.

For the specification seeing of 1 arcsec on the line of sight, GRAAL meets its requirements of 20% reduction of $Ø_{50\%}$. We explored different atmospheric conditions to better understand how often GRAAL is available at this level of 20% reduction of $Ø_{50\%}$: GRAAL is available about 55% of the time at this level of image improvement. Moreover, the average performance in this usable fraction of the time is of course even larger, as illustrated in Figure 3.

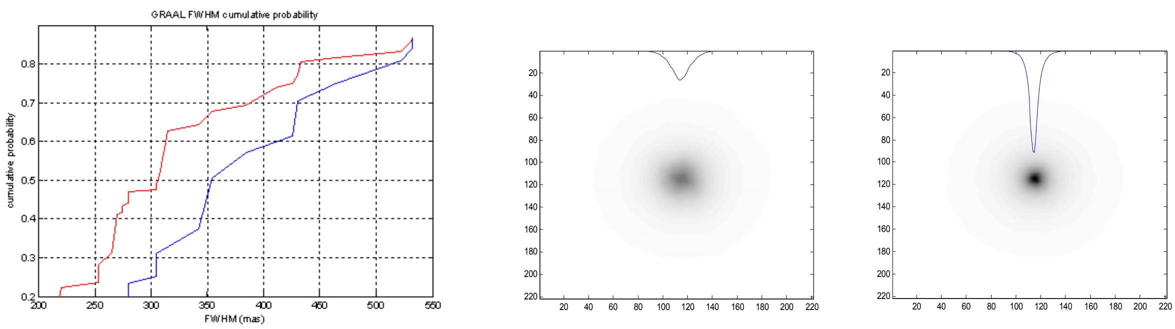


Figure 3: Left: FWHM cumulative probability (K-band). The red curve represents the occurrences with GRAAL (and taking into account a conservative 25% unavailability), the blue one without GRAAL. The sampling effect due to the finite size of the pixels is not taken into account here.
Middle: open-loop PSF corresponding to the 55% cases where GRAAL perform a Ø50% reduction larger than 20%. Square root representation. A cut through the PSF maximum is overlaid.
Right: same, in closed-loop.

Considering the FWHM, the situation is even more striking. Figure 3 shows the cumulative probability of occurrence with/without GRAAL as a function of the FWHM. This plot assumes no bias coming from the competition between instruments at the telescope focus.

2.8 Commissioning mode performances

In addition to the GLAO mode of GRAAL used for astronomical observations, a mode dedicated to the commissioning, maintenance and monitoring of the AOF deformable mirror is implemented in GRAAL. It is based on the same WFS with 40x40 subapertures, sampling well the deformable mirror actuator pattern, and with a closed-loop running at 1 kHz.

The system can provide diffraction-limited H- and K-band images (the images are undersampled at shorter wavelength). In K-band the performance will approach 80% as shown in Figure 4, and S.R. will remain higher than 70% for star R-magnitudes up to 14, for seeing up to 1" (at 500 nm).

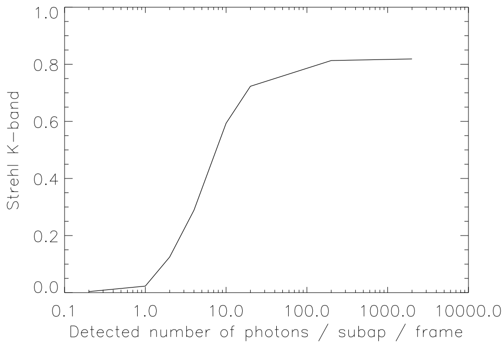


Figure 4: K-band Strehl ratio with the MCM of GRAAL. No error budget included here.

3. DESIGN OF THE MODULE

3.1 GRAAL

GRAAL main constraints are the very large field of view reserved for the science operation (10.5 arcmin) with a high sky-coverage (95%) in terms of operation. The system shall keep the emissivity of the science images as low as possible (less than 10% increase in emissivity). In optimal conditions, GRAAL should allow the instrument to sample optimally its FoV with 0.2" FWHM. Finally, the AO module is inserted between the telescope and Hawk-I, and this sets tight constraints on the volume of the system.

Two module configurations are available on GRAAL: the science mode with a GLAO system, and a maintenance mode with a NGS- on-axis adaptive optics.

Module configurations

GRAAL science mode is based on the use of:

- 4 LGS projected on-sky with the help of 4 dedicated launched telescopes
- The corresponding wave-front sensors located on a 12 arcmin diameter ring,
- one tip-tilt sensor using a NGS on a 14.5 arcmin ring
- truth sensing is realized by the telescope guide-probes, a 21x21 Shack-Hartmann sensor already in operation in Paranal since the telescope installation for active optics control. Note that the active optics control will be superseded by the fast adaptive optics loop, so that the active optics sensor will be blind to all modes but the ones invisible to the adaptive optics system, the first of them being the focus mode
- SPARTA, an RTC platform sharing commonalities of hardware and software design with other AO systems (GALACSI and SPHERE) and

- the deformable secondary mirror

LGS tip-tilts are filtered out and sent to the LGS launch systems to correct the jitter of each beam independently. Slopes computed from each of the four LGS WFS at the loop rate (1000 Hz) are split in two components, respectively tip-tilt and high orders, commands are then used to drive the LGS jitter actuators, respectively the deformable secondary mirror (DSM).

The NGS tip-tilt is read at 250 Hz, the measurement is rotated to match the pupil coordinates and sent to the DSM.

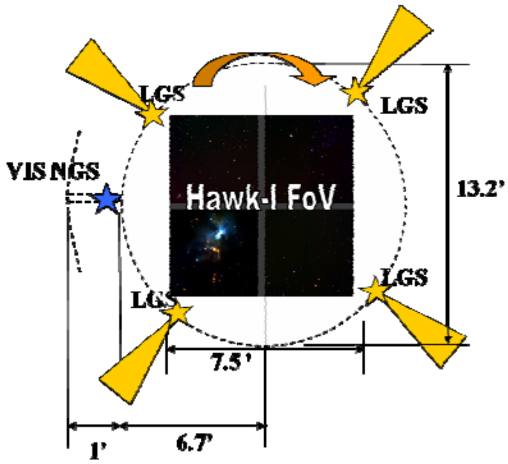


Figure 5: GRAAL focal plane illustration. The 4 LGS rotate with respect to the field of view. The visible tip-tilt star is selected outside of the LGS ring. The cones represent the Rayleigh scattering areas from the upward propagation of the Laser beams (Lasers are side-launched).

The active optics focus signal is used by GRAAL to command the 4 trombone systems compensating the averaged focus seen on NGS by the active optics. The trombone systems include as well a feed-forward loop to account for the geometrical effect of distance increase to the Sodium resonant layer caused by the telescope rotation. In addition to this, each trombone is actually driven separately to slowly offload its own focus term to allow its operation around its optical zero-focus position and prevent non-linearity affecting slope measurements on the WFS.

In this mode, SPARTA is configured in a common version with GALACSI (the other end-user of the AO facility). The phase of the ground layer is reconstructed by a simple average of the slopes and a matrix-vector multiplication, providing a set of position offsets for the deformable mirror. Commands are sent to the DSM for immediate application.

The latency of the RTC is kept low (less than 0.4 ms), and the overall latency (from the WFS to the DSM) is at 1.5 ms (integration time excluded). An IIR filter provides all necessary features to deal with all simple schemes for linear control of the loop, and gives some flexibility to correct some hardware discrepancies like. resonant frequencies or vibrations.

A second mode, called maintenance and commissioning mode (MCM) is available and is used by the AOF among other to commission the MCM. This mode uses a natural guide-star WFS, 40x40 subapertures, and picks the target on the centre of the telescope FoV. As the MCM arm is attached to the adapter-rotator, the latter will be rotating with the pupil.

On the science path, a relay optics is inserted that enlarges sixfold a 10” FoV, allowing one of the detectors of Hawk-I to sample the diffraction-limit spot provided by the system. Given the enlargement, the pupil dimension inside Hawk-I will be undersized, so that a rather large background level is expected in K-band, not to speak about scattered light along the mechanical parts inserted. We therefore plan to use the MCM mostly in the H-band.

The exposure time in this mode is limited by the differential rotation between sky and pupil, primarily depending on the elevation of the telescope.

The RTC in this mode has been made as common as possible with the SPHERE flavor of SPARTA, hence the lower latency (0.2 ms), not required in practice by GRAAL.

Operation sequence

A typical operation of Hawk-I with GRAAL will involve a sequence of tasks, we will describe the essential ones in this section.

Prior to the observation, the target being given by the science goal, the GRAAL preparation software selects from a catalogue the natural guide-star used to correct tip-tilt. The star R-magnitude is between 11 and 14.5, and the brightest star found in this range is selected. The position of this star with respect to the science target determines the position angle of the instrument, as the tip-tilt unit is fixed w.r.t. Hawk-I. For the rare case where such a star cannot be found, a choice is proposed between the brightest star available or the closest star bright enough (modifying the science target by up to 1 arcmin).

At the telescope, once the AOF is operational (Laser propagated, DSM active), an acquisition sequence will successively acquire the LGS by centering each of them on its respective WFS FoV (5” square), close the jitter loops, close the high-order (-LGS) loop, acquire the TT star, close the TT-loop, close the secondary loops and offloading process (e.g. LGS variable focusing distance, active optics, telescope tracking, pupil tracking, differential atmospheric refraction, instrument flexures).

Once these tasks are successfully completed or running, the science acquisition can start.

Between successive exposures, the science target is slightly offset (by up to 30 arcsec). During these jitter, the AO system will continue running its AO high-order loop, as the corresponding offset moves together the telescope and the LGS, which are mounted on the telescope centerpiece. Only the TT loop is then opened, and closed again after the telescope movement and a minimal re-acquisition sequence.

MCM operation is straightforward and is similar to the operation of any single NGS system.

3.2 Optical design

Three main optics compose GRAAL:

- TT re-imaging optics
- LGS WFS and trombone
- MCM WFS and relay optics

SESO, a French optics manufacturer, is currently manufacturing the main optics, and will provide them by the end of the year.

In addition, calibration units have been included and kept to the simplest possible (no more than one lens).

All our WFS being based on Shack-Hartmann, we designed and ordered lenslet arrays from the Swiss company Süss micro-optics. The lenslet arrays are delivered and show excellent performance (WFE lesser than 40 nm rms on all lenslets).

TT re-imaging optics

This block re-images a square FoV 51 arcsec edge-to edge at the telescope focal plane, onto a 5.8 mm square area, corresponding to the WFS camera detector dimensions (described later). The image delivered by the telescope at visible wavelength is seeing-limited, therefore the optics have been designed accordingly. The optical design is based on the current telescope guide-probes, modified to match the slight difference in FoV. The performance is such that the detector with its optics resolves down to 0.4 arcsec (0.21 arcsec per pixel). The distortion is kept minimal and will be calibrated out to perform accurate offsets between exposures.

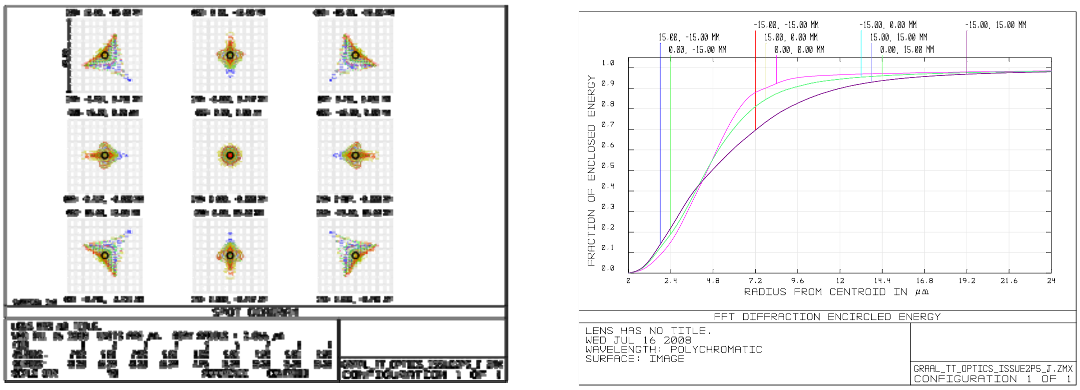


Figure 6: Left: spot diagram of the TT re-imaging optics. The box is 2 pixel wide (48 micron, 0.42”). The step between two successive spot diagram is 25.8”. On-axis position is in the middle.
Right: encircled energy for the same positions in the field. The maximum radius corresponds to two pixel diameter.

LGS WFS optics and trombone

Because the 4 LGS images at the telescope focal plane are located 202 mm away from the optical axis, the design of each LGS-WFS has been replicated four times, allowing the use of very small optics used on-axis. From an initial concept where the WFS cameras were moved to compensate the focus variations on the LGS images, we have moved to a trombone solution, were the WFS camera is fixed, increasing design density, reliability and stability, decreasing the weight and complexity of the system at the same time.
We use a high-index glass prism (N-LASF31A) for the trombone, a field stop follows to limit the background flux (especially from Rayleigh scattered uplink Laser light), and an air-spaced doublet (SF5/N-BK7) collimates the beam and images the pupil on a lenslet array.
The optics is tolerant to focal ratio variation, by adjustment of the internal spacing of the doublet. This feature will be used especially in the laboratory test set-up (named ASSIST), for which the focal ration differs slightly from the one of the telescope.
By design, the system is diffraction-limited at 589 nm over the whole FoV of the WFS, and we specified it to be better than 60 nm rms once integrated.

MCM WFS- and relay optics

It appeared necessary for the AOF to have a mode for the facility allowing a simple maintenance and check of the deformable secondary mirror. We develop at this effect the maintenance and commissioning mode, a high-order natural guide-star AO system.
On the WFS side, a dichroic sends the visible light through a focal extender allowing the rest of the optics to remain out of the scientific and technical FoV. The light is then directed towards the WFS field stop and collimated by an air-spaced doublet, imaging the pupil on the same lenslet array as for all AOF systems, 40x40 square subapertures, 144 micrometers pitch. Diffraction limit is reached between 400 and 100 nm by design, and will provide better than 60 nm rms after integration.
On the imaging side, the 10” wide infrared beam going through the dichroic goes through a catadioptric system, which reimages the VLT focal plane at the same distance, while enlarging the images 6-fold, and keeping a beam nearly telecentric. Two mirrors and one lens are used at this effect, and will provide a Strehl ratio higher than 92% in H-band. We already plan to include static aberration correction to compensate the non-common path aberration and reach an H-band Strehl ratio higher than 95% on-axis. The relay optics can be used at different wavelengths, with marginal deviation to this performance besides the Strehl dependency towards wavelength.

3.3 Mechanical design

All mechanical parts have been designed up to preliminary design internally, the final design and manufacture being performed by NTE. The main electromechanism (torque drive system) has been realized by Phase motion control (PMC), using a bearing manufactured by Rothe Erde and an encoder tape from Heidenhain.

GRAAL is composed of six ring assemblies fit together in a 2m diameter, 500 mm thick cylinder.

An optics-free science field of view (FoV) is provided to maximize the efficiency of the AO: a 400 mm diameter cylinder (11.5 arcmin) is free from any mechanics.

The main structure is attached to the Nasmyth telescope derotator and hosts the MCM relay optics and WFS optics. A steel structure is mounted on it, on which is mounted the TT-WFS. In addition, it filters the deformations eventually created by the thermal stress applied to the main structure and prevents them to affect the bearing, which allows the rotation of the steel flange and its 4 LGS-WFS. The design of the LGS-WFS is replicated 4 times, providing a naturally balanced assembly, favorable in terms of flexures. To maintain a very tight error budget and a line-replaceable unit concept, the pupil alignment on the lenslet array (and of the latter with respect to the detector) is kept better than 20 µm, including alignment, module flexures and thermal variations. Achieving this goal allows the exchange of a faulty camera by another unit without re-alignment or delicate re-calibration required.

A torque motor and a cable-guide system enable the rotation of the steel flange and provide the connections required by the WFS.

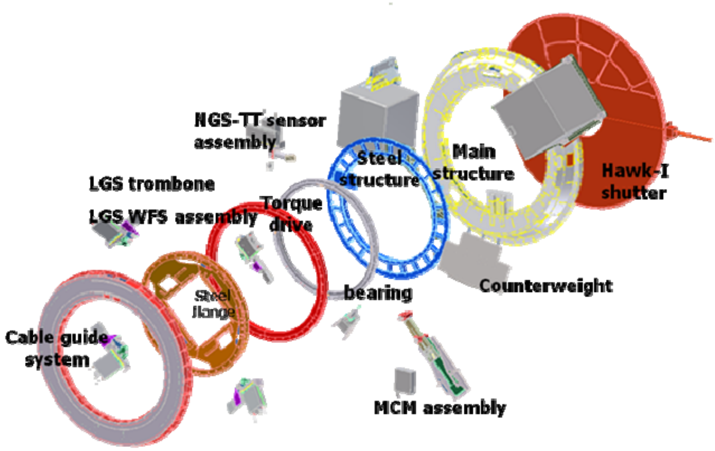


Figure 7: GRAAL exploded view. The light comes from the upper-right, and the shutter of Hawk-I protects the AO module from incoming dust and wind. Two electronics cabinets are attached to the main structure.

Hawk-I uses the adapter/rotator of the Nasmyth focus to derotate its field of view. The Natural guide-star tip-tilt sensor is attached to the same rotator and can only move radially to acquire its target, by 1 arcmin.

The only attachment between GRAAL and the instrument is a 2m diameter, 60 mm thick and wide ring on the main structure. Through this ring are passing all connections required for the AO-module. The number and location of feed-through has been studied in detail, especially when assessing the stiffness of the structure and its behavior in case of earthquake. A full finite element analysis has been performed to assess the performance of the module as well as its handling. The first eigenfrequency is beyond 30 Hz, and the first one having an optical impact is around 40 Hz. Thermal stress analysis in the structure led us accepting a noticeable mass increase to replace the main structure material from aluminium to steel, to match both the telescope and the GRAAL bearing CTE, and prevent the MCM arm to drift excessively with temperature.

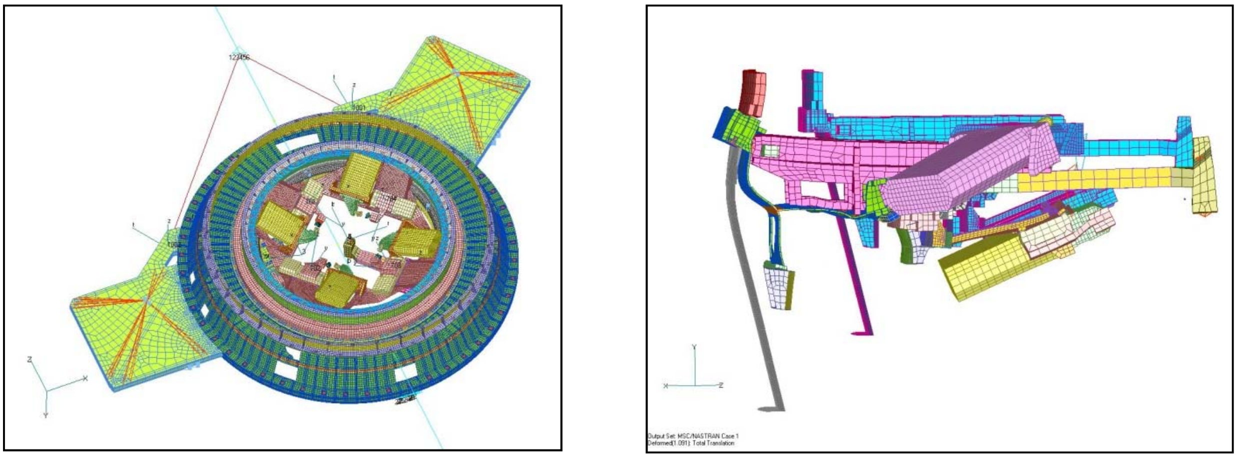


Figure 8: two views of finite element analysis for GRAAL. Left: handling case of GRAAL, right: thermal load on the MCM arm.

At the time of writing, all parts are delivered to NTE, and the company is now proceeding to the final mechanical integration steps. The GRAAL main assembly will then be tested before being delivered to the ESO headquarters beginning 2011.

Tests will be performed using a VLT simulator, allowing mounting and rotating the AO module to measure the behavior of the assembly prior to the integration of the optics. The measurement of the assembly flexures is a delicate operation and the test strategy has been revised to include optical measurements in addition to the initial 3D-measurement arm metrology foreseen initially. The 3D arm-metrology turned to be too risky for tilt measurement of the optics.

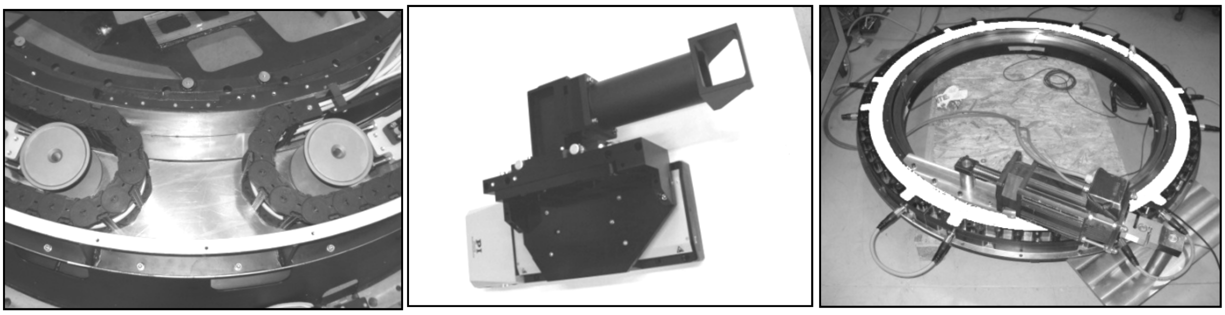


Figure 9: Subassemblies pre-integrated. Left: cable-guide system, steel flange and main structure (at NTE). Middle: tip-tilt unit without optics (at NTE). Right: torque-drive system (in test at PMC R&D laboratory).
http://dx.doi.org/doi.number.goes.here

3.4 WFS cameras

In GRAAL, 6 cameras are used in total; for the whole AOF the total amounts to 11 visible WFS cameras, meaning as many WFS-cameras that ESO has used on-sky in the VLT era. In addition, SPHERE will use the same camera, only with different lenslet array properties.

To enable this step, a large effort of standardization has been undergone, and all cameras are line-replaceable units. This has set tight constraints on the alignment of the lenslet array with respect to the CCD, and to the reference plate fo the camera. Moreover, very tight volume constraints have been set, and the cameras, which are sub-electron read-noise at kilohertz frame rate [10], remain within the dimensions of a cigar box: 235x200x75 mm. Each camera is powered and controlled by an external power supply assembly and workstation, while the pixel flow coming from each of the 8 output ports of the e2V chip is directly transmitted to the RTC wavefront processing units via an FPDP protocol.

We revised the specifications of the cameras after an excessively low temperature of the chip's window has been discovered in the thermal models (10º below ambient), with a risk of condensation on the window. The cameras shall now remain air-tight (leak rate < $5 \cdot 10^{-7}$ mbar $\cdot$ l / s) to make practical the maintenance of the units in operation. Once this leak level is reached, the addition of a small capsule of a dust-free molecular sieve in the housing allows a maintenance-free operation during the lifetime of the instrument (>10 years). In case of failure, the molecular sieve capsule can be accessed and replaced without opening of the camera. A dewpoint sensor embedded in the camera electronics boards will allow the detection of moisture content in the housing and the monitoring of the sieve saturation, allowing regular corrective maintenance to take place in due time and preventing losses of observation time.

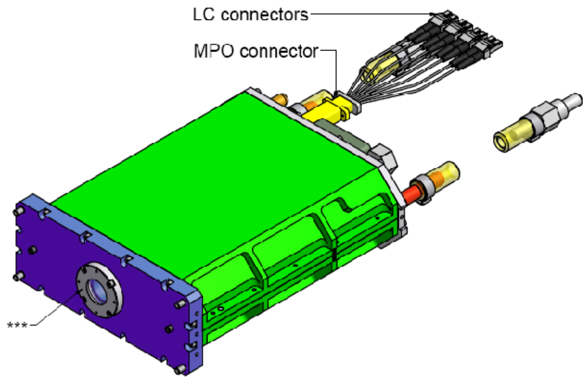


Figure 10: WFS camera unit. To the left, the entrance window, to the right the connections of the camera, including cooling supply, valves, electrical connections and fibre feed-through.

3.5 Electronics and software design

GRAAL electronics design follows the standards of Paranal instrumentation. Besides the usual alarm and motion control systems for instruments, it features a torque drive unit, which control required more attention in its development and specifications, given the constraints set at the system level.

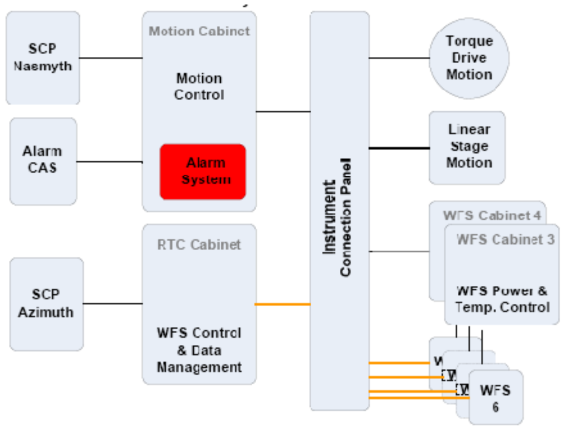


Figure 11: electronics system control overview. A minimal number of functions/controllers has been embedded on GRAAL rotating structure (right of the ICP), in order to minimize the impact on the mechanical design.

The GRAAL control electronics is distributed over four cabinets. Sensors, calibration lamps, 11 linear stages, 6 WFS and 2 cabinets are fixed to the GRAAL rotating structure. The structure does also include a torque drive motor for the LGS-WFS to track the pupil. An instrument connection panel (ICP) is attached to the structure providing a common cabling interface between HAWK-I Instrument and GRAAL Instrument, helping installation and maintenance of the instrument. All GRAAL cables routed through the HAWK-I co-rotator connect to the Instrument Connection Panel (ICP). GRAAL can be removed with a crane from HAWK-I after disconnection of all cables attached to this ICP.

Two cabinets are mostly dedicated to the WFS power supplies and embedded on the rotating main structure. The weight of the electronics is unfortunately large (up to 180 kg with the cabinets), due to the use of linear power supplies for the cameras and the number of cameras (6 units).
The other cabinets are used by GRAAL. They contain all motion controls for cabinet on the Nasmyth platform, and on the Azimuth platform is located the cabinet housing the SPARTA controllers and the New generation controllers for the WFS cameras, controlling the state of each camera.
Cables are linking all components of GRAAL, and over 1.5 km of cables and 100 connections are required to connect GRAAL internally and to the next connection points.
A special care has been brought to the safe operation of GRAAL.
Personal hazards have been addressed. The most specific feature of GRAAL in this matter is the torque drive system, which large dimensions can render interventions hazardous. Any intervention on the drive is normally performed while the system is disconnected, and emergency stop buttons are provided which require a specific acknowledgement before re-initialising the drive.
We addressed the reliability of the system by using redundancy whenever possible (e.g. by allowing the performance of GRAAL to remain acceptable even with 3 LGS instead of 4), by monitoring critical parameters, such as the moisture level in the WFS cameras and as well with the implementation of moisture sensors wrapped around the cooling liquid hoses, to detect failures of the cooling systems before they have dramatic consequences on the hardware.
Critical cooling failures inside the GRAAL structure are detected by a differential flow monitor, allowing the shutdown of the cooling system, and minimizing the potential damage brought to the instrument. Power and cooling supply are shutdown as soon as a flow rate difference is detected (>0.1-0.2 l/min).

GRAAL instrument software general architecture is standard for AO instruments in Paranal: a super-observing software (SOS) controls the functions of both the instrument Hawk-I and the AO module. The SOS controls directly the RTC supervisor, the wavefront sensors and the various motion controls.

The instrument software controls most offloads from SPARTA to the telescope like guiding offloads, as well as information flowing in the opposite direction, like true focus values from the telescope active optics. GRAAL software architecture is mostly common to the AOF, a noticeable difference being the development of the VLT library for derotator control, using a new version of a motor controller as a replacement for an obsolete one, widely used at ESO.

4. MANAGEMENT ASPECTS

In 2005, we started the first conceptual study for the module. After the conceptual design review in 2006 held in common with all other AOF subsystems, the project was approved for construction. Since then, a preliminary design review (PDR) took place in 2007, the final design review in 2009, and the construction of the module will be completed in 2011, driven by the arrival of the last WFS camera unit.

4.1 Resource conflict

Internal resources were associated to the project at the initial phases. However, it became obvious by the time the preliminary design phase was concluded, that a conflict of resources would appear in the course of the project development, with other AOF sub-systems as well as with other projects within the organization, especially the European ELT and ALMA. To prevent this affecting the course of the AOF development, we took the decision of outsourcing the final design and manufacturing of the GRAAL main assembly, including essentially all electro-mechanical assemblies attached to the Nasmyth focal plane. While a delay of about 8 months was created by this change of management strategy, the overall schedule for the AOF was relaxed by doing so. Later on, a similar approach was taken for the Laser source of the AOF, and to some extent for the Laser launch telescopes.

NTE has provided the final design following a detailed specification document issued three years ago. We issued a specification document providing all requirements necessary for the final design of the instrument, and covering all aspects of the system, mechanics, optical interfaces, electronics, integration aspects, safety at a stage where usually several iterations are needed.

Once the order placed with NTE, we progressed in common, learning in the process how to develop a common design. This has set additional constraints on the parts of the design remaining in our hands, like optics and some electronics. Adapting to the constraints of ESO was certainly a challenge for NTE, even though the company had an experience with other astronomical observatories, challenge that the Spanish team has met so far. Without cost increase, the schedule is as of now close to reach the final delivery of the main assembly very early 2011, without noteworthy deviation to the specifications besides a mass increase, chosen as a solution for solving an issue on differential thermal flexures.

4.2 Manufacturing and integration

Sorting chronologically the deliveries of GRAAL main subassemblies and associated components, the delivery schedule is:

May 2010: lenslet arrays (delivered)

August 2010: complementary integration structures for laboratory testing

Oct-Dec 2010: main optics (two batches)

Feb 2011: main assembly

Sep 2011-Mar 2012: WFS cameras (several batches)

July 2012: DSM acceptance

March 2013: installation in Paranal

GRAAL is on the critical path of the AOF schedule only after the delivery of the WFS cameras for final integration, and during its test period with ASSIST, a period of 13 months ending in 2013.

5. CONCLUSION

We have shown the performance, progress and perspectives for GRAAL, the Ground layer adaptive optics assisted by Laser. Doubling the surveying capacity of Hawk-I, its associated instrument. We reached a robust design by specification and redundancy. GRAAL will be available in 2012 for final testing in Garching and will be shipped and installed in the Paranal observatory in 2013.

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