The Adaptive Optics Facility Module GRAAL on its Way to Final Validation

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The VLT Adaptive Optics Facility (AOF) module GRAAL has been developed to provide ground layer adaptive optics correction for the HAWK-I infrared imager. This will improve the limiting magnitude and promote science cases requiring better spatial resolution. The gain in resolution is comparable to selecting a better site for the telescope. The GRAAL wavefront sensor signals are processed by a SPARTA real-time computer that drives the AOF deformable secondary mirror integrated in an upgraded secondary mirror assembly on Yepun, the VLT Unit Telescope 4. The system test phase of GRAAL has started in the integration laboratory in Garching and is described; provisional acceptance is expected to take place at the end of 2014.

The AOF project

The Adaptive Optics Facility, described in Arsenault et al. (2006), with progress reports in Arsenault et al. (2010a; 2010b; 2012; 2013), will transform the VLT's fourth Unit Telescope Yepun, (or UT4) into an adaptive telescope (Kuntschner et al., 2012). This is accomplished by replacing the conventional secondary (M2) mirror with an adaptive secondary, employing a deformable secondary mirror (DSM) described in Biasi et al. (2012), implementing the Four Laser Guide Star Facility (4LGSF; see Bonaccini Calia et al., 2011), and installing adaptive optics (AO) modules at the various foci. These AO modules consist of GRAAL (Ground Layer Adaptive optics Assisted by Lasers; described in Kissler-Patig [2005] and Paufique et al. [2012]) for HAWK-I, GALACSI (Ground Atmospheric Layer Adaptive Corrector for Spectroscopic Imaging; Stroebele et al. [2012]) for MUSE (Multi-Unit Spectroscopic Explorer), and ERIS (Enhanced Resolution Image and Spectrograph) to replace SINFONI (Spectrograph for INtegral Field Observations in the Near Infrared). The AOF components are tested on the ASSIST test bench (Adaptive Secondary Setup and Instrument Stimulator; Stuik et al. [2012]).

Project status

A GRAAL test readiness review was held in February 2013 and validated the plan to proceed with the system test phase. The GRAAL module was then integrated, with the exception of some wavefront sensor cameras needing refurbishment. It is presently mounted on the ASSIST test bench and the system test phase, using the GRAAL maintenance and commissioning mode, began in February 2014.

The ASSIST test bench itself was delivered by the Leiden Observatory and was granted Provisional Acceptance Europe (PAE) by ESO in October 2012. Shortly after, the DSM was mounted and aligned on ASSIST (see Arsenault et al., 2013). The optical tests of the DSM could then take place and lasted the best part of 2013, concluded by Technical Acceptance Europe, which was granted in December 2013.

In parallel with these activities the GRAAL module was mounted on ASSIST and aligned with the test bench; this turned out to be a complex task which took longer than expected. In January 2014 the alignment was judged to be satisfactory and several issues (such as ghost reflections and image quality) had to be solved. The infrared camera (CAMCAO) of the Multi-conjugate Adaptive Optics Demonstrator (MAD) instrument has been re-used and is installed on GRAAL in order to measure the resulting image quality after AO correction.

All the above elements were required in order to ensure a smooth and efficient transition to the conduct of the first phase of the AOF system tests with the GRAAL module.

The other AOF major systems can be developed on a parallel track for the time being. GALACSI module integration is well advanced but not completed. One of the four Laser Guide Star (LGS) optical paths has been aligned and furnished with a wavefront sensor camera (priority was granted to GRAAL). However, many of the module subsystems have been characterised and were validated during 2013. Technical templates are used to perform these tests in a consistent manner and the observing and instrument control software of GALACSI is also well developed (there was also a synergy exploited with the GRAAL software modules). The jitter loop actuator was validated as well, which allowed a complete loop with SPARTA (Standard Platform for Adaptive optics Real Time Applications), the wavefront sensor camera and the jitter actuator to be closed. The GALACSI module should be validated in standalone mode before the end of 2014 in order to take the place of GRAAL on ASSIST when the system tests with this module are complete.

The 4LGSF project is also progressing well. The first 22-watt laser unit has been delivered to Garching and PAE has been granted for this unit. The laser has been installed on the first launch telescope system and a full end-to-end test is well advanced. The second and third launch telescope system units will be integrated and aligned this summer and a subset of tests run on these units. The system test phase of the 4LGSF will start this summer with the aim for a complete system PAE in early 2015.

It is planned to ship the GRAAL module and the first LGS unit to Paranal towards the end of 2014, allowing an early installation of these systems on UT4 for the first quarter of 2015. This milestone will inaugurate the commissioning of the AOF in Paranal by combining these two systems to validate 4LGSF–GRAAL functionalities before the arrival of the DSM, planned for the fourth quarter of 2015.

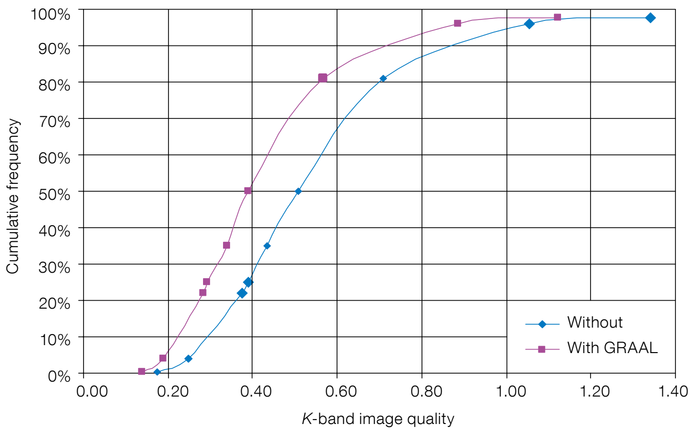

Figure 1. A plot of the cumulative frequencies of *K*-band image quality with (pink) and without (blue) the GRAAL module.

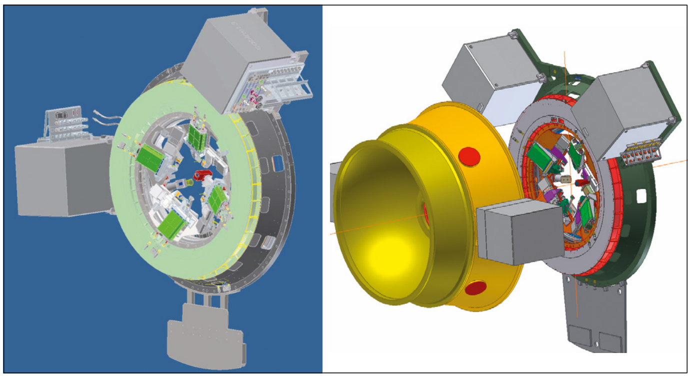

Figure 2. A schematic of the GRAAL module with the four laser guide star wavefront sensors shown in bright green (left). The HAWK-I spacer that comes over the GRAAL assembly is shown (right).

GRAAL module background

The basic idea of the GRAAL module emerged in 2005 while preparing the conceptual design review of the AOF (Arsenault et al., 2005). A basic description of the module can be found in Paufique et al. (2012). The challenge was to define how AO could serve an infrared imager with such a large field of view as 7.5 arcminutes. The proposed improvement, equivalent to moving Yepun with HAWK-I to a still better observing site, can be provided by Ground Layer Adaptive Optics (GLAO) correction (see Figure 1). Thus GRAAL allows the astronomer to perform the most challenging science cases nearly all of the time, rather than a small fraction of the time (as described in the science case document for GRAAL, Kissler-Patig [2005]).

GRAAL (see Figure 2) is designed to reduce the full width at half maximum (FWHM) for *K*-band images by 25% over the full 7.5 arcminute field of view of HAWK-I. Although it appears moderate as a goal, it represents a similar challenge to the GLAO mode of GALACSI for MUSE (the doubling of the ensquared energy per pixel over a 1-arcminute field of view at 750 nm).

GRAAL has the following features:
– The original field of view of HAWK-I is left unobstructed and a seeing-limited mode is available.
– Four laser guide star Shack–Hartman wavefront sensors (each with 40 × 40 sub-apertures) are located at 6.6 arcminutes from the field centre.
– A tip-tilt star sensor probes an annular region of 2-arcminute width, i.e., covering 13.2-arcminute inner diameter to 15.2-arcminute outer diameter.
– A natural guide star mode on-axis is provided, dubbed the maintenance and commissioning mode. The role of this mode is to ensure proper functioning of the DSM and allow a first commissioning of a basic single conjugate AO system.

The maintenance and commissioning mode will be used first on sky to evaluate the ultimate performance of the DSM in a simpler configuration. It requires a tight error budget and allows marginal failures of subsystems to be detected more easily, such as defective actuators or control issues.

In its nominal operational mode (i.e., GLAO), the four LGS wavefront sensors analyse the returned light from the four 22-watt lasers launched from the UT4 centrepiece. SPARTA determines the commands to be applied to the DSM from the four real-time video signals. The refresh rate of the command is 1 ms.

AOF synergies

GRAAL and GALACSI are the non-identical twins of the AOF; despite being different, they share similar “genetic baggage”. They of course share the 4LGSF and the DSM. In addition, their design was been also made common where possible, so as to optimise the test and operation of the systems, reduce development costs and share maintenance effort.

The SPARTA real-time computer hardware is identical for GRAAL and GALACSI (see Figure 3 left), which allowed either system to be used for development during the integration. The software is common between both, where applicable: GRAAL and GALACSI GLAO corrections are essentially identical for their real-time operation. The maintenance and commissioning mode is an additional instance of the version of SPARTA built for the SPHERE instrument.

The wavefront sensor cameras (see Figure 3 right) are also identical in GALACSI and GRAAL, which enables serial production and common management of spares. Six cameras using L3 CCD220 from e2v are used in GRAAL: one as tip-tilt sensor, one as natural guide star for the 40 × 40 Shack–Hartmann (maintenance and commissioning mode), and four as laser guide stars for the 40 × 40 Shack–Hartmann (GLAO) mode. These cameras use electron gain amplification in order to reduce the readout noise of the CCDs. Although the readout

Figure 3. The two SPARTA computers for GRAAL and GALACSI (left). They are based on identical hardware, but run different software codes adapted to the AO modules. These cabinets will be located in the *bodega* of UT4 to save room on the azimuth and Nasmyth platforms. An optical fibre pair needs to run to the wavefront sensor cameras for data transfer. A wavefront sensor camera running an e2v L3 CCD CCD220 is shown (right). The camera fulfills the expected performance of < 1 e- readout noise at 1 kHz frame rate.

noise is nominally high (70 e-) the gain amplification mechanism reduces its effective value to below one photoelectron. The gain in question can be selected from 1 to 1000 and the AOF cameras are used at a gain value of ~ 100 which reduces the readout noise to an acceptable level (1e-) to reach the system performance, while protecting the camera from quick aging (a risk at high gains). Last, but not least, this extraordinary performance is reached at 1 kHz frame rate to match the AOF closed-loop frequency.

Activities over the past year

The integration and validation of the GRAAL subsystems took place during 2012 and 2013. The co-rotator was a critical piece of equipment that necessitated careful attention during this period. Several technical templates were developed and early tests were carried out using these templates and the GRAAL observing and instrument control software.

The GRAAL main assembly concept was defined at ESO, but its final design and test was outsourced and executed by the company NTE-SENER, near Barcelona, Spain. At the heart of this concept lies the co-rotator, allowing the four LGS wavefront sensors of GRAAL to each track their artificial beacon and the pupil, while the rest of the instrument rotates with the science target field of view. The system tracks the guide stars with an accuracy on sky of better than 30 milliarcseconds, and avoids introducing any significant contribution to the laser jitter. Opto-mechanical interfaces have been verified by means of a laser tracker, both in terms of position and flexures.

The installation of GRAAL on ASSIST did not reveal any major discrepancy, thanks to the verifications performed separately on individual subsystems. Nevertheless, the large structure installed in the ESO assembly hall suffers from slow drifts due to some thermal variations, which are inherent to the design of the structure and to the laboratory environment. Vibrations related to human activities in or near the laboratory also restrict the operations with the system when delicate and long-lasting measurements are necessary. Vignetting, image quality and ghosts issues were solved in the last stages of the alignment in January 2014.

Start of system test phase: first results

The first issue of the AOF system test plan dates back to May 2009. Following the test readiness review in February 2013, a detailed test procedure document was prepared for GRAAL. A quick description is given for each test, detailing the expected duration, pre-requisites or inputs, detailed procedure and Pass/Fail criteria and the outputs. This has allowed the AOF to proceed swiftly with these tests when the GRAAL module alignment on ASSIST was completed.

The preliminary tests focused on establishing the basic characteristics of the setup:
– calibrating the wavefront sensor detectors: background versus gain, noise versus gain, etc.;
– pupil illumination on the detectors;
– measurement of slopes with various centroiding methods;
– estimation of optical aberrations;
– calibration of the flux received from the ASSIST source;
– infrared camera image quality.

Figure 4 shows some pupil images from these tests and Figure 5 shows GRAAL in its testing configuration.

Then followed the apparently simple task of measuring the pixel scale of the wavefront sensor (how many arcseconds of motion on the sky correspond to one pixel on the detector). However, it is a crucial task since it allows the good behaviour of many hardware and software components of the system to be checked, even before closing the AO loop. The measurement procedure is simple: sending small tilt offsets to the DSM hexapod and recording simultaneous images on the wavefront sensor.

Determining the interaction matrix

The next major task of the system tests concerns the generation of the AO interaction matrix (IM). It contains the response of the wavefront sensor to deformations of the DSM and allows, after inversion, the DSM commands, correcting the measured turbulence, to be applied at 1 kHz to be computed. In the case of the DSM, this matrix is composed

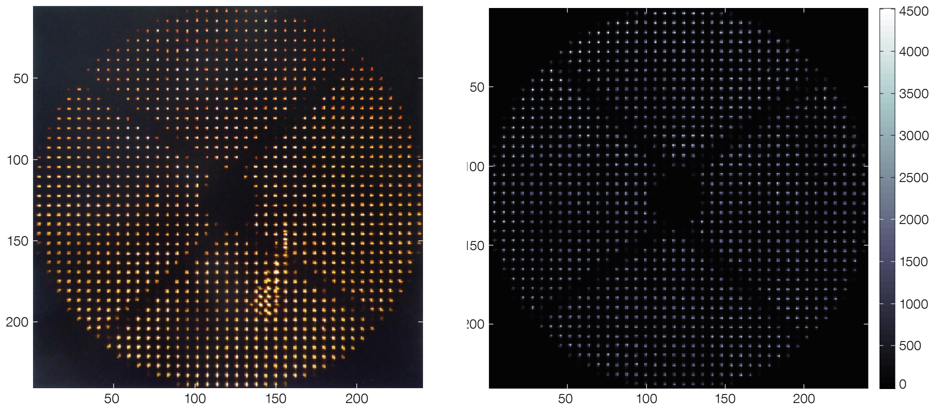

Figure 4. Pupil image on the maintenance and commissioning camera as seen on ASSIST. The spider on ASSIST is larger than the Unit Telescope design. Left: Ghost superimposed to the normal spot pattern, before correction; Right: After installation of the pupil baffle.

of 1156 rows (DSM valid actuators) and ~ 2480 columns (40 × 40 apertures in a circular area, each with two slopes — one in X and one in Y).

In classical post-focal AO systems like the VLT NAOS instrument, the IM can be re-measured at will by placing an artificial source at the entrance focal plane of the instrument. But this is not possible on an adaptive telescope like the VLT equipped with the AOF, as the DSM is part of the telescope optical train. Hence the baseline for the AOF is to use a pseudo-synthetic interaction matrix (PSIM), based on a computer model of the DSM and wavefront sensor, fine-tuned by matching it with measured characteristics of those same components: wavefront sensor response and DSM influence functions.

As this method is quite a novel concept to be implemented on a scientific AO instrument, it is important for it to be tested in the laboratory and ASSIST offers this possibility. The atmosphere emulated by optical turbulent phase screens can be removed, and an interaction matrix can be measured. Such matrices will be measured using several different methods and their performance will be compared with that of the PSIM. More precisely, zonal (each DSM actuator is poked individually) and modal (DSM stiffness modes or atmospheric Karhuenen–Loeve modes) IMs will be compared, either recorded with or without turbulence. For each method, several parameters, such as the amplitude and number of the cycles, can be varied to maximise the IM signal-to-noise ratio.

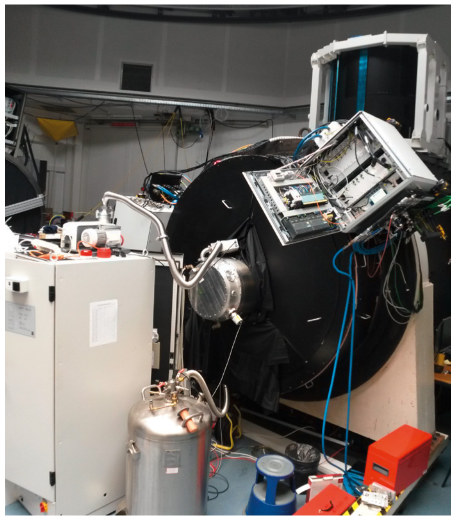

Figure 5. The AOF test configuration in the old integration laboratory in Garching. The DSM sits on top of the ASSIST bench and the GRAAL module is mounted on the Nasmyth focus simulator. In the foreground the CAMCAO silver cryostat can be seen; this camera is used to record output images corrected by the adaptive optics.

An AOF zonal IM is composed mostly of zeroes because the influence of one actuator is seen on a few sub-apertures only. Thus the display of such a matrix in full is pointless and is barely resolvable by a computer screen. Instead we have been using a display of the 40 largest signals along X and Y in the sub-apertures for each actuator. This reduces the matrix

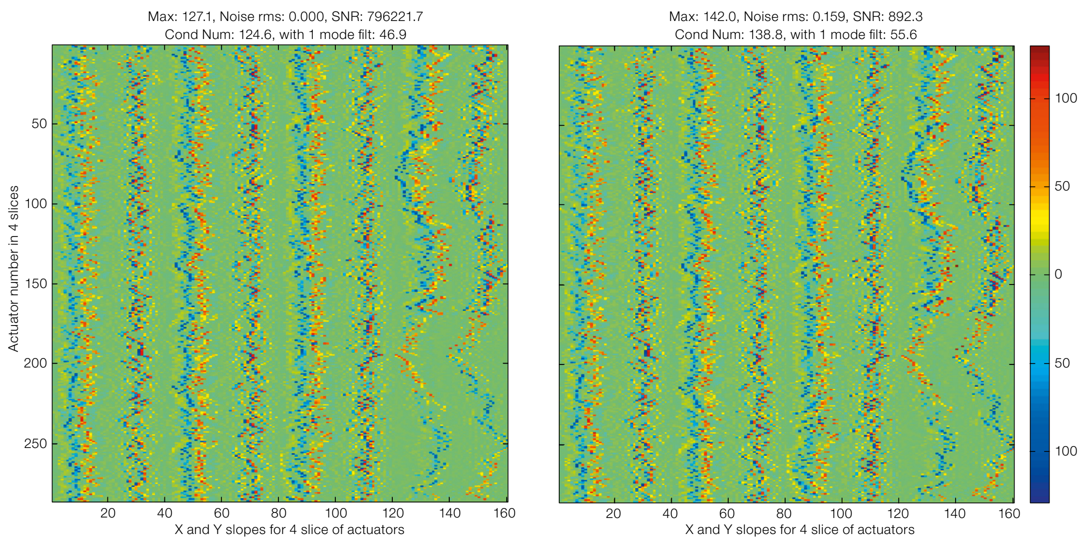

Figure 6. Pseudo-synthetic interaction matrix (left) *vs*. measured integration matrix (right) in a condensed display. The eight vertical stripes that compose them are, side-by-side, the X and Y slopes for the actuators 1–289, 290–578, 579–867 and 868–1156. The two matrices seem to differ only in their signal to noise ratio (SNR): ~ 900 for the measured integration matrix against almost infinite for the pseudo-synthetic integration matrix.

to 80 × 1156 elements, which we have then folded four times to produce a squarer and easier to display matrix of 289 × 320 elements (Figure 6).

Some parameters of the PSIM have to be tuned in order to match the real IM of the system. Those parameters, which describe the pupil mismatch between the DSM and the wavefront sensor, are the X and Y shifts, the rotation and the X and Y magnification. A method developed at ESO (Bechet et al., 2012) allows those parameters to be identified after iterative comparison of the PSIM with a measured one — hence the importance of being able to measure an IM even on-sky. This method has been applied and a PSIM could be generated that is very close to the measured one (see Figure 6). It has even been used to close the AO loop and, on a limited number of tests, managed to deliver the same performance as the measured one.

Closing the AO loop at 1 kHz between the wavefront sensor and the DSM via SPARTA revealed no major issues. This was tested at first on the calibration fibre, correcting only the local turbulence in the laboratory with an increasing number of modes. When few modes are truncated, the print-through of the spiders is visible, indicating that the sub-apertures behind them have to be handled carefully to avoid the "island effect" inherent to systems with a segmented pupil. In addition to a differential piston in the four islands, another problem to consider in the case of a force-controlled DSM is that the sharp discontinuities in the DSM shape behind the spiders require more force to control and thus limit the available range of correction. These issues will be fixed in the coming months during AOF system tests.

Finally, the optical phase screens that emulate turbulence with seeing of 0.65 arcseconds were introduced and rotated to reproduce the characteristic Paranal wind profile. The AO loop could be closed with an integral gain of 0.4 and three different sets of modes: 150, 550 and 950 (see Figure 7). It can be noticed that the major part of the turbulence is corrected and the GRAAL maintenance and commissioning mode delivers very sharp images, close to the one recorded on the calibration source (rightmost image on Figure 7). Preliminary results provide a reference Strehl ratio measured on the calibration fibre of 76% and on the closed loop images of 65%, i.e., a relative correction of 85% at 1.65 μm.

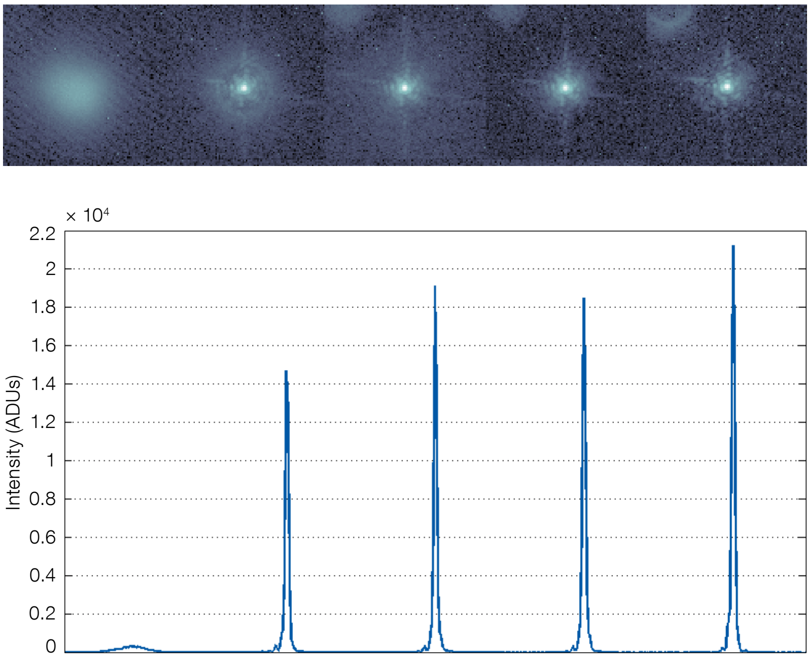

Figure 7. Long-exposure *H*-band images (top) and their horizontal cuts (bottom) recorded (from left to right): in open loop turbulence, in closed loop on turbulence with 150, 550 and 950 modes controlled, and in closed loop on the calibration fibre (rightmost image).

Prospects

With the completion of the integration of its AO module, GRAAL, the AOF project has entered the system test phase. With the maintenance and commissioning mode and a natural guide star wavefront sensor of 40 × 40 sub-apertures, combined with the SPARTA computer and the DSM, the AOF team has started obtaining data that validate the strategy developed and are already showing spectacular results.

The system test phase will continue with the GRAAL ground layer AO mode until the end of 2014. Then the GALACSI module will take the place of GRAAL on the ASSIST bench and this module will undergo similar tests until mid-2015.

The first commissioning activities in Paranal are planned to take place in early 2015 after the shipment of the GRAAL module and the first LGS unit. The DSM with GALACSI will be delivered toward the end of 2015.

Acknowledgements

It is becoming more and more difficult to select a list of authors for articles concerning the AOF project because it has been going on for a long time and so many ESO staff have been involved in one way or another. The first author wishes to thank the collaborative and pro-active attitude not only of all the project team members, but also of all ESO staff who have contributed and are always willing to help.

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