The VLT Adaptive Optics Facility Project: Telescope Systems

Robin Arsenault[1]
Norbert Hubin[1]
Stefan Stroebele[1]
Enrico Fedrigo[1]
Sylvain Oberti[1]
Markus Kissler-Patig[1]
Roland Bacon[6]
Richard McDermid[7]
Domenico Bonaccini-Calia[1]
Roberto Biasi[3]
Daniele Gallieni[4]
Armando Riccardi[5]
Rob Donaldson[1]
Miska Lelouarn[1]
Wolfgang Hackenberg[1]
Ralf Conzelman[1]
Bernard Delabre[1]
Remko Stuik[7]
Jerome Paufique[1]
Markus Kasper[1]
Elise Vernet[1]
Mark Downing[1]
Simone Esposito[5]
Michel Duchateau[1]
Marijn Franx[7]
Richard Myers[2]
Steven Goodsell[2]

[1] ESO
[2] University of Durham, United Kingdom
[3] MicroGate
[4] ADS International
[5] INAF – Osservatorio Astrofisico di Arcetri, Italy
[6] CRAL, Observatoire de Lyon, France
[7] Leiden University, the Netherlands

The Adaptive Optics Facility is a project to convert UT4 into a specialised Adaptive Telescope. The present secondary mirror (M2) will be replaced by a new M2-Unit hosting a 1170-actuator deformable mirror. The three focal stations will be equipped with instruments adapted to the new capability of this UT. Two instruments have been identified for the two Nasmyth foci: Hawk-I with its AO module GRAAL allowing a Ground Layer Adaptive Optics correction and MUSE with GALACSI for GLAO correction and Laser Tomography Adaptive Optics correction. A future instrument still needs to be defined for the Cassegrain focus. Several guide stars are required for the type of adaptive corrections needed and a Four Laser Guide Star Facility (4LGSF) is being developed in the scope of the AO Facility. Convex mirrors like the VLT M2 represent a major challenge for testing and a substantial effort is dedicated to this. ASSIST, is a test bench that will allow testing of the Deformable Secondary Mirror and both instruments with simulated turbulence. This article focusses on the telescope systems (Adaptive Secondary, Four Laser Guide Star Facility, RTC platform and ASSIST Test Bench). The following article describes the AO Modules GALACSI and GRAAL.

History of the project

Pioneering efforts were made at the MMT to equip the 6-m telescope with a Deformable Secondary Mirror (DSM). The system was designed and fabricated by an Italian consortium composed of MicroGate, ADS Intl and the Osservatorio Astrofisico di Arcetri. The same consortium is now involved in the development of the two DSM's for the Large Binocular Telescope (Mount Graham). The technology has matured substantially and it seemed appropriate to investigate whether this technology was promising for the VLT.

A feasibility study was launched in June 2004 with MicroGate as the main contractor (including also ADS and OAA). The goal was to demonstrate the feasibility of such a design for one of the VLT 8-m telescopes. The study came to a positive conclusion in August 2005 and a corresponding data package was delivered covering all main aspects of the design.

In the course of the feasibility study, it became obvious that the scope of the project needed to be broadened in order to answer some basic questions: What are the scientific advantages of such an improvement to the UT? What are the implications on the various systems for the UT and its operation?

A conceptual design review took place in September 2005 to address these questions; it involved several ESO staffs and a few external review board members. The conclusion was positive and it was later endorsed by ESO management as a high priority project and by the STC in October. In December, ESO Council also approved the AOF which is the final approval and gave the green light for the project.

Strategy rationale

There are fundamental advantages to have one mirror of the telescope train being adaptive. The whole telescope then becomes an adaptive optical system offering fast wavefront correction without the addition of supplementary optics or mechanics. Moreover, with the two Nasmyth and Cassegrain foci this gain is threefold. The system gives better throughput to science instruments, lower emissivity for thermal IR instruments, large field of view accessible to all instruments and less complexity/crowding at the focal planes.

The alternative to a DSM is a 'post-focal' AO system (à la NAOS) which involves an optical train of five to six supplementary warm mirrors at the image focal plane. Table 1 provides a trade-off analysis that justifies the choice of a DSM, although there are other drivers for this choice.

During the elaboration of the AO Facility design it became clear that such a combination of several complex systems raises important questions particularly in term of AIT, commissioning and control strategy. Such questions, typical of

Criterion	DSM	Post-Focal	Comment
Throughput	Optimal	~ 75 % optimal	
Field of View	Full UT FOV (10′ for Hawk-I LGS)	Smaller due to relay optics (1′ for NAOS)	Post-Focal optical design and the mechanical implementation for relay optics is difficult and provides smaller FOV
Emissivity	Optimal	Larger; exact factor not well known but likely around three	
Cost	€ 1.4 M saving per AO system versus cost of DSM		
FTE	Gain not well defined	Gain not well defined	Possibly a slight advantage to DSM
Spare M2-Unit	Yes	No	The decommissioned Dornier M2-Unit becomes spare for the three other UT's
GRAAL-Hawk-I	OK	Not feasible because large FOV	
GALACSI-MUSE	OK	Very cumbersome mechanical implementation (has been studied)	
Cass. AO + INS	Undefined	Undefined	Great advantage of DSM if instrument exploits Thermal IR
VLTI	Piston: 1170 capacitive sensors with 3 nm RMS accuracy	No impact	
Chopping	~ 6″ on sky	~ 20″ on sky	Reduced chopping of DSM w/r actual M2-Units

Table 1: Technical trade-offs for the AO Facility.

any telescope design including several deformable mirrors (ELTs), and their corresponding answers would benefit tremendously from a hands-on experience gained on a VLT "prototype". In this perspective the AO Facility becomes a highly relevant pathfinder for any ELT design. This argument became an important motivation for ESO management to pursue the AOF concept *with* a DSM. The list below illustrates common issues between AO Facility and an ELT:
- Develop a high-order adaptive telescope at the diffraction limit
- Secure and improve current large DM with 30 mm spacing (~ M6 for OWL)
- Secure manufacturing and handling of large thin shells
- Develop and monitor robust Laser and CCD technologies
- Provide large computing power for AOF ~ 1 kHz (factor 200 w/r NAOS)
- Develop, operate and master Laser Tomography AO and Ground Layer AO systems
- Elaborate and control a detailed error budget to reach the Strehl ratios required
- Master interaction matrix measurement strategies (in-lab and on-sky)
- Manage multiple interlaced control loops and offloading processes
- Develop extensive DSM testing procedures in the laboratory
- Manage efficient commissioning of such a complex facility

Facility description

The following systems/projects are being conducted in the context of the AO Facility:
- A new-generation M2-Unit hosting a 1170-actuator deformable mirror
- A four-Laser Guide Star Facility using fiber lasers and four Launch Telescopes on the UT centrepiece
- SPARTA: a flexible Real Time Computer Platform to perform the AO correction of the AO modules (and others)
- GRAAL: the AO module allowing wavefront sensing and Ground Layer AO correction for Hawk-I
- GALACSI: the AO module allowing wavefront sensing and GLAO and Laser Tomography correction for MUSE
- ASSIST: a complete test facility allowing complete testing and characterisation of the AO Facility in Europe
- A dedicated effort to address AO calibration issues for the various AO modules

Second-generation M2-Unit

The concept of thin shell and force actuators is one of the most promising in the field of large deformable mirrors; the largest deformable mirrors have been built/designed with this technology. A 642 mm diameter convex secondary mirror with 336 actuators has been developed and is being used by the MMT (Mount Hopkins, Arizona), while the two 911 mm diameter and 672 actuators concave secondary mirrors of the LBT (Mount Graham, Arizona) are being integrated. A similar design is envisioned for one of the VLT Unit Telescopes; the deformable secondary design is 1120 mm in diameter and the thin shell is 2 mm 'thin' while offering 1170 actuators for adaptive correction (see Figure 1).

These mirrors are composed of three basic elements: a back-plate, hold, a reference body and the thin shell. The back plate has two functions: holding the voice coil actuators and evacuating heat dissipated by the coils with the help of an integrated cooling fluid circuit. Each voice coil applies a force to a corresponding magnet glued onto the back face of the thin shell. A ring of conductive material is deposited around each magnet and is mirrored on the reference body. These two opposite coatings constitute a capacitance used as gap sensor. The reference body being a calibrated optical surface, an equal spacing for all capacitive sensors insures a relatively good optical quality on the shell.

An internal control loop at 80 kHz insures that the force applied maintains the capacitive sensor to a constant gap. Note also that the derivatives of the capacitive sensor positions provide a measure of the velocity of the shell displacement which in turn is used by the system to define an electronic damping; this feature insures high bandwidth for all mirror modes.

The reference body is a conventional, thick, Zerodur optical component, with the exception of the numerous cylindrical openings allowing passage for the actuators. The VLT design explored a light-weighting scheme (50–60 % light-weighted Zerodur or SiC) to reduce the weight of the complete assembly (realistic without being a huge cost driver). SiC offers the added advantage of being extremely rigid compared to Zerodur. This is important since the rigidity of the reference body insures a reliable shell figure.

The thin shell provides, at rest, the same optical properties as the actual Beryllium mirrors of the VLT M2. The optical surface is thus convex and the optimal shell thickness has been defined as 2 mm thin. To remain within a known field of expertise, the shell is manufactured from a thick Zerodur blank, and is therefore a costly and delicate component. Note that other avenues are explored for thin shell manufacturing in the context of large DM for ELTs (i.e. slumping).

Detailed simulations show that the residual error with all modes corrected is 62.5 nm rms, fulfilling the specifications (see Table 2).

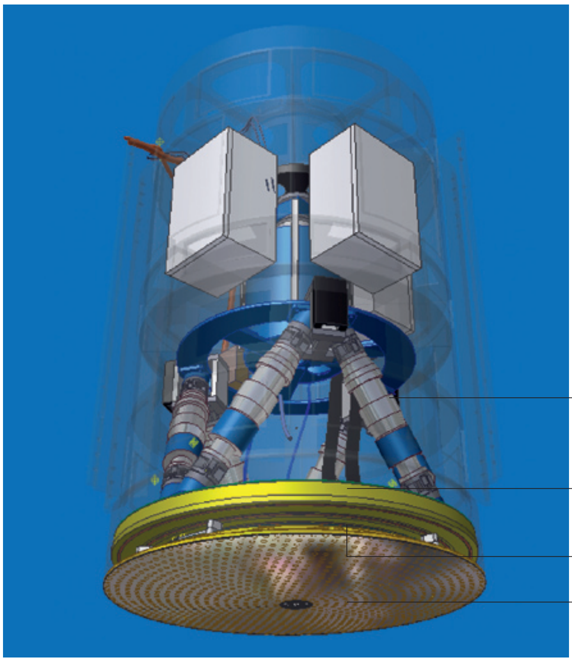

Figure 1: Conceptual design for the 1120 mm diameter, 1170 actuator VLT deformable secondary mirror. The M2-Unit contains the electronics (top), Hexapod for centring and focusing (middle) and the deformable thin shell (bottom).

Parameter	Value
Median seeing at 30 deg: r_0 (0.5 μm)	12.1 cm (0.85″ at 500 nm)
Specified fitting error	78 nm rms
Fitting error (all modes) 1170	*62.5 nm rms*
Zernike modes fitting error	70.0 nm rms
1170 KL modes fitting error	60.2 nm rms
max PtV actuator displacement	13.6 μm
max rms actuator displacement	1.66 μm rms
max peak force	0.82 N
max rms actuator force	0.17 N rms
rms force	0.157 N rms

Table 2: Summary of the simulation results in the median seeing case. Results of fitting 10 000 uncorrelated wavefronts (this represents the capability of the DSM to fit a turbulent wavefront. It does not take into account the time delay of the AO control loop).

Calibration requirements

A fundamental limitation of AO systems based on an adaptive secondary mirror like the VLT M2 is that there is no intermediate focus before the deformable mirror. Therefore, it is not possible to install an artificial calibration source, seen by the DM and the Interaction Matrix (IM) measurement in a conventional way is not possible. An extensive program has been initiated at ESO to study this limitation and explore alternatives.

Several solutions are being envisioned for the IM measurement. First, Synthetic (simulated) IM using measured influence functions of the DSM in the laboratory and calibration of the WFS optical path, and second, several different methods of performing on-sky IM measurements.

Even if the synthetic IM is the most seductive solution (noiseless, simplicity, no calibration time required), it still has to be demonstrated that the accuracy of the models (DM and WFS) can be high enough to ensure the expected performance. Regarding the experimental estimation of the IM, novel techniques are investigated in order to deal with the new issues that we have to face: There is turbulent noise either because the calibration is performed on sky or because of the telescope internal turbulence. The calibration time might dramatically increase because of the larger number of degrees of freedom. Several methods are being investigated through simulations and laboratory tests as well as on sky tests when possible. The different schemes aim at minimising the noise and bias on the measurement in order to optimise the quality of the reconstructor.

Using various modal bases (zonal, Hadamard, system modes/mirror modes, Zernike or Karhuenen-Loeve), several techniques are foreseen and being compared: (1) Open loop fast DM actuation, which allows freezing the disturbances between modal push and pull and thus minimise turbulent noise as well as any low-frequency effect. (2) Open-loop DM modulation and demodulation by FFT detection. The stimulus power is concentrated on a single frequency beyond the modal atmospheric bandwidth. Low-frequency effects are cancelled out and it allows for multiplexing. This way, several modes can be measured simultaneously, reducing the total calibration time. (3) Closed-loop calibration. Dynamic bias is applied as offset on the WFS signal. The DM command is measured as a response to this bias and therefore the reconstruction matrix (or control matrix) is measured directly.

Furthermore, there is a key issue related to calibration. A pupil offset may have a strong impact on the system performance and must be addressed properly. Indeed, for high-order AO systems such as VLT with DSM, the tolerance is very tight. Dynamical pupil alignment is envisioned to minimise this effect. The several investigated techniques appear promising and have convinced the AO Facility review board of our sound approach.

Therefore, in terms of simplicity and time consumption the most attractive choice is to simulate the IM. A few more aspects of this method need to be secured, and in particular the AO Department will assess the impact of the model errors on the system performance and robustness.

Four Laser Guide Star Facility

Four Laser Guide Stars are required for the type of corrections needed; it is envisioned to perform Ground Layer Adaptive Optics for Hawk-I and MUSE involving averaging turbulence measurements in four different directions around the field of view.

The choice of four launch telescopes on the centrepiece is preferred in order to avoid the so-called 'fratricide' effect. This degrades the wavefront sensor measurements when, for instance, four beams are launched from behind M2; inevitably, the beams cross the path of the neighbour sensors and 'pollute' some subapertures increasing the background light level and therefore noise. This effect is reduced if lasers are launched from outside the telescope pupil (centrepiece).

The upgrade of the LGSF to four LGSF takes full advantage of the existing *Laser Clean Room*. As much as possible, the electronics cabinets are in the LCR, the interlock panel and the fibre laser sources are in the LCR, and most of the heating/cooling is confined to this space. The easy access to LCR helps in servicing and maintenance, and the numerous safety issues become more manageable. The existing LCR was already dimensioned to host multiple lasers, in the LGSF project. Moreover, with fibre lasers the power consumption is much reduced. Hence very little modifications are required to the Laser Clean Room for the upgrade to 4LGSF. Other systems from the existing LGSF are being re-used, such as the Aircraft Avoidance System.

The baseline lasers are 1178 nm fibre Raman lasers, which are frequency doubled to 589 nm. The fibre delivers 20+ W CW at 1178 nm, 1 GHz linewidth. The frequency doubling is done via a single pass on PPSLT, a non-linear crystal. The fibre laser is an on-going development at ESO, together with the companies IPF Technology Ltd (UK), Toptica (D) and the Russian branch of the company Volius. ESO has so far reached 2.9 W CW at 589 nm in its lab, aiming to reach full power in the second half of 2006.

The polarisation maintaining single-mode fibre will directly reach the Launch telescopes using a fireproof fibre cable and going through the altitude cable wrap up to the UT4 centrepiece. At each launch telescope, a small box contains the frequency doubling PPSLT crystal, its temperature controller and the frequency feedback control sensor. The frequency doubling unit is located at the Launch Telescope.

The four Launch Telescopes located on the centrepiece (Figure 2) have demanding requirements. The projected laser beam quality has to be diffraction limited to guarantee the minimum LGS angular size, which imposes constraints on the optical train and calls for the maximum simplification possible. Care has to be applied for optics working at high power densities. This requirement coupled with the flexibility to point the LGS at 0, 60 or 330 arcsec off-axis, as required by MUSE and Hawk-I, has driven the choice of the Launch Telescope optics toward a refractive, single-lens f/5 design, with the fibre laser output at its focal plane. The first Eigenfrequency of the LTS has to be > 60 Hz, in order to avoid LGS wandering and unwanted jitters. This imposes strict choices on the mechanical support structure of the LTS, which is in CFRP to ensure stiffness and reduce weight.

Above the Launch telescope, there is a movable shutter curtain to protect the lens when it is not in use, and a long baffle to avoid as much as possible scattering light in the telescope environment. In operation the diagnostic system can be in or not. A motorised flipper mirror can optionally send the output beam to a Coherent LM-45 calibrated power-metre, to measure the output beam power.

ASSIST

A complete testing of the 'AO system' as done for conventional ones (NAOS and such) is not possible without the telescope, or a sophisticated facility reproducing the opto-mechanical interfaces. In the present case there is the additional complexity of testing a large convex optical component.

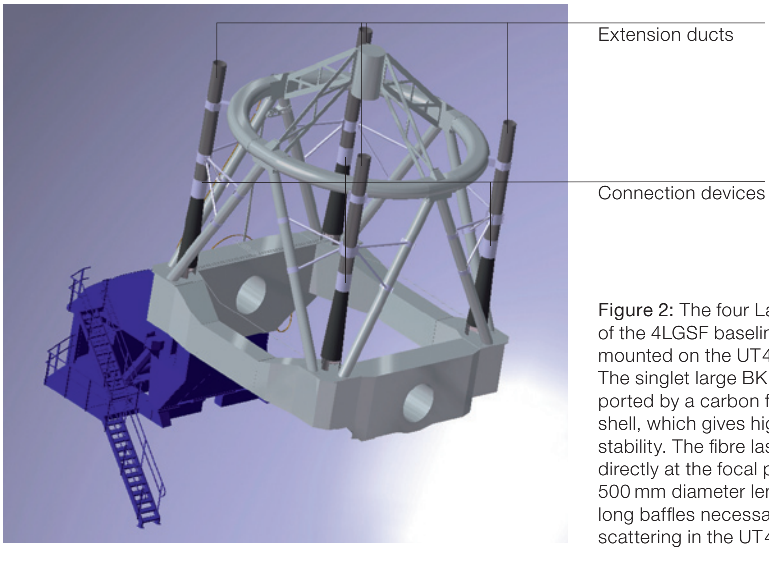

Figure 2: The four Launch telescopes of the 4LGSF baseline design are mounted on the UT4 centrepiece. The singlet large BK7 lenses are supported by a carbon fibre cone-shaped shell, which gives high rigidity and stability. The fibre laser output goes directly at the focal plane of the f/5, 500 mm diameter lens. Note the long baffles necessary to avoid light scattering in the UT4 dome volume.

The Test Facility described below is in itself a complex and relatively costly system; think only of the 1.65 m concave mirror required. However, one must not neglect the usefulness of investing in a versatile and complete test facility in order to characterise and understand these systems. It will allow the designer team to gain sufficient confidence and invaluable experience with the adaptive optics systems before re-assembly and integration on the telescope. In the end this will save valuable telescope time by minimising commissioning time.

This facility will not only allow testing of the DSM itself, but it will also provide a turbulence generator to simulate AO correction in realistic conditions and VLT standard opto-mechanical interfaces to the AO pre-stages GRAAL and GALACSI for the instruments Hawk-I and MUSE respectively.

The opto-mechanical design shown in Figure 3 is composed of two mirrors plus the VLT DSM. The latter is mounted on a vertical structure holding the M2 unit thus providing a support identical to the one of the VLT. The gravity vector is along the M2 optical axis. Two other optical components are required: a main 1.65 m diameter aspheric mirror and a smaller 140 mm diameter aspheric mirror. The asphericity of the former can be handled by conventional polishing techniques while the fabrication of the second would require diamond turning. This setup would offer a 2-arcmin field of view and no pupil distortion.

Conclusions

ESO is fully dedicated to this major endeavor, requiring some 110 FTE's over the 6-year lifespan. Table 3 shows the major milestones ahead of us. The AO Department of ESO heads the development of the AO Facility, the transformation of one 8-m UT into an adaptive Telescope. This multi-division effort, including also European partners, aims at delivering to the ESO community:

- An 8-m UT4 with a new M2-Unit hosting a 1170 actuators for AO correction
- A 4LGS Facility launching four Na lasers from the telescope centrepiece
- GRAAL: the AO module allowing Ground Layer correction for Hawk-I
- GALACSI: the AO module allowing Ground Layer correction for MUSE Wide Field and Tomographic correction for the MUSE Narrow Field
- ASSIST: a sophisticated test bench allowing complete characterisation of the AOF performance in Europe (this effort is led by the University of Leiden part of the MUSE consortium)

The project passed a Conceptual Design Review last September and Preliminary and Final Design Reviews will be held over in the course of 2007–08. Commissioning activities will be in full swing in the course of 2010–11 and the AOF should be available to the community by 2012.

Acknowledgements

The work described in this paper is partially funded by the European Commission Sixth Framework Programme under contract No. RII3-CT-001566.

The authors wants to thank in particular Prof. Gerry Gilmore and Dr. John Davies, respectively OPTICON Scientific Coordinator and Project Scientist, for the support provided by OPTICON to this project.

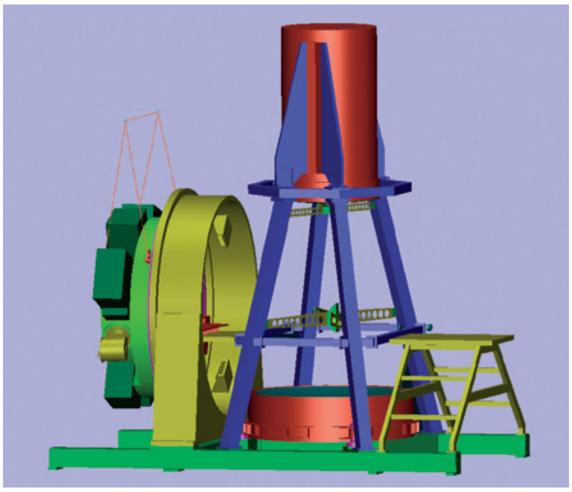

Figure 3: Opto-mechanical layout of the VLT DSM test set-up. The image plane is located at the centre of curvature of the three-mirrors system: 1.65-m concave aspheric (bottom red), 1.1-m convex DSM (top red cylinder), and strongly aspheric 140 mm third mirror (just below DSM). A 45° flat mirror and beamsplitters are used to deport the source and image planes at convenient locations on each side of the vertical set-up. The NACO test bench is re-cycled to provide a Nasmyth opto-mechanical interface (left). The 'table' on the right-hand side will support the turbulence generator and source modules.

Milestones	GRAAL	GALACSI	DSM	4LGSF	ASSIST
AOF green light	December 2005	December 2005	December 2005	December 2005	December 2005
PDR	January 2007	June 2007	October 2006	June 2007	January 2007
FDR	January 2008	June 2008	August 2007	June 2008	October 2007
End of MAI	October 2009	April 2010	May 2009		October 2008
PAE	February 2011	July 2011	February 2010	July 2010	October 2009
End of Commissioning	December 2011	February 2012	November 2011	February 2011	—

Table 3: Milestones for the various systems of the AO Facility.