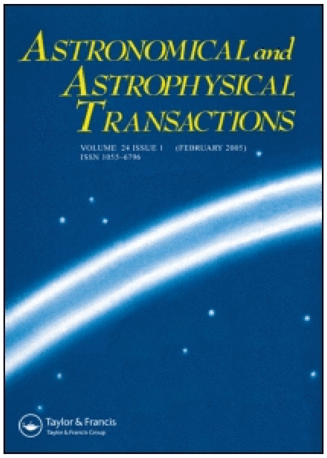

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THE ESO VLT ADAPTIVE OPTICS PROGRAMME

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We introduce the ESO VLT Adaptive Optics programme. This programme includes several activities and projects such as the ADONIS project, COMIC and SHARP II cameras, a data reduction package dedicated to AO observations, the low-noise fast readout CCD camera development for wavefront sensor and the Quad cell Avalanche Photo Diodes development. One of the main projects is currently the Nasmyth Adaptive Optics System (NAOS). The high-level requirements and conceptual design of NAOS for Unit Telescope 1 of the Very Large Telescope project are described. An introduction to the Laser Guide Star programme at ESO is also presented.

KEY WORDS The VLT ESO: adaptive optics

1 INTRODUCTION

Adaptive optics is one of the main features of the Very Large Telescope of the European Southern Observatory (ESO). The use of large telescopes for high spatial resolution imaging, high spectral resolution spectroscopy and astronomical spatial interferometry basically depends on the availability of adaptive optics, which allows diffraction-limited imaging in the near-infrared wavelength range (2.2–5 μm) and partial correction of atmospheric distortions towards the visible wavelength range.

2 ADONIS–SHARP II PROJECTS

ESO has followed a long-term strategy to evaluate and demonstrate the feasibility of an adaptive optics system for 8-m class telescopes. Prototypes such as Come-On and Come-On-Plus (COP) were developed and tested on the ESO 3.6-m telescope at La Silla Observatory (Kern *et al.*, 1990; Rousset *et al.*, 1990, 1996; Rigaut *et al.*, 1991; Hubin *et al.*, 1992). After the promising technical results obtained at the telescope, Come-On-Plus was offered and is now normally used as a standard instrument by the European astronomical community (Léna and Monnet, 1996). At this stage adaptive optics is still a complex observation technique requiring specialized staff to operate it: a long way from the turn-key VLT adaptive optics system. Therefore it was decided to use the COP system as a software platform for the VLT. This allows the testing of observing procedures, better understanding and optimization of the parameters and development of a user-friendly interface keeping in mind the needs of the user. This development known as ADONIS project (Hubin *et al.*, 1993; Beuzit *et al.*, 1996), although already offered to the astronomical community for more than 100 observing nights, has been progressively implemented and will be completely available at the beginning of 1996. In parallel to the ADONIS implementation, we are developing high angular resolution cameras in order to perform high-level scientific observations in the infrared: COMIC (3–5 μm range) by Observatoire de Paris and Sharp II (1–2.5 μm) by the Max Planck Institut Garching.

3 DATA REDUCTION FOR ADAPTIVE OPTICS OBSERVATIONS

Data reduction dedicated to AO high-resolution imaging and spectro-imaging is one of the key problems if not the key to the success of this new technology which should be closely kept in view in the very near future. To provide all astronomers with facilities to enable them to easily work out their scientific results from observations with AO systems, ESO is now proceeding with the definition of precise obsrvingmethodology studies, design and writing of a data reduction software dedicated to infrared high-resolution data. This package will be divided into small subpackages starting with the very basic cosmetic processing, shift and add and image selections up to blind deconvolution methods, PSF restitution from AO data, photometry evaluation, spectro-imaging processing, polarimetry processing, coronography processing and speckle data reduction. The enormous work to be done in this field, the complexity of AO data reduction and the spread of expertise is leading ESO to build very intensive collaborations with several institutes.

4 VLT NASMYTH ADAPTIVE OPTICS SYSTEM (NAOS)

The current plan includes the construction of a first generation Adaptive Optics System (NAOS) (Hubin *et al.*, 1994) for the Nasmyth focus of the Unit Telescope 1 in collaboration with European astronomical institutes and industries. NAOS will provide correction for an infrared spectro-imaging instrument (CONICA) currently under construction.

4.1 Requirements for NAOS

The design of an adaptive optics system is a complex trade off that depends on the general scientific goals pursued, the physical limitations, the technology available at a given time and the budget involved.

For example, the wavelength has to be evaluated so that the correction and the physical limitations will provide the best image quality or spectrum. Concerning the VLT, the choice is to perform low-frequency tip-tilt corrections with the secondary mirror for the long wavelengths (10 μm) in order to sharpen the image while limiting the background sources from additional mirror surfaces. At this wavelength, D/ro is in the range of 1–2 (ro Fried diameter) under good seeing conditions and an 8 Hz tip-tilt correction can provide an image Strehl ratio of 50–70%.

At 5 μm, where D/ro is in the range of 4–6, the background produced by the adaptive optics additional mirrors which is an order of magnitude lower than at 10 μm, is however a critical limitation, but a low-frequency tip-tilt correction does not allow us to have a Strehl ratio better than 20% under average seeing conditions. In the L band (3.8 μm) (D/ro in the range of 5–8) the background emission is again approximately an order of magnitude lower and a Strehl of 10% is hardly achievable with a tip-tilt correction only. Between 2.5 and 1 μm (D/ro in the range of 10–30) both high spatial and temporal frequency corrections become essential: we are within the adaptive optics field where the technology is demonstrated and currently available. In the visible, the isoplanatism limitation and the spatial sampling of the wavefront requires brighter reference stars which leads to the use of expensive artificial star techniques especially for 8-m telescopes.

This discussion outlines the driving factors why ESO decided in favour of a near-infrared adaptive optics system for the VLT allowing partial correction in the visible (I band).

As a primary scientific goal, the top-level and functional requirements for NAOS are such that they should maximize as a primary scientific goal the sky coverage for a natural guide star and reach the diffraction limit (Strehl ratio = 0.7) for wavelengths larger than 2.2 μm under 0.8 arcsec seeing conditions and 10.5 m s^{-1} average wind speed for a visible reference star magnitude of 13. The image motion stabilization is required to be better than 10 marcsec rms on the sky. In addition, it is planned to implement infrared wavefront sensors in order to perform a correction for object or reference stars with a visible counterpart which is too low. The infrared wavefront sensor will have a limiting magnitude of about 11–13. NAOS using the visible wavefront sensor will provide an on-axis Strehl ratio at 2.2 μm at least equal to the requirements shown in Figure 1, under the following conditions.

(1) FWHM seeing (at 0.5 μm): between 0.25″ and 1″.

(2) Adaptive optics correlation time (at 0.5 μm): > 3 ms.

(3) Performance stability over: > 20 min.

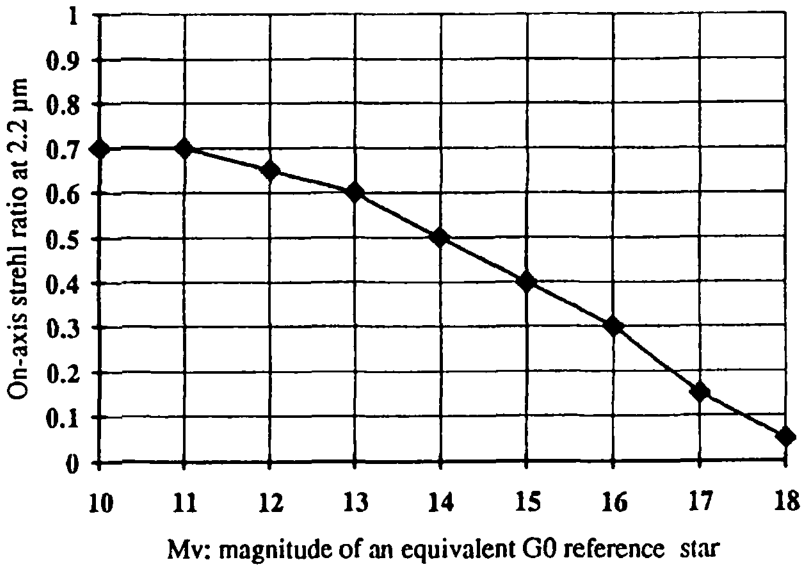

Figure 1 Strehl ratio at 2.2 μm.

(4) Telescope altitude angle: < 30 deg (0 deg. zenith).

(5) Reference source apparent diameter: from point-like up to 2 arcsec.

(6) Reference source spectrum: G0.

(7) WFS bandpass: 450–900 nm.

4.2 Preliminary Design of NAOS

Optimized for full correction at 2.2 μm, the subaperture size at the primary mirror location should be of the order of the Fried diameter at the considered wavelength. This leads to about 250 actuators for the deformable mirror. The minimum inter-actuator spacing currently achievable is 6–7 mm which sets a clear aperture pupil diameter of about 110 mm. Below this spacing value, local stresses and reduction of the actuator differential stroke drastically increase the wavefront high spatial frequencies and consequently degrade the image quality of the system.

Apart from the pupil size requirement, another design driving factor is the adaptive optics field of view (FOV). It is mainly given by the best finding reference star angle where a correction can still be achieved at the maximum observing wavelength specified (in our case 5 μm). Based on simulations using Paranal's seeing measurements, we set this value to a diameter of 2 arcmin.

Figures 2 and 3 show the optical design minimizing the number of reflective surfaces and delivering an F/15 output beam to the instrument. The first parabola images the pupil of the telescope on the deformable mirror unit. The second parabola

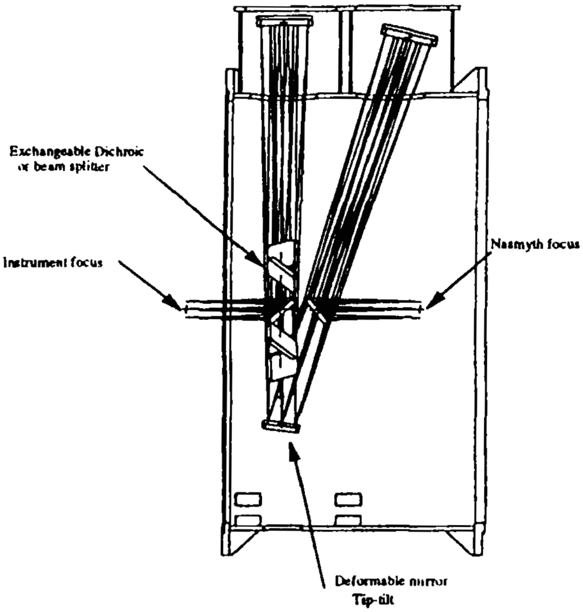

Figure 2 Preliminary optical design of the adaptive optics adapter (side view).

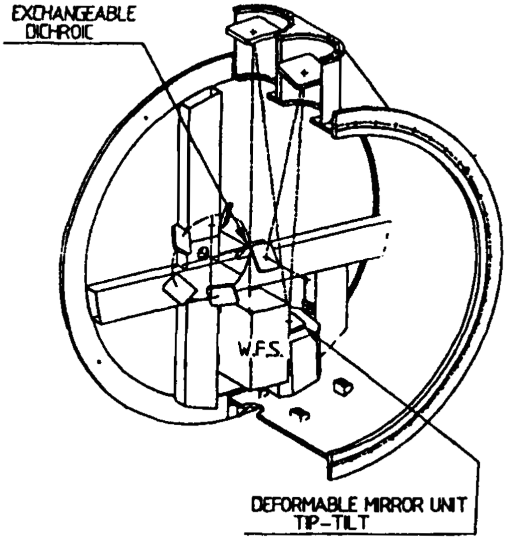

Figure 3 Preliminary optical design of the adaptive optics adapter (perspective view).

delivers a new F/15 beam and keeps the image of the telescope pupil at 16 m as it was at the Nasmyth focus. Both parabolas are mounted so as to compensate the off-axis coma. The only remaining aberration is the field aberration which is 1110 mm.

The second flat mirror is an exchangeable dichroic which reflects the infrared ligth towards the instrument and transmits the visible light (or the 1–2.5 μm light in the case of the infrared wavefront sensor) towards the wavefront sensor unit.

The astigmatism created by the crossing of this dichroic–1120 nm — and seen by the WFS is taken into account in the reference wavefront stored in the real-time computer. The tip-tilt correction is performed by the deformable mirror unit in two stages: low-frequency correction by a mirror mount and the rest by the deformable mirror itself. This complex approach is mainly driven by the choice of a simple design and by the fact that any other optical element can be used as tip-tilt mirror without producing a pupil matching error between the deformable mirror and the wavefront sensor. The instrument is attached to the AO system and rotates with the Nasmyth adapter allowing the field rotation compensation. All the adapter run-out and wobble errors produced by this rotation are seen by the AO system and are compensated for. Only the adapter field rotation tracking error produces a 3 marcsec rms differential tilt when a reference star is at the edge of the AO FOV.

The wavefront sensor unit consists of two selectable wavefront sensors and a field viewing camera. An additional low-order visible wavefront sensor based on APDs currently under study at ESO may be used in order to provide better sky coverage at low light levels.

The visible wavefront sensor will be based on a *low noise fast readout CCD camera* currently under development. The high-level requirements for this camera are provided in Table 1.

Table 1.

Parameters	*Minimum*	*Goals*	*Remarks*
Pixel size	25–30 μm	50–60 μm	Big pixels by binning 2 x 2 of a 256 x 256
Exposure time	2–200 ms	NA	
Frame readout time	< 2 ms	< 1 ms	
Number of pixels	128 x 128	256 x 256	Useful pixels
Quantum efficiency	< 80%	Max	In average
Wavelength range	450–950		
Readout noise (rms)	2–4 e-/pixel	Min	At 500 Hz frame rate
Readout noise (rms)	< 2 e-/pixel	Min	At 100 Hz frame rate
Dark noise (rms)	< 0.4 e-/pix/s	Min	Cooling temperature < −40° C
Frame transfer	20 μs	10 μs	An optical masking for the storage area of the CCD will be provided
Photometric size	100%	100%	
Binning capability	2 x 2; 3 x 3; 4 x 4; 5 x 5	NA	

In addition, some studies to develop *high-efficiency Avalanche Photodiodes* for low-order correction to provide better sky coverage at low light levels and for future Laser Guide Star applications are being pursued.

The interest in modal control has been extensively described in the literature and successfully applied to our Come-On-Plus/ADONIS prototype system (Wang *et al.*, 1978; Gendron, 1993) and an astronomical AO system often implying low light levels for wavefront sensing cannot deviate from using such a powerful tool.

The computing time is widely dominated by the readout time of the visible wavefront sensor detector. Indeed, relatively low-cost DSP boards, i.e. C40 with sufficient computing power are now on the shelf products (Beuzit *et al.*, 1996) and can send the deformable mirror commands as soon as the last pixel is read (a few 10s of microseconds). This type of computer has been recently implemented on our ADONIS prototype system at La Silla.

The complete system is expected to be ready in 1999.

5 LASER GUIDE STAR PROGRAMME

One of the key problem of adaptive optics is the low sky coverage which considerably limits the use of AO for extragalactic observations. In order to palliate this limitation, ESO is currently launching an internal system study for the implementation of a prototype Laser Guide Star for ADONIS on the 3.6-m telescope at La Silla. This system study will be followed by the implementation of this prototype in 1996 and by a Laser Guide Star system study for the VLT in 1997. The purpose of this prototype is to further investigate Laser Guide Star specificity such as the tip-tilt measurement problem, the cone effect, the effective photon budget and all operational aspects of the use of lasers in an observatory environment. Depending on the results of these studies, ESO may launch the development of a second generation adaptive optics system using Laser Guide Star which could be implemented for Unit Telescope 4 of the VLT on the horizon 2000.

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