The VLT Adaptive Optics Facility Project: Adaptive Optics Modules

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

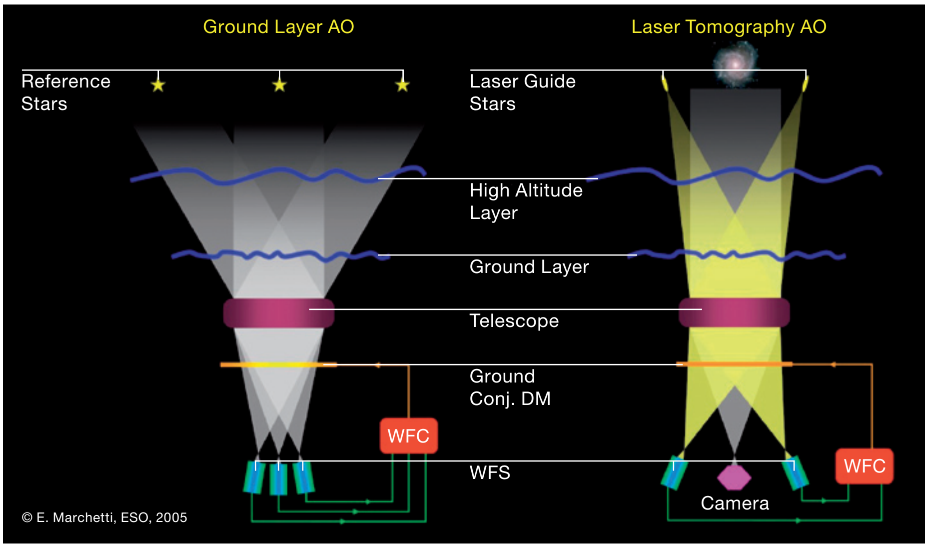
The Adaptive Optics Facility is a project to convert UT4 into a specialised Adaptive Telescope with the help of a Deformable Secondary Mirror (see previous article). The two instruments that have been identified for the two Nasmyth foci are: Hawk-I with its AO module GRAAL allowing a Ground Layer Adaptive Optics correction (GLAO) and MUSE with GALACSI for GLAO correction and Laser Tomography Adaptive Optics correction. This article describes the AO modules GRAAL and GALACSI and their Real-Time Computers based on SPARTA.

Requirements for the instruments

The three UT focal stations will benefit from the image correction provided by the Deformable Secondary Mirror (DSM). At the time of this writing two instruments are identified: Hawk-I and MUSE on the opposite Nasmyth foci. The corresponding AO modules are GRAAL (GRound layer Adaptive optics Assisted by Lasers) and GALACSI (Ground Atmospheric Layer Adaptive Corrector for Spectroscopic Imaging). The STC has requested ESO to propose options for the future use of the Cassegrain focus; in the meantime SINFONI will remain at this focal station and will be available on the AO Facility.

The AO corrections to be provided are new: Ground Layer Correction (GLAO) and Laser Tomography (LTAO). The former consists in measuring the turbulence in four different directions outside the instrument FOV and to average it in order to provide a homogeneous image improvement across the instrument FOV. The latter compensates for the laser cone effect (not sampling all the turbulence seen on the astronomical target) and optimises high strehl correction on-axis; therefore, the need for four Laser Guide Stars. Figure 1 illustrates these correction modes.

Figure 1: Illustration of the Ground Layer adaptive correction (left) and Laser Tomography (right).



The present article details mainly the AO modules for Hawk-I and MUSE and the Real-Time-Computer platform SPARTA. Note that Hawk-I is an ESO-led effort. This instrument completed its Final Design Phase at the end of 2004 and is in the manufacturing stage.

MUSE is an external consortium effort led by the Observatoire de Lyon (CRAL) including the University of Leiden, the Eidgenössische Technische Hochschule Zürich, Astrophysikalisches Institut Potsdam, the Observatoire Midi-Pyrénées (LAOMP), and the Institut für Astrophysik Göttingen.

Description of the AO Modules

GRAAL for HAWK-I

Concept

The GRound layer Adaptive optics system Assisted by Lasers (GRAAL) is a module designed to provide GLAO correction for the HAWK-I NIR wide-field imager (7.5′ × 7.5′ FoV with ~ 0.1″ pixels). GRAAL is designed as a module hosting four WFSs for LGS and a tip-tilt sensor for a NGS. The atmospheric turbulence is sampled in four slightly different directions over the instrument field of view to send an average correction, homogeneous over the scientific field of view, to the DSM. The improvement provided by GRAAL can be summarised in saying that it will allow HAWK-I to work most of the time under better than median seeing conditions (e.g. the FWHM of the PSF will be reduced from 0.94″ to 0.73″). Even under most conditions (1″ seeing in the visible), the 50 % encircled energy diameter will be reduced by 15 % in the *Y* and 30 % in the *Ks* over the entire field of view.

The system will use the Deformable Secondary Mirror (DSM) having enough stroke and degrees of freedom to correct for the atmospheric seeing (up to 2″ seeing) including the atmospheric tip-tilt and for VLT field stabilisation. Four Sodium Laser Guide Stars emitted from four 50-cm laser projectors located on the VLT centrepiece will be sensed by four 30 × 30 Wave-Front Sensors (WFS). These wavefront sensors must rotate to compensate for the pupil rotation at the Nasmyth focus and they must acquire and track the focus of the corresponding laser spots.

As baseline a visible tip-tilt sensor has been considered. To avoid obscuration of the HAWK-I FoV the visible NGS will be acquired outside the HAWK-I FoV. As an alternative an IR Natural Guide star could be used to sense tip-tilt aberrations. The IR NGS will be selected inside the HAWK-I FoV. The sensing would then be performed using the guide mode of the HAWK-I Hawaii2RG infrared detectors: a small window (16 × 16 pixels) around the IR NGS will be read out at high frequency to sense tip-tilt.

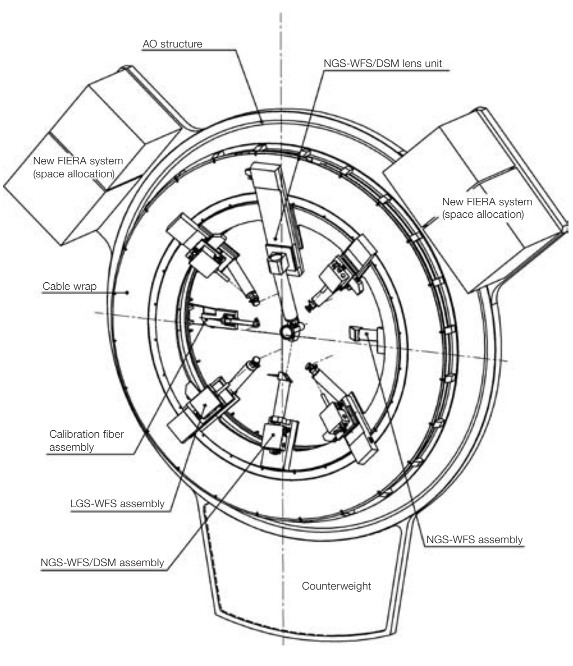
Note also that the correction modes of the DSM and SPARTA are not restricted only to GLAO and LTAO. GRAAL contains an on-axis high-order WFS 40^2 subaperture used for the DSM commissioning and maintenance activities. Figure 2 shows the opto-mechanical concept for GRAAL and the performance expected. The relative improvement with respect to no correction can be seen by comparing crosses (GLAO) and diamonds (no correction). The homogeneity of the improvement across the field of view can also be assessed from the plot on the right.

Performance improvement for SCIENCE

HAWK-I with GRAAL would constantly reach 1.5 mag fainter on point sources than without correction, for the same integration time. GRAAL will thus emphasise HAWK-I's strengths: very deep imaging at high spatial resolution. But note also that HAWK-I with GRAAL will reach the same magnitude limit as VISTA 16 times faster, i.e., even with the significantly smaller FoV, HAWK-I with GRAAL would reach 1/2 the survey speed of VISTA but with at least a factor of two improvement in spatial resolution.

HAWK-I prime science cases include deep multi-colour surveys at high *z*, stellar population studies in nearby galaxies, and investigations of star-forming regions in our Galaxy. These programmes critically rely on the deepest possible exposures with the highest possible spatial resolution – both of which will be improved by GRAAL. HAWK-I with GRAAL will typically reach 0.5 mag deeper in *J*, *H* and *K* for a fixed exposure time. For high-*z* observations, this is equivalent to a gain of 1.26 in distance (adopting a standard cosmology). This translates in turn into ~ 25 % more volume probed by the survey in the same time (surveys will reach $z \sim 1.2$ instead of $z = 1$ or $z \sim 3.6$ instead of $z \sim 3$).

For surveys aiming at studying galaxies at fixed redshift, or stellar populations in a given nearby galaxy, this translates into vastly increased number statistics, as the galaxy luminosity function increases exponentially and the stellar initial mass rises with a power > 2 in the regime of interest. Proposals addressing forefront science often require the



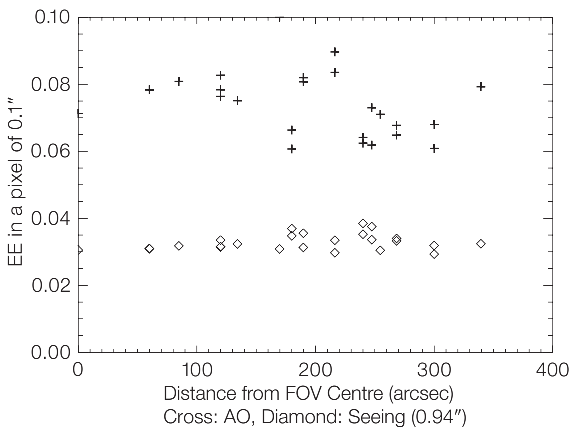


Figure 2: GRAAL opto-mechanical layout. One sees the four LGS wavefront sensors, the visible wavefront sensor and the central natural guide star sensor for the commissioning and maintenance of the DSM. The plot shows the fraction of energy in a 0.1″ rectangular pixel *K*-band; crosses represent GLAO correction and diamonds represent seeing-limited observations.

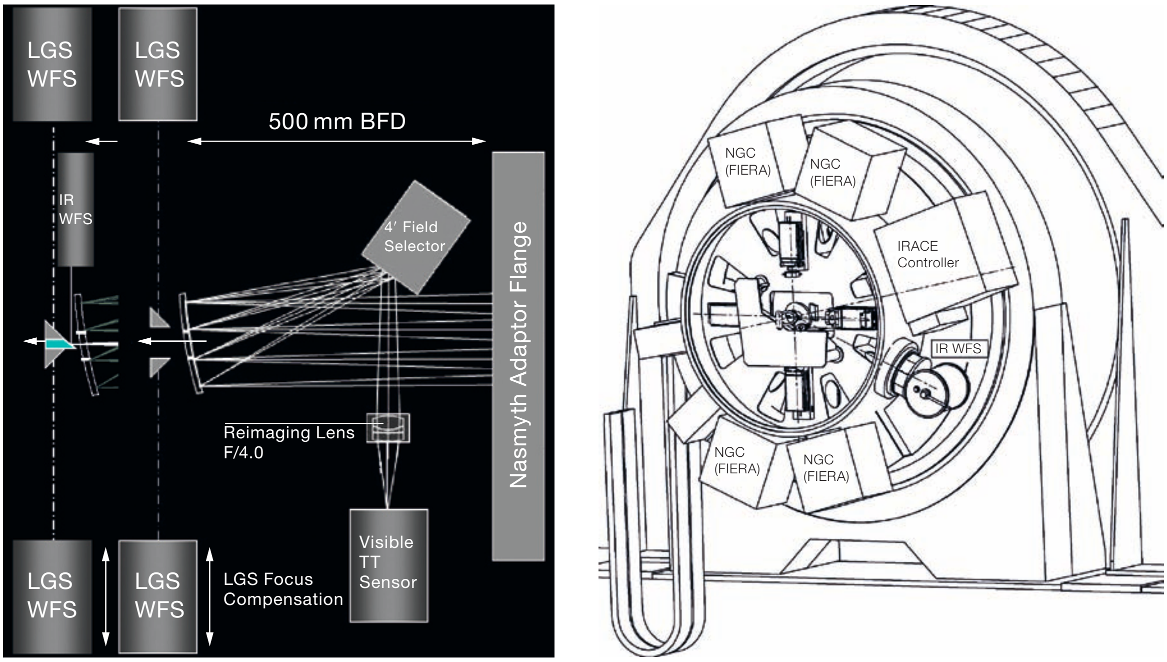


Figure 3: GALACSI opto-mechanical layout. GALACSI is mounted on the Nasmyth A/R which is used to correct for pupil rotation. This insures that the WFS pattern remains fixed with respect to the DSM actuator geometry.

best seeing conditions. Currently, the natural seeing in the *K*-band is better than 0.4″ only 20 % of the time. With GRAAL, an image quality in the *K*-band below 0.4″ will be achieved ~ 80 % of the time. GRAAL will provide a fourfold increase in time for the most challenging proposals.

GALACSI

Concept

GALACSI is a module very similar to GRAAL. It will include four LGS WFS and one tip-tilt natural star sensor. It will offer a correction mode identical to GRAAL GLAO (laser stars closer since FoV smaller), that is seeing improver, except for a smaller field of view called Wide Field Mode (1 arcmin). Although the field of view is smaller, the gain in ensquared energy gain is similar to GRAAL since the wavelength is shorter (750 nm). The Narrow Field Mode is the real challenge since it aims at a strehl ratio of some 10 % a 650 nm in a 7.5″ field of view. Laser Tomography means that the WFS data are used to assess the altitude distribution of turbulence, compensated for the laser cone effect, in order to provide a correction vector to the DSM optimised to allow high strehl ratio on-axis.

It will serve MUSE, a visible spectrograph (0.46–0.93 μm) sitting on the Nasmyth platform and composed of 24 identical Integral Field Units. MUSE will obtain 90 000 spectra (370 × 106 pixels) with a resolution of 3 000 in a single exposure.

Since the DSM is attached to the telescope structure, its actuator geometry will rotate like the pupil at the Nasmyth focal plane of the VLT. To maintain the matching between the WFS and DSM pattern the WFSs must rotate like the telescope pupil. This corresponds to a co-rotation of the WFSs with the Telescope altitude axis. The same applies for the field position of the LGSs. The rotation is done by co-rotating GALACSI with the Nasmyth rotator. The field de-rotation for MUSE is done inside MUSE.

The visible tip-tilt natural guide star sensor for the Wide Field Mode is expected to have a limiting magnitude around $M_V \sim 17.5$. Natural tip-tilt star will be acquired within a 4′ technical FOV but out-side the 1′ square scientific FOV to prevent occultation of the scientific FOV. An IR on-axis tip-tilt natural guide star sensor will be used for the 7.5″ Narrow Field Mode. Light separation will be done with a VIS/IR dichroic located after the Adaptive Optics focal plane. Figure 3 shows the optical design and opto-mechanical layout of GALACSI. Figure 4 shows the simulated performance of the WFM and the NFM.

Science

MUSE and GALACSI will tackle a wide range of astrophysical problems. MUSE has been designed from the start to take great advantage of the combination of IFU spectroscopy and the high spatial resolution provided by AO.

1. Narrow-Field Mode (NFM)

The very high spatial resolution of this mode (0.025 arcsec^2 spatial elements) allows only relatively high surface brightness science targets. The science drivers are therefore quite specific, although still scientifically relevant and totally unique to MUSE. During the operational period of MUSE, the science community may not have access to a space-based (diffraction limited) optical spectrograph, such as the successful STIS long-slit spectrograph onboard HST. Such spatial resolution at optical wavelengths, combined with an 8.2-m aperture, will be at a premium. We give in the following a few examples

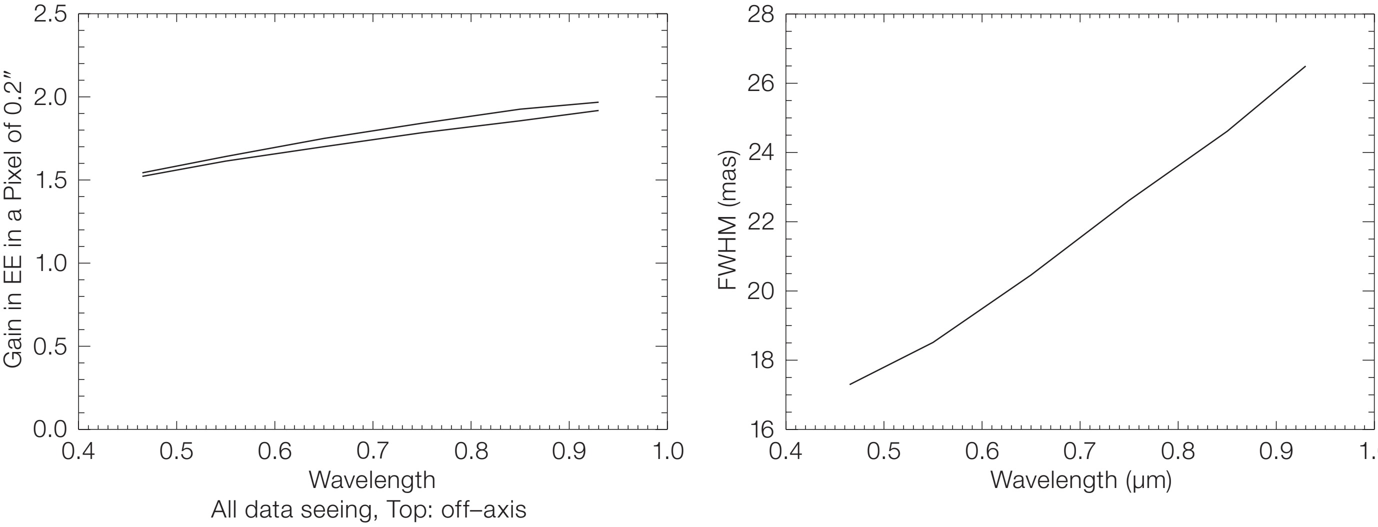


Figure 4: **Left:** Gain in Ensquared Energy (EE) in 0.2″ versus wavelength. These curves were obtained by simulations using recent Cn^2 profiles measured at Paranal and show a gain in EE of about 1.8 at 750 nm. **Right:** The Narrow Field Mode FWHM performance as a function of wavelength. The instrumental error budget as well as LGS spot elongation and Na height variations have been neglected here.

of scientific questions which could be addressed by MUSE NFM.

In recent years it has become clear that supermassive black holes (SMBHs) are intimately linked with the mass evolution of their host galaxies and are therefore key ingredients of the formation and evolution of galaxies. The SMBHs formation processes should leave signatures in their immediate environment either in terms of stellar orbital structure or chemical enrichment history. These key issues can only be fully addressed with optical IFU observations at near-diffraction-limited resolution.

The MUSE NFM will also provide spectral insight (density, temperature and ionisation) and high spatial resolution over a relatively large field of view of Young Stellar Objects. This will allow the physical processes involved in the formation and structure of the jets to be investigated in details. The MUSE NFM is also ideally suited to the spatially resolved spectroscopy of solar-system bodies. While much more detail can obviously be obtained by space probes, one visit is not the whole story given the significant time evolution of atmospheres and surfaces of most solar-system objects. Monitoring volcanic activity on the Galilean satellites will yield new insights on planetary resurfacing. Other examples include monitoring Titan, Uranus and Neptune atmospheres.

2. Wide-Field Mode (WFM)

The main target of the MUSE surveys is to find and study the building blocks of the local, normal galaxies such as our Milky Way, at an epoch when the Universe was typically 1 Gyr old. The observation of such objects will be of great value to clarify the way galaxies form. The benefit of AO correction is obvious since these sources are typically 0.1–0.3″ in size.

Presumably, mass assembly is a long-timescale process that starts early and goes on to the present time. Making the census of large and small objects in the early Universe, when the cosmic age was 1 Gyr, and studying their properties, will set strong constraints on detailed models of hierarchical galaxy formation. In this prospect, the specific questions which one wants to address by studying this population of objects are the following: how did galaxies like our Milky Way assemble from small fragments? What are the stellar and gaseous masses of these fragments? What are the masses of the dark matter haloes they are hosted in? What are their typical star-formation histories?

Intermediate-redshift galaxies at $z \sim 1$ are well suited to be studied by MUSE-GALACSI WFM since the 0.3″ PSF corresponds to a ~ 2 kpc scale allowing the study of internal variations of stellar population ages, metallicities and gas enrichment. Gas kinematics (2D) allows exploration of star formation and metal enrichment histories of bulges and discs, of the size, intensity and topology of coherent large-scale starbursts and of the development of galactic structure.

Nearby galaxies will also be prominent targets, especially their central regions containing important information on the fossil record of mass assembly, black-hole formation, star formation requiring resolution of ~ 100 pc spatial scales.

Last but not least, the instrument also has an enormous potential for enabling massive point-source spectroscopy in crowded fields, by using the large contiguous 3D data cubes to deblend and deconvolve sources in the combined spectral and spatial domains. This allows superior performance in dense regions such as the Galactic Bulge and Magellanic Clouds, but also allows extremely dense fields to be observed. At larger distance the investigation of nearby galaxies through detailed spectral analysis of their stellar populations, resolved into individual stars, can provide quantitative templates for the calibration of integrated light studies of higher redshift systems.

SPARTA

The AO Department has identified the need for a flexible real-time application platform for the new-generation AO systems being developed in the context of the AO Facility. SPARTA (Standard Platform for Adaptive optics Real Time Applications) is the answer to this need. The RTC's of GRAAL and GALACSI will be based on SPARTA.

SPARTA is a project that starts from the OPTICON/JRA-1 framework to provide a solution to the challenge of building a real-time computer for high-order/high-bandwidth systems but at the same time using mainly Components Off-The-Shelf (COTS). SPARTA goals are to serve all the second-generation VLT instrumentation (AO Facility and the Planet Finder) and to create a basis for growth towards ELT-size AO systems.

The requirements for the new generation of AO systems are beyond the current computational power of single board computers used today. For instance, the requirements for the Planet Finder is 200 times higher than the capacity of the NAOS RTC (plus keeping the latency very low). The latency is the major challenge of SPARTA: the RTC must not only compute the control commands fast enough to cope with the increased loop frequency, but it also has to complete the computation earlier to reduce time-related errors. This is equivalent to a system much faster than the nominal loop frequency. On the other hand, it is clear that the time required to develop an AO system is rather long and the final result consists primarily of infrastructure, data management and interface: the core real time application is a tiny portion of the whole AO RTC system. These are the main reasons to create a common platform to serve all these projects.

The complexity of the control software and the required flexibility would suggest the use of high-end CPUs, programmable with standard programming languages (C/C^{++}) with a relatively fast developing cycle. That was the natural choice for the first SPARTA prototype, based on multi-CPU board connected together to achieve the required throughput. Unfortunately with such architecture the low latency requirements cannot be achieved due to structural problems of the CPU architecture.

To solve this problem one has to change the technology. This is where FPGAs come into play. An FPGA is a chip that provides millions of logical elements that can be connected by means of a programme to create any function that will then execute at the speed of the FPGA core clock. Moreover, many functions can be programmed, until all elements are used. All of these functions run in parallel and this is the great advantage of FPGAs. However FPGA programming is a difficult exercise; it uses the same language as for designing integrated circuits and microprocessors.

Consequently the development cycle of an FPGA application is much slower and the debugging much more difficult. Where the FPGA is unbeatable is the communication infrastructure: being implemented in hardware, there is no additional latency. The perfect application for the FPGA is to manage all the critical communications of SPARTA so that data are routed within the system at the fastest possible speed and the lowest possible latency. Hence the collaboration between ESO and Durham, under the OPTICON/JRA-1 project. Durham is developing an FPGA-based acquisition processor that receives the pixel stream and processes them up to the computation of the gradients. The gradients will then be further processed by a DSP array.

A DSP is fundamentally a CPU, so it shares the same problems if used as a CPU. However a DSP is also equipped with fast communication ports and a big (3 MB) on-chip memory. Using fast I/O and the internal memory a DSP can deliver a high throughput while significantly simplifying the development cycle being a CPU. A DSP can be programmed in C/C^{++}. The market recently made available a board with several DSPs whose link ports are interfaced directly to FPGAs, a good match for our architecture. The I/O is managed by the FPGAs and the DSPs act as an array of co-processors.

The GALACSI SPARTA has four Shack-Hartmann sensors providing four pixel streams coming from the NGCs. They are connected to a switch that converts the optical signals to electrical ones and routes them to four independent front-end FPGAs, hosted in two boards. Each FPGA will run the Durham module that will produce the gradients. Each FPGA sends the gradient vector to a different DSP board equipped with eight DSPs. Each DSP board will process the related portion of the control matrix and then results are gathered on the back-end FPGA that will complete the processing with the time-domain filter, and finally results are sent to the corrective optics device. This architecture can run at 1 KHz with a latency of about 120 μs.

Conclusions

The AO Department of ESO is heading the development of the AO Facility, the transformation of one 8-m UT (presumably UT4) into an adaptive Telescope. GRAAL and GALACSI, the AO modules for Hawk-I and MUSE respectively, are two major building blocks for this project. The corresponding science cases have convinced the CDR review boards of the scientific competitiveness of the AO Facility. A third instrument and AO module is in the work for the Cassegrain station but has not been yet identified.

The project passed a Conceptual Design Review last September and Preliminary and Final Design Reviews will be completed in the course of 2008. The 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 want 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.