Re-baselining the ESO ELT project

Adaptive Optics

Analysis and roadmap from the ELT Adaptive Optics Working Group

28th February 2006

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List of acronyms

ADC	Atmospheric Dispersion Corrector
AFIRE	Advanced Fibre Raman Emitter
AO	Adaptive Optics
AOF	Adaptive Optics Facility
APD	Avalanche Photo-Diode
ASIC	Application Specific Integrated Circuit
ASSIST	Adaptive Secondary Setup and Instrument STimulator
ATM	Adaptive Telescope Mirrors
AURA	Association of Universities for Research in Astronomy
BOA	Banc d'Optique Adaptative
CAAO	Center for Astronomical Adaptive Optics
CCD	Charge Coupled Device
CFHT	Canada-France-Hawaii Telescope
CILAS	Compagnie Industrielle des LASers
CPU	Central Processing Unit
CTIA	Capacitive TransImpedance Amplifier
CW	Continuous Wave
DM	Deformable Mirror
DSM	Deformable Secondary Mirror
DSP	Digital Signal Processor
EE	Ensquared Energy
ELLAS	ESO Laser Layer-oriented Advanced Sensing
ELT	Extremely Large Telescope
ELT DS	Extremely Large Telescope Design Study
EMCCD	Electron Multiplying CCD
EPICS	Earth-like Planets Imaging Camera and Spectrograph
FD-PCG	Fourier Domain Pre-Conjugate Gradient
FFT	Fast Fourier Transform
FOV	Field-Of-View
FP6	Framework Program
FPGA	Field Programmable Gates Arrays
GALACSI	Ground Atmospheric Layer Adaptive Corrector for Spectroscopic Imaging
GFMAC	Giga Floating Multiply and ACcumulate
GLAO	Ground-Layer Adaptive Optics
GMT	Giant Magellan Telescope
GRAAL	GRound layer Adaptive optics Assisted with Lasers
GSAOI	GEMINI South Adaptive Optics Imager
HC	Hollow Core
HOMER	Hartmann-Oriented Mcao Experimental Resource
HOT	High Order Testbench
JRA	Joint Research Activity
IFS	Integral Field Spectrograph

IFU	Integral Field Unit
IM	Interaction Matrix
IR	Infra-Red
LBT	Large Binocular Telescope
LGS	Laser Guide Star
LGSF	Laser Guide Star Facility
LINC	LBT INterferometric Camera
LLNL	Lawrence Livermore National Laboratories
LLT	Laser Launch Telescope
LMCT	Lockheed - Martin Coherent Technologies
LPSI	Laser Phase Shifting Interferometry
LTAO	Laser Tomography Adaptive Optics
MACAO	Multiple Application Curvature Adaptive Optics
MAD	Multi-conjugate Adaptive optics Demonstrator
MCAO	Multi-Conjugate Adaptive Optics
MEMS	Micro-ElectroMechanical Systems
MG-PCG	Multi-Grid Pre-Conjugate Gradient
MMT	Multiple Mirror Telescope
MOAO	Multi-Objects Adaptive Optics
MOEMS	Micro-OptoElectroMechanical Systems
MOMFIS	Multi-Objects Multi-Fields Infrared Spectrograph
MPE	Max Planck institut für Extraterrestrische physik
MPIA	Max Planck Institut für Astronomie
MUSE	Multi-Unit Spectrographic Explorer
NAOS	Nasmyth Adaptive Optics System
NGS	Natural Guide Star
NGST	Next Generation Space Telescope
NIR	Near Infra-Red
NIRVANA	Near Infrared / Visible Adaptive iNterferometer for Astronomy
ONERA	Office National des Etudes et Recherches Aérospatiales
OWL	OverWhelmingly Large Telescope
PARSEC	Powerful Artificial Reference Source for Extended sky Coverage
PCF	Photonic Crystal Fibres
PF	Planet Finder
PIGS	Pseudo-Infinite Guide Star
PPPP	Projected Pupil Plane Pattern
PSD	Power Spectral Density
PSF	Point Spread Function
PWFS	Pyramid Wave-Front Sensor
PYRAMIR	PYRAMid wave-front sensor in the IR
QE	Quantum Efficiency
RMS	Root Mean Square
RON	Read-Out Noise
RTC	Real-Time Computer
SESAME	multi-purpose adaptive optics bench
SH WFS	Shack-Hartmann Wave-Front Sensor

SLODAR	SLOpe Detection And Ranging
SOAR	Southern Astrophysical Research telescope
SPARTA	Standard Platform for Adaptive optics Real-Time Applications
SPHERE	Spectro-Polarimetric High-contrast Exoplanet REsearch
SPLASH	Sky Projected Laser Array Shack-Hartmann
SBC	Single Board Computer
SBS	Stimulated Brillouin Scattering
SRS	Stimulated Raman Scattering
SCAO	Single Conjugate Adaptive Optics
SR	Strehl Ratio
TBC	To Be Confirmed
TBD	To Be Determined
TMT	Thirty Meter Telescope
TT	Tip-Tilt
VLT	Very Large Telescope
VME	Versa Module Eurocard
WF	Wave-Front
WFS	Wave-Front Sensor
WHT	William Herschel Telescope
WG	Working Group
XAO	eXtreme Adaptive Optics

1 Introduction

This report has been prepared by the ELT AO Working Group (WG), set up by the ESO DG end of December 2005, following the stated Terms of Reference in order to synthesize the AO requirements for re-baselining the ESO ELT project. It is based on the expertise of the WG members, the experience of their laboratories and the current status of the research in AO around the world.

This report:

- synthesizes the main AO requirements (Section 2),
- proposes baseline AO systems and corresponding LGS concepts to be developed which should best fulfil the expected capabilities of an ELT (Sections 3 and 5),
- establishes the specific AO related requirements on telescope, site and instruments (Section 4),
- identifies the key technologies required to build such AO systems (Sections 6 and 7),
- summarizes the on going demonstrators and path finders (Section 8),
- and proposes a roadmap to develop the required AO systems, based on the some necessary tradeoffs and on a number of identified risks to be mitigated (Section 9).

Another document, associated to this report as a collection of appendices, includes some details on a number of relevant topics.

We have made a number of assumptions to write this document, firstly based on ESO constraints summarized in the following sentences:

- "the project is centred on a 30 to 60-m optical/infrared single telescope, with a consolidated cost in the 750 MEuro range, to be built within a competitive timescale.
- The goal of the first phase is to pass from conceptual to preliminary design by the end of 2007."

Secondly, we have used the acquired experience in building AO systems in the Community, the current performance achieved on the 10m class telescopes, the today available technology and some projections for its evolution and development in the future.

Before to start the detailed analysis presented hereafter, the AO WG wants to raise the following statement. While it is well recognized that adaptive optics is absolutely essential for an ELT, we have to keep in mind that it represents a challenge. The complexity of the systems to be built is very high when compared to the systems in operation today. Most of the key components are substantially "larger", like the number of actuators in deformable mirror for instance. However, some key technologies, relevant for ELT, are already under development through FP6 programs like OPTICON and the ELT Design Study. With a sound roadmap, it should be possible to avoid any major showstopper.

The AO WG report does not include any feedback from the other ELT WG, or marginally. The time, allocated to establish it, was really too short! The AO WG members want to strongly underline the necessity to perform this cross-check and synthesis in order to converge to a truly consolidated plan for the ESO ELT project. We recommend the readers to keep in mind this fact and to not draw definite conclusions.

The Members of the ELT AO Working Group are:

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2 Requirements for AO

The requirements of the AO systems are driven by the scientific goals of the ELT, converted into scientific instruments. Additional requirements are given by the telescope needing adaptive correction to reach its performance.

At the time of writing, science instruments and the telescope still need to be detailed and their requirements towards AO will be one result of the studies of those WGs. However, in order to emphasise this approach and to perceive the performance numbers as *requirement* for the AO and not as a result of a technical feasibility study we define working assumptions for the AO requirements. This is a first step towards "improving the consistency between the AO performance predictions and the science cases" as requested by the OWL review board.

The working assumptions for requirements are mainly derived from the results in the OWL Blue Book, as are the potential AO systems that we present here. The requirements were also influenced by preliminary discussions with the other WGs. In a second iteration, these requirements will have to be cross-checked and refined against the results of the science instruments and telescope WGs.

2.1 From Science Programmes/Instruments

Science programmes can be categorised (in AO relevant categories) by regarding the required field of view. Since it is not our task to identify these programmes we only define the three categories small, medium and large field of view. These categories are driven by the anticipated performance of potential AO systems ranging from a very high Strehl ratio for a very small field to a rather modest improvement for a large field of view. We assume that the requirement for sky coverage is as close as possible to 100% which is not achievable with Natural Guide Stars (NGS), therefore requiring laser guide stars (LGS), and that the wavelength range is from the R- to the Q-band.

We are aware that this is a very coarse categorisation and that for instance for a small field of view different science programmes with different requirements (e.g. planet finder) exist. Therefore we assume a range of performance for the small field.

When all scientific instruments are defined, the requirement table will have to be modified and it will be checked if the potential AO systems that we discuss here meet with these requirements. If science programmes require a much higher performance, then upgrades or completely new systems need to be discussed. Possible upgrade paths for the AO systems discussed in this document will be outlined in Sect. 3

Table 2-1 summarises:

1. The requirements in terms of field of view and performance.
   Eventually, the categories will be replaced by the individual science programmes and the field of view and performance requirements will be altered accordingly.
2. The impact on the corrected wavelength range, driven by the performance, and on the PSF uniformity, driven by applied AO system.
   The fundamental connection between performance and wavelength is independent of the choice of AO system, and the high PSF uniformity will be difficult in connection with a high Strehl ratio. Thus, a good performance in the R band always means an excellent performance in the K-band.

3. Potential AO systems achieving these requirements.
   These systems are the *tools* in the toolbox that we were asked to provide. There is a discrepancy in that not all potential systems fully meet the requirements. Most importantly, a sky coverage of 100% cannot be reached as long as laser guide star AO systems require a natural guide star for the tip-tilt measurement. Of the individual systems, SCAO has a good performance in Strehl but very low sky coverage since it is using a NGS, and GLAO has a performance at the very low end but very high sky coverage. It remains to be seen if there are science programmes for which these exceptions are acceptable.

	Category I	Category II	Category III
Corrected FoV (diameter)	Small = isoplanatic angle (20” in K)	Medium (1’-2’ in K)	Large (5’-10’ in K)
Performance Metric	60-90% Strehl (K) 20-72% Strehl (J)	50% Strehl (K) 11% Strehl (J)	16-40% (K), 5-10% (J) EE in 50mas (4x resp. 2.5× seeing)
Obs. Wavelength	R–Q	I–Q	J–Q
PSF uniformity	Low	High-Medium	Medium-High
Potential systems (see Section 3) (Metric in K)	SCAO (1DM, 75% Strehl, NGS, low sky coverage)	MCAO (2 DMs, several LGS)	GLAO (16% EE, 1DM, several LGS)
	LTAO (1DM, 60% Strehl, several LGS, high sky coverage)		MOAO (40% EE, 1DM, several LGS, ‘islands’ in the FoV)
	XAO (2 DMs, bright NGS)		

Table 2-1: AO performance requirements – working assumptions. For all categories, maximum sky coverage, i.e. laser guide stars (LGS), are required (except SCAO and XAO). (all specification numbers in 0.5” seeing and with a 40-50-m telescope.)

2.2 From telescope

Very likely, the telescope will have a segmented primary mirror with local positioning control loops at the segments, and active optics. The positioning control loop with a bandwidth of several Hz ensures that the form of the mirror is maintained with the exception of the spherical shape, of the tip-tilt and of the lateral mirror position. This translates into the aberrations tip-tilt, defocus and coma that need to be corrected by the active optics and/or by an adaptive optics.

The active optics measures the aberrations about every 30 sec in order to average out the influence of the atmospheric turbulence. However, wind buffeting (or other sources for mechanical deformations) can vary these aberrations with a frequency of about 1Hz. The requirements for a telescope adaptive optics system are driven by the power spectrum of these aberrations.

Figure 2-1 shows the power spectra of aberrations caused by atmospheric turbulence grouped in radial orders (n) of Zernike polynomials. n=1 corresponds to tip-tilt, n=2 to focus (and astigmatism) and n=3 to coma (and trefoil). These kinds of power spectra are the input to ‘atmospheric’ AO systems and can be handled by them. If the power spectra of the aberrations due to wind buffeting are significantly smaller than those of atmospheric turbulence (see dotted line in Figure 2-1), the atmospheric AO systems can correct for them. However, if the wind buffeting power spectrum looks more like the dashed line in Figure 2-1 with much higher power (requiring larger actuator stroke on the DM) at low frequencies, then a dedicated telescope AO is required. Then, the telescope would require AO even for seeing limited observations and might be limited in sky coverage if the telescope AO requires a guide star within the isoplanatic patch.

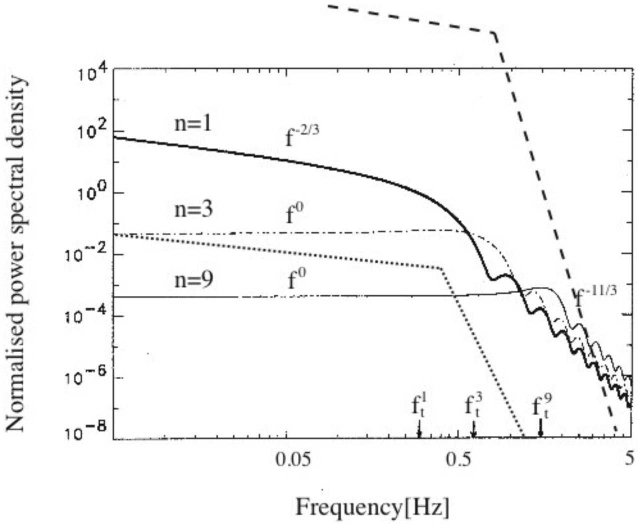


Figure 2-1: Power spectra of aberrations caused by atmospheric turbulence for different radial orders *n* of Zernike aberrations, and two dummy power spectra (dashed line and dotted line) of low order telescope aberrations due to wind buffeting. If vibrations cause the telescope aberrations the power spectra would contain individual peaks at the vibration frequencies. (Curves for Zernikes taken from Conan et al. JOSA A 12, 1559-1570, 1995)

Three scenarios for a telescope AO are possible depending on the bandwidth and stroke requirements of the perturbations:

- Telescope AO with dedicated wave front sensor and DM
- The wave front sensor of the Atmospheric AO is used but an extra DM with larger stroke corrects for the telescope aberrations
- A special wave front sensor with longer integration times and higher sensitivity takes advantage of the rather slow changes but the atmospheric DM is used for correction.

Discussions with the members of the telescope WG indicate that the required DM stroke could be critical (i.e. of the order of the atmospheric values) but the bandwidth being of the order of 1Hz is not. We need more information, ideally power spectra of the aberrations, from the telescope WG to write down the requirements. It is of course desirable, to minimise the disturbances of the telescope, ideally to or below the values of the atmosphere.

3 AO systems fulfilling the requirements

This section describes the different AO systems that may fulfil the science requirements. They have been classified in the 3 categories defined in the former section. The main assumptions on the telescope, conditions and AO systems are given in Section 3.1. It is assumed focussed Sodium beacon are used as LGS (Section 3.2).

3.1 Assumptions about the telescope and the systems and 1st order performance evaluation

The AO concepts provided in this section are based on a number of assumptions which permits to provide an order of magnitude of performance:

- Telescope diameter: 42-m (mean in terms of surface between 30 and 60-m)
- 85^2 actuators large deformable mirror integrated in the telescope
- visible SHWFS and PWFS (for SCAO and XAO only)
- Atmospheric conditions: good seeing: 0.5 arcsec (r_0=20-cm), coherence time: τ_0=4ms, L_0=25-m, isoplanatic patch θ_o = 3" (all values for 0.5 microns)
- 'bright' LGS (V=9)
- no LGS spot elongation simulated.
- bright enough NGSs for tip-tilt

Note on computing power: Throughout Section 3, we take the VLT-AOF narrow field mode with 4 LGS at 1 KHz frame rate as a reference point for computing power requirements. This mode is the most demanding application that can / will be supported by SPARTA in 4-5 years (~10 GFMAC), assuming classical matrix-vector multiply.

At this stage, a continuous face sheet 2 to 3 m diameter DM (~30 mm actuator pitch leading to ~85^2 actuators for a 42-m) based on the "Italian LBT" technology seems to be the less risky approach for a large DM to be directly integrated in the telescope. An alternative solution, to increase the number of actuators for instance, could be to have a post-focal DM, based for instance on piezoelectric actuator technology, at the expense of reduced throughput and increased complexity with LGS.

Curvature sensors, although the noise propagation is less favourable than for a SHWFS, might be revisited to address the LGS spot elongation problem. A NIR PWFS has potentially performance advantages for SCAO in diffraction limited regime.

The AO complexity and performance varies with seeing, telescope diameter, corrected wavelength, atmosphere coherence length r_0 and time τ_0, and isoplanatic angle θ_0 as follows:

- the number of actuators varies as D^2 and r_0^{-2}
- the temporal frequency of correction as r_0^{-1} (or τ_0^{-1}) and D^0 (generally less critical for the AO systems)
- the needed computing power as D^4 and r_0^{-5}
- the performance in terms of SR is approximately given by $SR = \exp(-(2\pi/\lambda)^2\sigma_W^2)$ where σ_W is the wave-front rms error (in meters)

- wavelength (given by SR definition above): for instance a performance of SR=60% in K band corresponds to 18% in J band.
- residual seeing: $\sigma_W \propto r_0^{-5/6}$, for instance, SR~60% in good seeing (0.5 arcsec) degrades to SR~30% for median seeing (0.85 arcsec)
- servo-lag: $\sigma_W \propto \tau_0^{-5/6}$
- anisoplanatism: $\sigma_W \propto (\theta/\theta_0)^{5/6}$ where θ is the angle between the reference star and the observed object.

It is clear that the choice of a good site is very critical in terms of AO characteristics through the dependence in r_0, as the choice of the telescope diameter. These choices will directly impact the risk on the performance and the cost of the systems.

3.2 Laser Guide stars assumptions : focussed Sodium Beacon

Single 'classical' LGS AO has the following limitation:

- **the tip-tilt un-determination** due to the upward propagation of the laser through the atmosphere,
- f**ocus anisoplanatism** or 'cone effect': $\sigma_W \propto (D/d_0)^{5/6}$ where d_0 is the second Fried parameter.

The LGS being located at 90km and not infinity, the rays of light coming from the LGS do not follow the same path as those from the NGS. Therefore, an error is made when measuring the wavefront from an LGS to correct an object at infinity. Focus anisoplanatism is acceptable for 8-10 m telescopes in NIR but becomes critical for ELTs. To overcome this problem the use of Laser tomography with sufficient multi-LGS is essential. In that case the tip-tilt un-determination of each LGS degenerates into low order modes un-determination which need to be measured on one or several NGS (LTAO-MCAO). This leads to an unavoidable limitation in the final sky coverage, even with LGS, which has still to be quantified.

In addition to the problems mentioned above, other issues have been identified, becoming more critical in the Multi-LGS scheme on ELTs:

- **Spot Elongation:** due to the thickness of the atmospheric sodium layer. On the WFS sub-apertures the LGS is strongly elongated (up to 5" for 50m telescope). Possible solution: spot tracking in the mesosphere, using a pulsed laser.
- **Depth of field:** due to the finite thickness of the sodium layer. Possible solution: refocusing membrane mirror tracking the spot on the mesosphere.
- **LGS wave-front quality imaged by telescope:** due to the focussing of a finite distance source with a telescope optimized for infinite distance sources. Solution: optimized telescope design, active correction in the WFS.
- **Laser defocus:** The laser focal plane is in average 2 to 5 m behind the natural star focal plane due to the LGS finite distance, from 90 to 160 km, which makes difficult to separate (spatially or in colour) the LGS wave-front sensing and the science field of view. In addition this defocus varies with telescope zenith distance and also with the change in Sodium density and concentration altitude. Solution: zoom in the WFS + active tracking of the Sodium Layer.

- **Fratricide Effect:** due to the Rayleigh scattering cone of a LGS crossing the SHWFS pattern of another LGS. This may also perturb the active optics WFS.

The requirements for both the laser technology and laser transport needed for focussed Sodium beacons are presented in sections 7.11 and 7.12.

It is important to note, that the following system description are based on the assumption that the problems described above have been solved (see Section 5)!!!

3.3 Category I – small field of view

3.3.1 SCAO – Single Conjugate Adaptive Optics

3.3.1.1 Concept and projected performances

The Single Conjugate Adaptive Optics (SCAO) is essentially an extension to ELTs of the current AO systems in operation at the 8-10m class.

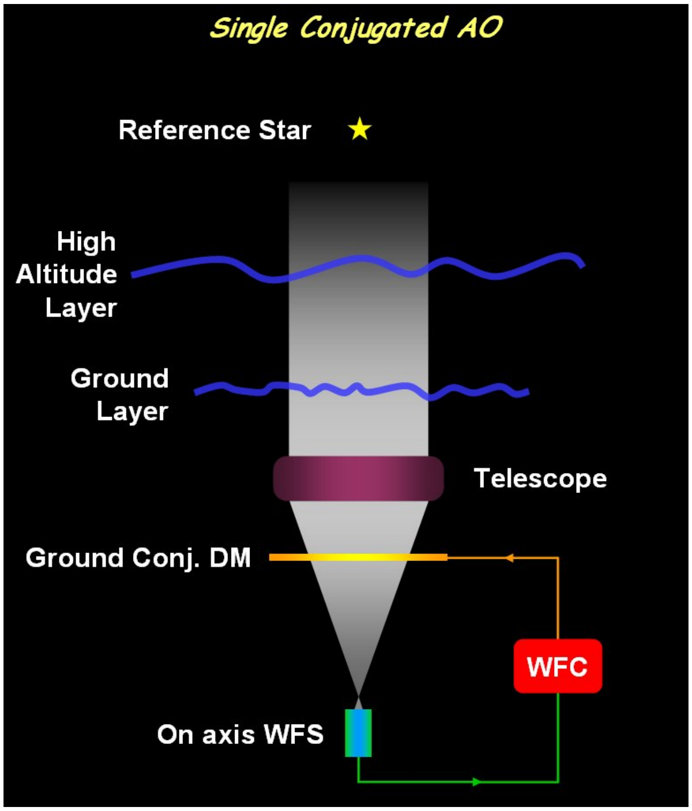


Figure 3-1 Single Conjugate Adaptive Optics concept

The AO correction is provided by a Deformable Mirror optically conjugated at the telescope pupil. The wavefront deformation is estimated by a wavefront sensor looking at a NGS located in the observed (scientific) Field of View which typically is not larger than 30-40 arcsec diameter. The correction is maximal in the direction of the guide star and degrades by increasing angular distance from it. The correction remains effective within the isoplanatic patch of typically few tens of arcsec in the near infrared.

The guide star is a NGS in the FoV and its limiting magnitude is typically $\mathbf{m_v=17}$ today, but could be improved by using no-noise CCD technology (see Section 7). The latter is driven by the required sub-aperture size of about 50cm for an AO with an 85x85 actuator DM on a 42-m telescope. For this reason the availability of such targets on the sky is very limited and the Sky Coverage with SCAO is few percent.

SCAO typically delivers diffraction limited images in the near infrared (J to K band) and only partial correction below 1 μm. The typical correction performances for the assumed system with an 85x85 actuator DM are:

- On-axis Strehl: 75% (K band), 40% (J band)
- Anisoplanatism: 30% of Strehl at 20 arcsec off axis (K band) (value very dependent on the turbulence profile)

The SCAO could be viewed as the first light system and a mandatory first step in the implementation of the different AO systems in the ELT in order to validate the operation of some key components.

3.3.1.2 Design approaches

A SCAO system is based on three key elements:

- A deformable mirror unit
- A wavefront sensor
- A real-time computer (RTC)

Deformable Mirror

The deformable mirror is **85x85** actuators and about 2.5 m diameter located in the telescope optical train optically conjugated to the telescope pupil within ±200 m. It is not excluded to consider a post focal DM (actuators TBD) to increase the actuator density and improve the Strehl ratio.

Wavefront Sensor

The wavefront sensor is located post-focal after the deformable mirror(s) (wherever located) and can be moved on the FoV to acquire the NGS. There are two options:

- Visible WFS: Shack-Hartmann configuration **84x84** sub-apertures, sensitive from 0.4 to 1 μm, read-out frequency up to 1 kHz. Each sub-aperture is covered by 6x6 pixels and the CCD detector has very low RON (<< 1 e^-);
- Infrared WFS: based on Pyramid **84x84** sub-aperture, sensitive from 1 to 2.5 μm, read-out frequency up to 1 kHz. Each sub-aperture is covered by 1x1 or 2x2 pixels and the IR detector has moderately low RON (~5 e^-);

Since the two concepts are complementary in terms of natural guide star availability it is not excluded to have the two WFS coexisting.

Real-Time Computer

The control of the SCAO system will be performed by a centralised Real Time Computer and conventional control algorithms already implemented today.

3.3.1.3 Required technologies

Based on the design approaches described in the previous section, the following technologies are required for the SCAO system:

- Large deformable mirror **85x85** actuators of about 2.5 m diameter
- or a post focal deformable mirror with ~100^2 actuators with 4-5 mm pitch and 10-20 µm stroke (for higher Strehl ratio);
- CCD array with 600^2 pixel very low noise (<<1 e^-)
- IR detector 200^2 low noise (<5e^-).
- Real-time computer with 5 times VLT AOF computing power.

3.3.1.4 Risks and mitigation

- SCAO systems are very well known.
- Pyramid WFS performance. <u>Mitigation:</u> the HOT test-bench will permit to test extensively the modulated Pyramid sensor for XAO applications. Additionally, feedback is expected from the PYRAMIR systems and the LBT 1st light AO system in the near future.
- Visible detectors: see Section 7.6.
- NIR detectors: see Section 0.
- Large DM: see Section 7.1 (large DM technology) and 7.2 (thin shell) and Section 9 (roadmap) for risks and mitigation.
- Design feasibility of a post-focal DM (if needed). See section 7.4.

3.3.2 LTAO – Laser Tomography Adaptive Optics

3.3.2.1 Concept and projected performances

In the case of SCAO, the sky coverage is limited by the availability of bright (magnitudes 16-17) guide stars within the isoplanatic patch (~30''-1') from the object. The sky coverage is barely a few percent. This is a well-known problem of this kind of AO system. To improve this, one needs to resort to multiple laser guide stars. Indeed, using a single LGS is not sufficient, because of the cone effect (or focus anisoplanatism). To overcome this issue, several LGSs have to be used, to probe the whole volume of turbulence above the telescope. This so-called LTAO (Laser Tomography AO, see Figure 3-2) allows to use a single DM optically conjugated to the telescope pupil and to optimise the correction on-axis over a small FoV.

In the case of an ELT, the LGSs should be located far enough off-axis to sense the whole volume of turbulence (geometrically the optimum distance is **45 arcsec radius** off-axis). If we want to limit the number of LGSs to 4-5, the optimum LGS off-axis angle should be compromised with the meta-pupil overlap at let say 8 km. For a given performance the corresponding optimum values remain to be determined by simulations. LTAO still needs to sense 1 to 3 natural guide stars in the corrected FoV for compensating the very low order atmospheric aberrations.

The typical correction performances for a system with an 85x85 actuator DM are:

- <u>On-axis Strehl: 60% (K band), 20% (J band)</u>
- <u>Anisoplanatism: 30% of Strehl at 20 arcsec (K band)</u>
- <u>NGS limiting magnitude:</u> **19 (TBC)**
- <u>Sky coverage:</u> **TBD**

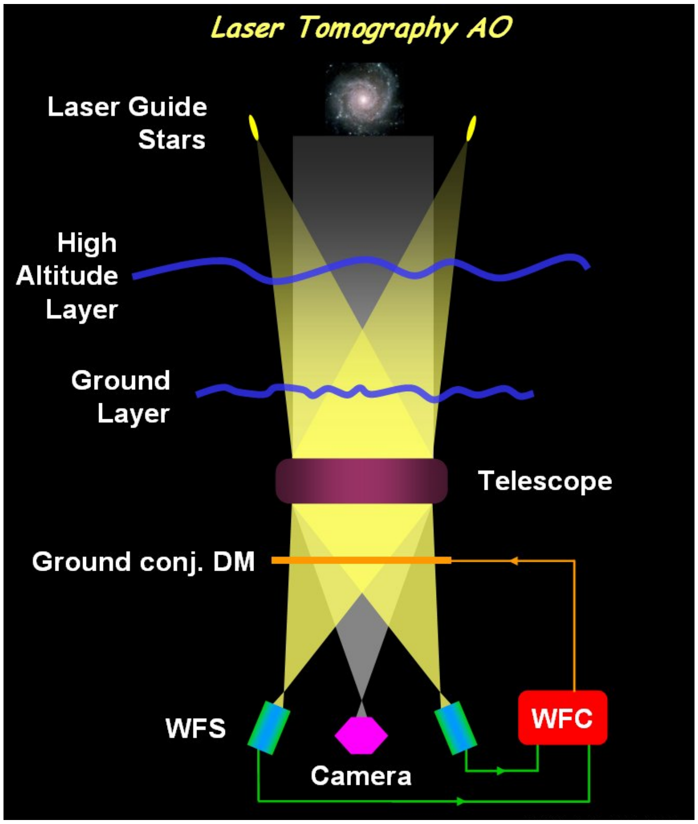


Figure 3-2 Laser Tomography Adaptive Optics concept

3.3.2.2 Design approaches

The LTAO system is based on the SCAO configuration plus the additional key elements:

- Multi Sodium Laser Guide Stars
- LGS wavefront sensors
- Low order NGS wavefront sensor(s)

Deformable Mirror
(see SCAO)

LGS Wavefront Sensors
The LGS wavefront sensors (one per LGS) are located post-focal after the deformable mirror and can be moved in the technical FoV (**45 arcsec radius**) to acquire the LGS in the case they are movable. The LGS WFS have Shack-Hartmann configuration very similar to SCAO one. The LGS wavefront sensor optics should be able to correct for the

apparent sodium altitude change with telescope zenith distance (LGS foci are respectively of the order of 5 m and 2.5 m behind telescope focal plane for 90 and 160 km) and the spot elongation via, for instance, a zoom and dynamic refocusing optical system. The impact of the dynamic refocusing system on the final LTAO performance remains to be studied carefully. In addition, a static or/and dynamic (TBC) corrector should be implemented to correct for the large telescope LGS aberrations versus Field positions and zenith distance (to be minimised by a proper telescope design). The small LGS aberrations might be taken into account by offsetting the WFS calibration, for instance.

NGS wavefront sensor(s)

The low order modes not measured by the multi LGS WFSs should be measured on 1-4 faint (19-20 TBC) NGSs located in the technical FoV (1 arcmin radius, TBC). The wavefront sensing can be done either in the NIR (better limiting magnitude thanks to the MCAO correction but higher detector noise) or in the visible. The option to perform the low order mode sensing on the science chip itself looks attractive although limited by the available FoV and therefore may limit the sky coverage (science FoV much smaller than the technical FoV). The outer scale of turbulence will reduce the low order mode variance to be corrected but also their angular correlation (to be quantified).

Multi Sodium Laser Guide Stars

LTAO requires the projection of several Sodium LGSs (4-5 TBC) in the technical FoV (size **45 arcsec radius**) either behind the secondary (minimisation of the spot elongation) or from the telescope center-piece (minimisation of the wavefront sensor fratricide effect and minimisation of the low altitude Rayleigh scattering within the science FoV). The geometry and size of the optimum laser constellation remains to be studied.

Control algorithms

Specific control algorithms should be developed to compensate for the cone effect by LGS tomography and for tip tilt and low order modes by NGS tomography. In order to achieve the expected high performance, special care should be taken in the temporal controller to properly filter the telescope vibrations.

3.3.2.3 Required technologies

The required technology for LTAO consists of the same sub-systems of SCAO with additionally the technology related to Laser Guide Stars.

- CW or pulsed sodium lasers with respectively 60-100 W and 15-20 W emitted power (TBC)
- Fibres for laser beam transport compatible with a peak power without SBS is desirable
- Large deformable mirror: same as SCAO
- Large enough CCD for CW Laser WFS, or gated WFS with spot elongation reduction capability (dynamic refocussing)
- No noise high QE CCD detector (up to 1KHz) for NGS wave-front sensing (128^2) (TBC);
- Low noise ($<5e^-$) IR detector for NGS wavefront sensing (128^2);

- Real-time computer with 20 times VLT AOF computing power
- Control algorithms for LTAO performance optimization
- Analytical and numerical simulation tools (and computing power) able to provide performance estimate of LTAO systems with up to 6 LGSs, with up to 100^2 actuators.
- On-line Cn^2 profiler for LTAO control optimization
- On-line Sodium density profiler for focus control

3.3.2.4 Risks and mitigation

- Laser Tomography Adaptive Optics concept has never been demonstrated neither on the sky nor in the laboratories.
  Mitigation: it is planned with the MAD demonstrator to test the optimization of the correction on a specific direction of the FoV by combining the signals from the NGS. It will be proved both in the laboratory and on the sky (2006-7). An equivalent LTAO system, the narrow field mode of the Adaptive Optics Facility (GALACSI on sky in 2011), is in development at ESO and will provide optimized LGS correction with one large DM (VLT secondary) on a small FoV (~10 arcsec) down to 0.65 μm. The need for a on sky LTAO demonstration at a shorter time should be explored.
- Calibration of LTAO system is a complex problem which has started to be looked at with MAD.
  Mitigation: Research in this field remains of prime importance.
- Wavefront sensor linearity in LTAO system is of prime importance.
  Mitigation: MAD will provide some answers to that question but it has a limited number of degrees of freedom. The need for a laboratory higher order LTAO demonstrator should be explored.
- LTAO performance with LGSs needs further simulations including sky coverage calculation.
- Dynamic refocus and radial CCD array: See section 5.3 and appendix C.
- Visible detectors: see section 7.6.
- Large DM: see section 7.1 (large DM technology) and 7.2 (thin shell) and section 9 (roadmap) for risks and mitigation.
- Design feasibility of a post-focal DM system (if needed). See section 7.4.

3.3.3 XAO - eXtreme Adaptive Optics

3.3.3.1 Concept and projected performance

The concept for eXtreme Adaptive Optics (XAO) is essentially the same as SCAO with a much higher number of corrected modes. Moreover an XAO system is most of the time associated to a coronagraph and an instrument based on differential methods in order to get both :

- high Strehl ratio (typically **90% in H** and **60% in R**) to maximize the signal for detection of a point source
- high contrast (~10^{-6} to 10^{-7} for 8-m class telescope, **5×10^{-8} to 5×10^{-9} for a 42-m telescope in NIR**) to minimize the noise by scattered starlight.

The corrected FOV is small and is about 1 to 2 arcsec. The size of the 'cleaned area' in the PSF is equal to λ/d in diameter, where d is the XAO sub-aperture size and λ the science wave-length.

The XAO system has to be an integral part of the whole instrument in order to permit to get the high contrast required for exo-planets detection, as demonstrated by the VLT Planet Finder studies. That is why we present in this section not only the XAO itself but also coronagraphy and instrumentation.

Actually, in the frame of the ELT DS (instrument small studies Planet Finder) two options are being studied for a 42-m telescope: a 160^2 sub-apertures (26 cm sub-aperture as projected on the primary) and a more optimistic 240^2 system (17.5 cm sub-aperture as projected on the primary).

The AO residuals can essentially be separated in dynamical terms and static terms:
The dynamical terms: this component translates into a **'smoothed' halo** so that, the detection is similar to background limited observation. At fixed observation time the achievable contrast scales then as D^{-2} where D is the telescope diameter thanks to the increase in resolution. Typical value of wave-front error: **~60 to 80 nm rms.**
The static terms sets the ultimate contrast one can achieve whatever the integration time. This error translates into a **static speckled halo**. Typical value: **< 1 to 10 nm rms (on spatial frequencies < ~100 cycles/pupil for a 40-m class telescope)** depending on the goal contrast versus angular separation.
It is important to note that the achievable contrast is always limited by the static errors. This means that the theoretical increase of contrast of an ELT can be attained only if the static wave-front error budget of the instrument+AO permits it. This implies more severe requirements for the control of systematic errors on ELTs, a very challenging task.

3.3.3.2 Design approaches

The general design approach is given in the figure below. The very high number of degrees of freedom required for the corrector imposes the use of a post-focal deformable mirror (MEMS or piezo-stack). The usual limited stroke of high density adaptive mirrors may require to use a woofer to correct large amplitude and slow aberrations. This woofer can be located in the telescope itself and could be the large DM considered in the SCAO and LTAO systems.
A specialized wave-front sensor is needed in order to fulfil the requirements on very high contrast. The two main WFSs that have been proposed for Planet Finder instruments for 8-m class telescopes are:

- The spatially filtered Shack-Hartmann WFS: an upgrade of the classical SH to obtain better halo rejection.
- The Pyramid WFS: this WFS theoretically has a better sensitivity for correcting the halo at small angular separations. An additional feature of the Pyramid sensor could also be the ability to better correct for static co-phasing errors.

New yet unproven concepts have also been proposed like the Mach-Zehnder and the focal plane interferometers.

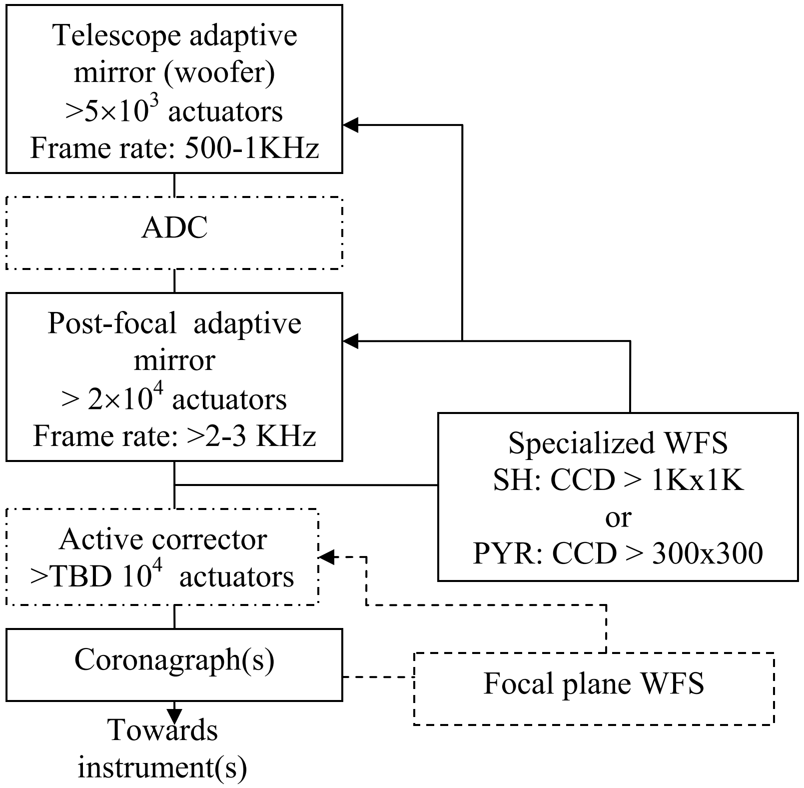


Figure 3-3: Implementation concept of an XAO system in an ELT. The numbers given are for a 160^2 actuators system.

The requirements for systematic errors control will be more demanding for an ELT than for 8-m class telescopes. For this reason new concepts need to be investigated as highlighted in dashed line in the figure:

- <u>Focal plane interferometer/WFS</u> probing the image defects the nearest possible to the instrument detector .
- <u>Additional dedicated active corrector before the coronagraph:</u> may be required for nanometric precision of optical defects control.
- <u>Upstream Atmospheric Dispersion Correction:</u> for high contrast imaging, an ADC as upstream as possible in the optical train is highly desirable to limit differential chromatic errors.

Special requirements of XAO to the telescope are also presented is Section 4.1 and in appendix F.

3.3.3.3 Required technologies

- **Adaptive mirrors**: MEMS or Piezostack adaptive mirrors with a high number of actuators: 160^2 – 240^2 actuators controllable at 2-3 KHz , stroke (assuming a woofer) of a 1-2 microns (TBC, simulations needed), inter-actuator-stroke of 1 micron (similar to VLT-PF). The actuator pitch should be of about 1 mm.
- **Detectors**: CCDs: 1Kx1K-1.5K-1.5K pixels (for Shack-Hartmann), > 320x320 – 480x480 (for pyramid, TBC may be split in 4 detectors) detectors with fast read-out (2-3 KHz) and 0 noise (< 1e) are required for Wave-Front Sensing.

Wavelength will be visible or preference for I band (TBC, depends if chromatic errors need to be minimized), with high QE > 90%.

- **Very high quality optical components** are needed since this fixes the ultimate contrast achievable: a few optical elements will require very high optical quality, needing possibly thermally controlled optics for extremely high precision/stability.
- **Atmospheric Dispersion correction:** This is a major problem for high contrast imaging and dedicated ADCs have to be developed for the AO and the instruments.
- **Dedicated focal plane wavefront sensor, calibration procedures and control algorithms to reduce the static aberration errors.**
- **Simulations** are a very important part of the development of an high contrast imaging instrument.

3.3.3.4 Risks and mitigation

The VLT-Planet Finder (SPHERE) instrument will be a pathfinder for future high contrast imaging systems on ELTs. Several new concepts need to be introduced for an XAO system on an ELT. The major risks are that these concepts don't perform as expected.

- **The spatially filtered Shack-Hartmann sensor:**
  No on-sky tests with spatial filter have been done yet. Laboratory tests have been performed at ONERA.
  Mitigation**:** Further test will be performed with the **HOT testbench** and valuable feedback is expected from **VLT SPHERE**.
- **The pyramid wave-front sensor:**
  Some stability/robustness issues of a non-modulated Pyramid sensor have been highlighted using simulations in the frame of VLT-PF study. The Pyramid sensor is also very recent and only a low order system is working on the sky.
  Mitigation: The **HOT testbench** will permit to test extensively the modulated Pyramid sensor for XAO applications. Feedback is expected from the **PYRAMIR** systems and the **LBT 1st light AO system** in the near future.
- **Woofer / tweeter scheme**: this scheme is the control of a large amplitude corrector with small number of actuators (the telescope DM) together with the post-focal DM with high number of actuators.
  Mitigation: this scheme will be tested on the HOT testbench using a 60 element bimorph mirror and a 1000 element MEMS.
- **Focal plane interferometer/WFS:**
  This concept is very new, limited simulations and experiments have been conducted. The system will be rather complex and the limits are not well known.
  Mitigation: The concept will be studied in the frame of **FP6 ELT design Study**. No laboratory tests planned yet but desirable.
- **Availability of high actuators density DMs:** see sections 7.4 and 7.5.
- **Coronagraphy.** The performance of the high contrast imaging relies entirely on the best combination of XAO with coronagraphy.

- **Real-time computers:** The computing requirements is **180 – 900 times AOF**. Important developments on hardware are required. See sections 7.9.
- Algorithms: new algorithms to speed up the computation time need to be developed (see 7.10)
- **Detectors:** see section 7.6.
- **Instruments:** the science instruments themselves are the last chain permitting to get the needed contrast. Some of them are already part of the SPHERE project (Tigre-type IFS, Differential Polarimeter, differential imager) and some other need new developments (Fourier Transform Spectrograph, focal plane interferometer…).

3.4 Category II – medium field of view

3.4.1 MCAO – Multi Conjugate Adaptive Optics

3.4.1.1 Concept and projected performances

Multi-Conjugate Adaptive Optics (MCAO) aims to enlarge the FoV size of diffraction limit corrected image (1-2' FoV). MCAO can be seen as a forward step of the GLAO concept were the correction is not applied only to the ground layer but also to other altitudes above the telescope aperture where additional deformable mirrors are optically conjugated to.

MCAO benefits from the simultaneous wavefront sensing of several reference stars located in and/or around the FoV which is the target of the correction. The light of these reference stars probes the atmospheric volume interested by the FoV and provides, up to a certain extent, the information on the vertical distribution of the atmospheric turbulence.

To offer high sky coverage with a Strehl ratio beyond 50% in K-band over 1', MCAO requires several Laser Guide Stars to sense tomographically the volume of turbulence above the telescope. The PSF uniformity (few % of Strehl variation) over the corrected FoV and the average Strehl at a given wavelength depends on:

- Number of LGSs & LGS constellation geometry/size for the tomography
- Number of NGS and positions in the field
- Number of deformable mirrors to perform the MCAO correction
- Conjugation altitudes of these DMs (to be optimized)
- Number of actuators per DMs
- Turbulence profile (C_n^2)

However the sky coverage is limited by the availability of 1-4 NGSs (m_v of 19-20 TBC) over a technical FoV of 1-3' (TBC) to correct for the low order modes not seen by the LGSs.

The full parameter space based on the science expectations should be explored to provide the expected MCAO performance.

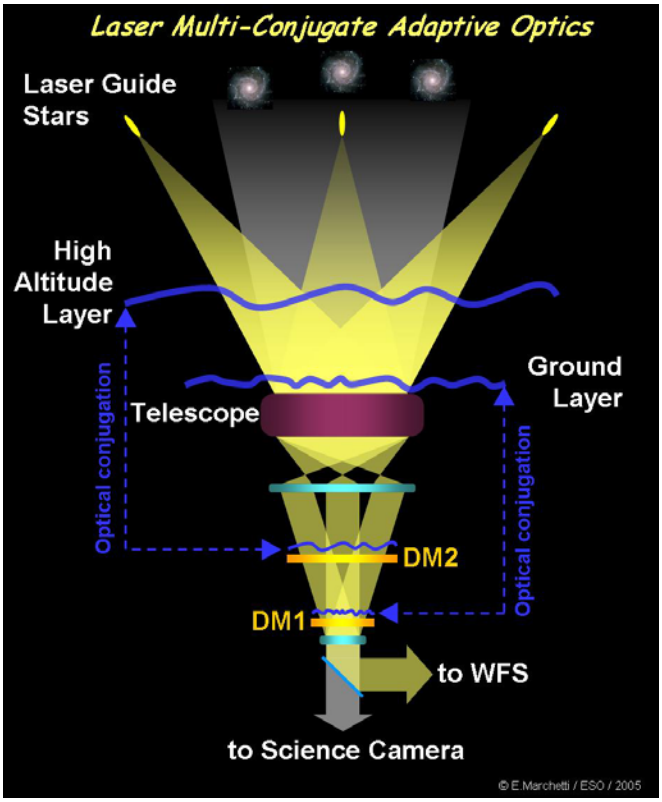


Figure 3-4: General MCAO concept with LGSs

3.4.1.2 Design approaches

Assuming that a large deformable mirror DM1 conjugated to the "ground" is integrated into the telescope as baseline, a second and possibly a third (depending on performance requirements) deformable mirror needs to be implemented either after the telescope focal plane (post-focal AO) or within the telescope itself (see Section 6). This decision depends on the following:

- Calibration and flattening issues of the in-telescope DMs for non-MCAO modes?
- Conjugation altitudes of the deformable mirrors are fixed by telescope design; it is not clear at this stage what are the optimum conjugation altitudes for the MCAO DMs especially with a varying zenith angle
- LGS constellation/DM1 actuator pattern rotation with respect to the post-focal DM2-3 / LGS wavefront sensors, potentially leading to the rotation of the full & heavy post-focal AO adapter.

Note that a fully post-focal MCAO system -without DM1 integrated into the telescope optical train- with 1' corrected FoV might be feasible although it will make the MCAO module with 3 DMs extremely complex to design and develop.

The conjugation altitudes of the DM 2 and 3 needs to be optimised but 1st order estimate for an average observing zenith angle of 30 degrees are: 4-6km and 10-12 km. In the case of 2 DMs MCAO, conjugation altitudes are typically 10-12 km (TBC) for the second DM.

Multi Sodium LGS
In the "classical" laser MCAO scheme, MCAO requires the projection of several Sodium LGSs (5-6 TBC) with the same alternatives as in LTAO. In the case of other LGS projection scheme (see Section 5.5), the full opto-mechanical implementation concept needs to the studied and the impact on the telescope design needs to be established.

LGS wavefront sensors
In the case of a full MCAO telescope, the LGS wavefront sensors should rotate to follow the rotation of the LGS constellation (pupil rotation TBC). In the case of a post-focal MCAO system the MCAO module should probably rotate to follow the LGS constellation and DM1 actuator pattern (TBC). The LGS wavefront sensors should be able to correct for the apparent sodium altitude change with telescope zenith distance and for the telescope aberrations (see LTAO).

NGS wavefront sensors
(see LTAO) Here the technical FoV should be larger, leading a potentially higher sky coverage.

3.4.1.3 Required technologies

Based on the design approaches described in the previous section, the following technologies are required for the MCAO system:

- Large deformable mirror for DM1: same as SCAO
- Additional large deformable mirror of about 4 m diameter (in case DM2 in telescope) (TBC)
- Post focal deformable mirror with ~100^2 actuators with 4-5 mm pitch and 10µm stroke (TBC)
- CW or pulsed sodium lasers: same as LTAO
- Fibres for laser beam transport desirable: same as LTAO
- CCD and detector for Laser WFS and NGS WFS: same as LTAO
- Real-time computer with **60 times VLT AOF narrow field** mode computing power or with optimised algorithms to reduce computation requirements
- Dedicated control algorithms for MCAO performance optimization including tomography and temporal aspects
- Analytical and numerical simulation tools and computing power able to provide performance estimate of MCAO systems with up to 10 LGSs, several NGS, 3 DMs with up to 150^2 actuators.
- On-line Cn^2 profiler for MCAO control optimization
- On-line Sodium density profiler for focus control

3.4.1.4 Risks and mitigation

- Multi-conjugate Adaptive Optics concept has been demonstrated for Solar observations. MCAO for night astronomy is being developed for instance at ESO with the so-called MCAO demonstrator (MAD) but only using NGS. Closed loop MCAO results have recently been obtained in the laboratory. In the coming year more results and experience will be gained with MAD and an on-sky demonstration will be pursued at Paranal.

- MCAO combined with multi-LGSs tomography is not yet addressed experimentally in Europe. Only existing pathfinder for ELT is the GEMINI MCAO system in development in US. A plan to extend the VLT AOF with a postfocal LGS MCAO prototype might be an interesting path to investigate.
- MCAO performance with LGSs needs further simulations. All parameter space as described above should be explored.
- Statistics about the expected turbulence profile, C_n^2, will be useful to better determine the optimum altitude of the conjugated DMs and to estimate the performance
- Design feasibility of a 2 DMs post-focal MCAO (DM2 & 3) system needs to be studied. See section 7.4.
- Calibration of MCAO system is a complex problem which has started to be looked at with MAD. Research in this field remains of prime importance.
- Wavefront sensor linearity (see LTAO).
- Dynamic refocus and radial CCD array: See section 5.3 and appendix C.
- Large deformable mirror –DM 2 & 3 – of 4 m diameter –large DM in telescope- has not yet been developed and no plan exists right now to expand the present technology to this size. See section 7.1.
- Piezoelectric DM: see section 7.4.
- Detectors: see section 7.6.

3.5 Category III – large field of view

3.5.1 GLAO – Ground Layer Adaptive Optics

3.5.1.1 Concept and projected performances

The goal of Ground Layer Adaptive Optics (GLAO) is to improve the seeing over a wide field of view. The GLAO correction is based on the fact that most (~50% or more) of the atmospheric turbulence is concentrated in the first few hundred meters above the ground for the best astronomical sites. Correcting these low altitude layers allows to obtain a significant and uniform improvement of the PSF over a field of several arc-minutes in the near IR, about an arc-minute in the visible. A diffraction limited PSF is (usually) not achieved, even if a very small diffraction limited core can be present (this core would then contain at most a few percent of the total energy of the PSF). The quality of the correction depends critically on the targeted field of view. The larger the field, the smaller the improvement.

In the K band, when correcting a 6’ (diameter) field of view, a gain of a factor 4-5 in EE in a 50 mas pixel can be expected wrt. seeing. This pixel contains then ~16% of the energy. In the J band, these numbers become a factor of 3 gain, and 5% of the energy in a 50 mas pixel). These numbers are for good seeing conditions (0.5’’).

In the visible, one can expect to double the energy within a pixel of 0.2’’ in a 1’ FOV, even in bad (~1’’) seeing conditions (MUSE wide field mode type performance).

Depending on the required field of view and the required sky coverage, multiple laser guide stars may or may not be required (the larger the field, the larger the sky coverage). If the field of view is large enough (say 6'-8'), a non negligible sky coverage (40% at medium galactic latitudes) seems to be achievable with a solution based on NGS only. The advantage of LGSs is that a high sky coverage can be provided (to be quantified). Also PSF variations are likely to be better controlled in an LGS based system, because the WFS geometry is always the same and optimized for that purpose (except for tip-tilt).
The full parameter space based on the science expectations should be explored to provide the expected GLAO performance.

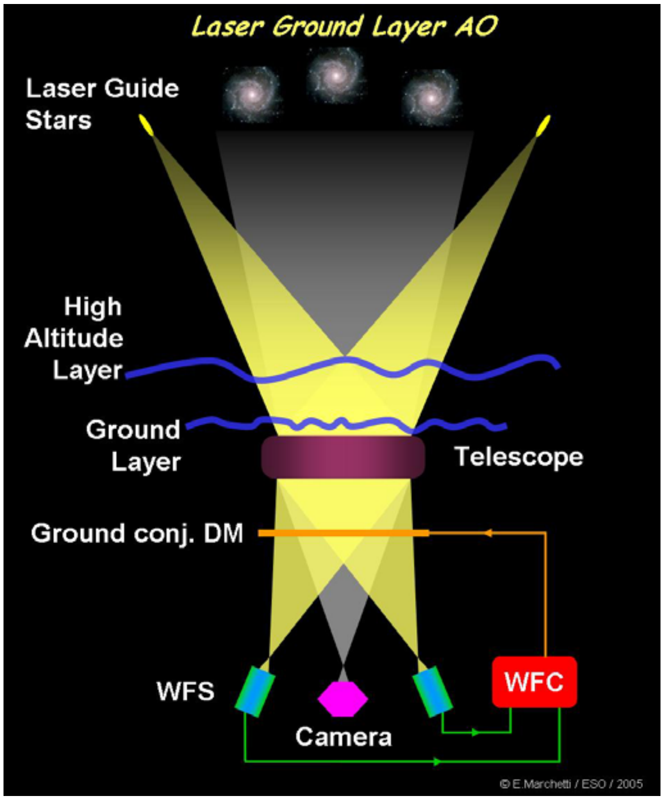


Figure 3-5: General GLAO concept with LGSs

3.5.1.2 Design approaches

The wide field of view in the near IR offered by GLAO is hardly achievable with a post-focal AO system. Indeed, achieving a post-focal 6' field of view would require very large re-imaging optics, in case a conventional deformable mirror solution was used. In addition to being large and expensive, these optics would reduce significantly the transmission of the system, and the gain brought by GLAO (light concentration in a pixel) could be significantly reduced (see also Section 6).
The natural solution is to use a deformable mirror integrated in the telescope design, conjugated to an altitude near the ground (~0-200m, TBC). This has the double advantage of not necessitating re-imaging optics and of having the maximal transmission (minimal number of surfaces).

For a visible light GLAO system with ~1’ FoV, a post-focal design becomes easier, and an adaptive mirror in the telescope is not necessarily required (although it may be desirable, for emissivity / transmission aspects).

The tip-tilt sensing can be done either in the visible or in the near IR. In the visible, noiseless detectors allow high limiting magnitudes. In that case, a patrol field, scanned by the TT sensor allows not to vignette the science field, and allows to increase the search area to find a suitable NGS. In the near-IR, TT sensing can be done either with a separate IR detector, or on-chip (with a Hawaii2-RG type detector). The advantage of near-IR TT sensing is the accessibility of very red objects. The drawback is the higher noise of IR detectors.

The laser power depends on the GLAO performance required and on the ability to correct for the spot elongation with, for instance, the dynamic refocusing approach (10-15W per laser TBC).

In GLAO dedicated control algorithms should be able to optimally ensure the best performance of the system on the whole scientific FoV.

3.5.1.3 Required technologies

Based on the design approaches described in the previous section, the following technologies are required for the GLAO system:

- Large deformable mirror: same as SCAO
- CW or pulsed sodium lasers: same as LTAO
- Fibres for laser beam transport desirable: same as LTAO
- CCD and detector for Laser WFS and NGS WFS: same as LTAO
- Real-time computer (frame rate 500 Hz) with **2.5 times VLT AOF narrow field mode** computing power
- Dedicated control algorithms for GLAO system
- On-line Cn^2 profiler for MCAO control optimization
- On-line Sodium density profiler for focus control

3.5.1.4 Risks and mitigation

- The largest conceptual risk in GLAO is the amount of turbulence contained within first few hundred meters. The correlation of the ground layer structure and the seeing itself is not yet fully understood. For example, it is anticipated that the periods of mediocre seeing (>1’’) are largely due to a strong ground layer turbulence layer, and would therefore benefit most from GLAO. On the other hand, periods of good seeing are expected to have a low contribution of the ground layer to the total turbulence. This is why a GLAO system is sometimes seen as a seeing stabilizer. However, comprehensive statistics are still lacking.
- The calibration of the AO system (e.g. making the interaction matrix) is not yet demonstrated in the case of the DM in the telescope, especially if an intermediate focus (to allow placing a calibration fibre) is not available.

To mitigate these risks, several steps are being taken:

- The turbulence profile is being measured on Paranal, with a SLODAR device, which allows to measure both the seeing and the ground layer of turbulence. Statistics are being gathered to get a better knowledge of the ground layer.
- MAD will work in GLAO mode. This will allow to verify the GLAO concept. Although MAD will work with NGSs only, we expect to be able to verify over the 2' corrected FOV that GLAO indeed improves the correction quality.
- Two second generation VLT instruments (MUSE Wide Field mode in the visible and Hawk-I in the near IR) are being developed in the framework of the AO Facility and will allow to better understand the engineering hurdles of GLAO systems (like the use, fabrication and calibration of an AO system based on an adaptive secondary mirror). It will also validate different tip-tilt sensing schemes (Visible and IR, on-chip and dedicated TT sensor). Other observatories (Gemini and SOAR) are also developing GLAO systems (either based on single or multiple LGSs).
- To assure the availability of lasers, a fiber laser is being developed for the AOF.

In terms of AO simulations, a full set needs to be made once the FOV, wavelength range and required sky coverage is known. In addition, updated atmospheric models are required to be fully confident that the simulations reflect reality.

3.5.2 MOAO - Multi Object Adaptive Optics

3.5.2.1 Concept and projected performances

The primary goal of the Multi Object Adaptive Optics (MOAO) concept is to fulfil the requirements for the observation of galaxies at high redshift by 3D spectroscopy. These objects are extremely faint sources and their emission is redshifted to the near and mid infrared. Their size is only of the order of a few tenths of arc seconds, hence a target field of view very small for each object. To study the formation and evolution of the galaxies, a statistical approach is required. Therefore the analysis of a very large number of objects is mandatory, leading to the requirement of simultaneous observations (in a multiplex mode) of around 10 to 20 (N_{obj}) objects located in a very large field of view (of the order of 5 to10 arcmin) delivered by the telescope. The principle of the MOAO concept is therefore to optimize the turbulence correction in specific tiny areas, where the galaxies are, in the very large cosmological field.

The specifications are to achieve around 40 to 50% of encircled energy in K band in one spatial resolution element of the order of 50mas (TBC) for a 40m class telescope with a high sky coverage of the order of 50%.

In one hand, MCAO concept is not suitable because the compensated FOV will only be of the order of 2 arcmin at most. In addition, the size of the required observed FOV leads to very large angles inside the instrument. In another hand, a GLAO system will provide marginal efficiency in turbulence compensation due also to the very large size of the FOV.

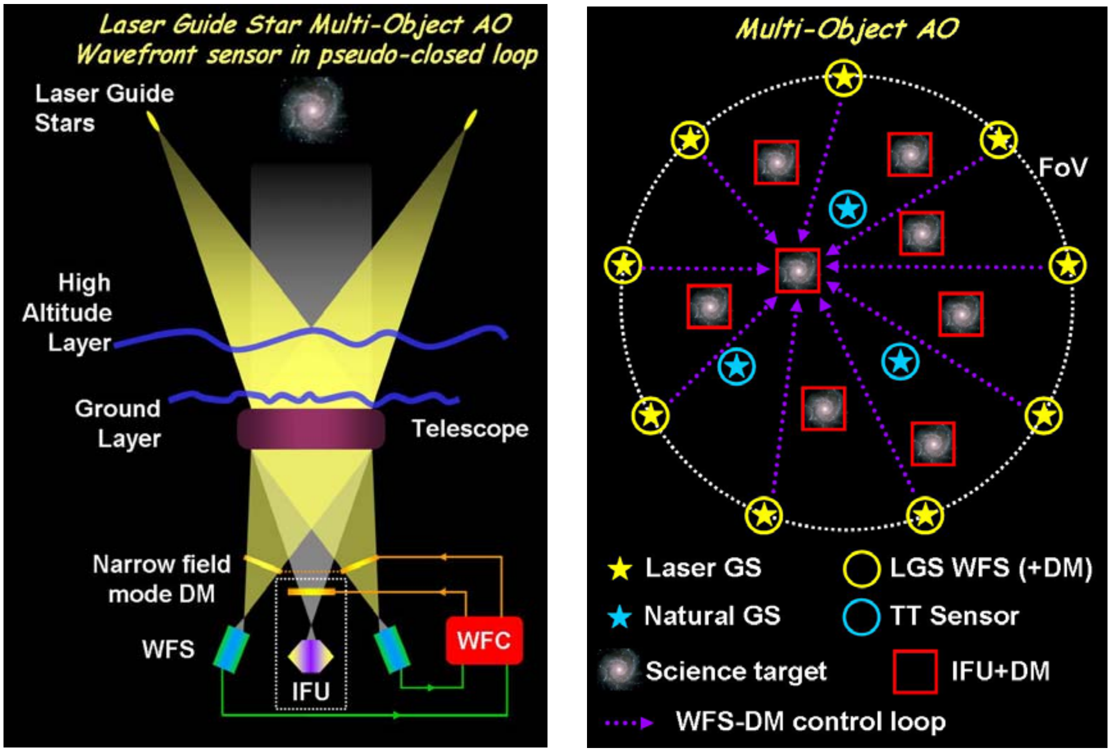


Figure 3-6: General MOAO concept here considering LGSs

3.5.2.2 Design approaches

The MOAO concept (see Figure 3-6 as an example with LGSs) is to equip the N_{obj} integral field units (IFU) with a dedicated deformable mirror in order to only compensate the tiny sub-FOV covering one galaxy and to sense the turbulence in a large number of independent directions in the FOV, using the available sufficiently bright stars (mR<18, TBD) to feed the set of wave-front sensors. A global tomographic phase reconstruction is required to ensure a good performance in all the directions of interest. The main goal is to optimize the correction in each galaxy tiny sub-FOV.

The initial concept, so-called Falcon, is based on dedicated buttons of two types: 1) for the IFU channels including the DM and 2) for the wave-front sensing channels to be also directly installed in the telescope focal plane. Miniaturized optics has to be developed for this purpose. Other types of implementation with pick-up mirrors near the focal plane (see MOMFIS study) should be investigated but the size of the optical pieces to be put in the focal plane is a concern. **Therefore MOAO is an integral part of the scientific instrument.**

In any case, the concept of such an instrument is very modular with a large number of standardized components and channels. This is a clear advantage for maintenance and substantially reduces the probability for a severe failure of the instrument during operation.

One specificity of such an AO system is the open loop configuration for the DM control: using wave-front measurements performed off-axis and through different optical trains, resulting in no feedback from the DM on the set of WFS.

To reduce the constraint on the DM in the IFU channel (i.e. DM stroke), a two stage correction should be studied. It could involve a pupil DM already integrated in the telescope optical train as a first stage and a second stage integrated in each IFU channel.
It is not yet demonstrated that the required high sky coverage can be achieved only using NGS. Therefore, LGS should be also considered. A possible trade-off for the wavefront sensing issues could be to couple measurements on a relatively low number of LGS and measurements obtained with the available NGS, sufficiently bright, in the cosmologic field.

3.5.2.3 Required technologies

Adaptive mirrors:

- A possible first stage located in the telescope to be use as a woofer could be considered to relax the specifications of the second stage (see SCAO)
- MEMS for a high level of miniaturization or piezostacked array DM (small pitch 1 mm, small stroke if first stage), possibly as second stage to be directly integrated in the IFU channel if first stage in the telescope
- Characteristics: high fidelity (reproducibility + reliability), dynamics, linearity…

Integrated WFS:

- High dynamics and linearity
- Reduction of the volume, possibility of light coupling in fiber bundles
- If use of LGS, take into account the LGS defocus (see LTAO)

WFS detector:

- Zero noise CCD preferred (EMCCD or equivalent technology in order to achieve high limiting magnitude) (see section 7)
- CCD with very high quantum efficiency and fast read-out (~1 kHz) (see section 7)
- atmospheric dispersion compensation

Optimized control algorithms:

- Tomographic phase reconstruction with specialized optimization in the galaxy directions
- Open loop DM control or alternative solutions to be investigated (DM local control loop, DM in WFS channels, first stage in telescope…)

LGS specific technologies (see Section 5)

3.5.2.4 Risks and mitigation

The major risk is first in the capability to achieve the specified performance with such a very new concept. This requires intensive numerical simulations, alternative concept studies and selections, laboratory validation of the key points of the MOAO concept, performance demonstration in realistic conditions in laboratory (SESAME) and in a second phase on telescope.

The most critical issues / risks for the subsystems are the availability of the DM technology (but not specific to this type of system), the real performance of the WF sensing scheme (WFS concept performance in terms of dynamics and linearity, CCD noise, NGS versus LGS, LGS performance…) and the real performance of the control algorithms for tomography and “quasi open loop” approaches.

Numerical simulations (analytical models, partial end-to-end models for specific issues or component behaviours) for: concept choice (i.e. LGS implementation, open or pseudo-closed loop), trade-offs (i.e. 2 stage correction), design, low level specifications and performance evaluation.

DM: technology selection in terms of number of actuators, mirror size, fidelity, dynamics and linearity and laboratory demonstration of the achievable performance.

WFS: miniaturization of Shack-Hartmann WFS or similar concept, elementary component technology development (i.e. microlens array, fiber bundles), demonstration of high dynamics and linearity in laboratory (SESAME).

CCD: the no noise CCD is a key technology for this type of system, driving directly the complexity (I.e. introduction or not of LGS). Present developments at EEV (Opticon) are already an important step. Investigate the possibility to parallelized a number of CCD heads per WFS channel instead of using a unique large CCD…

Control: development of the control strategy, demonstration of the efficiency of the new control approaches first by numerical simulation, then in laboratory on AO benches (BOA, SESAME) and finally on sky.

4 AO requirements on Telescope, Site and Instruments

4.1 On Telescope

The list of requirements and technical onstraints from Adaptive Optics on the telescope is presented in this section. The section is separated between unavoidable requirements and requirements depending on technological constraints. It includes special requirements from High contrast Imaging with XAO and coronagraphy.

Unavoidable requirements

- The technical FOV must be the FOV of the instrument + 3 to 4 arcminutes (in the case the LGS) outside the scientific FOV (spatial separation of the science field and the WFS field)
- If the science requirements call for a corrected field-of-view larger than 1 - 2 arcminutes
  - → The Deformable Mirror 1 should be in the telescope if GLAO and MOAO over >6' is required (see section 6)
  - → if MCAO corrected FOV is below 1-2' then DM2 and/or DM3 can be post-focal (see section 6)
- The telescope optical quality (design + polishing + co-phasing) should be:
  - → For most of the AO systems: < 50 nm for spatial frequencies larger than 1-m for 3' FOV (< 50 nm for ALL spatial frequencies for negative altitude conjugated mirrors)
  - → For XAO: < 10-20 nm (TBC) for spatial frequencies larger than 0.4-m.
- Telescope high temporal frequency (> 50 Hz) vibrations should not degrade the image quality by more than 50 nm rms (TBC).
- The optical conjugation altitude of DM1 should be:
  - → 0 – 200 m (TBC)
  - → The variation across the mirror should be less than $\pm 100\,\mathrm{m}$
- Optical quality of Laser Guide Stars (see also section 5.2):
  - → The static error after correction should be < 1 μm (goal 0.6μm) (TBC)
  - → The dynamic error (varying with zenith angle) should be < 1 μm (goal 0.6μm) (TBC)
- The error in the imaging of DM1 onto the wave-front sensor : the distorsion should be $< 10^{-4}\,Diam_{DM1}$
- Distortion of the imaging of the ground layer on DM1 : TBD
- Pixel scale ≥ 3 mm/arcsec
  - → focal length of the telescope: approximately 400m – 600 m
  - → F-ratio approximately 15
- The mechanical back focal distance should be larger than 0.5m for AO plus some amount required by the instruments
  - → probably F-ratio = 15

- Space and access for both the Laser Launch Telescope and the Laser clean room should be planned for (as well as access to service connection points).

Requirements related to current technological constraints

- DM should not do large stroke field stabilization
  →different mirrors for DM and field stabilization.
- Diameter of DM1 : approximately 2 to 3 m for a 40 m telescope
- Design space for DM1 : $1.2 \cdot Diam_{DM1} \times 1m$
- DM1 optical shape : less risky if flat or concave (spheric or aspheric)
- Gravity-stable AO module, since high stability required for the wave-front sensors
- Availability of a diffraction limited calibration source upfront DM1 for NGS and LGS modes in the AO-corrected FOV (desirable)
- Baffling of Rayleigh light as much as possible
- Sufficient design space at a possibly existing inner edge of DM1
- Identical signs for the field curvature and the telecentricity, preferably field curvature equal to zero
- High contrast requirements:
  - segment shape, size, gaps size, and gaps size variation should be optimized for high contrast imaging (see Appendix F) keeping the optical quality of the segments and minimizing the turn down edges.
  - Coating reflectivity uniformity segment to segment should be better than 1% rms (TBC) (see appendix F).

4.2 On Site

The key parameters for AO design related to the Site are: the seeing at 0.5µm λ/ro, the correlation time τo=0.36 V/ro, the turbulence profile C_n^2 and the anisoplanatic angle θo and the outer scale of turbulence Lo. Let us underline first that ro has the most important impact on the cost of the AO systems (Section 3). Lo is important for ELT since it significantly reduces the variance of the low order modes to be corrected by the Adaptive Optics system, hence the actuator stroke requirements. The knowledge of the turbulence profile is specifically important for the determination of the performance of GLAO (turbulence in the 1st kilometre), MCAO and MOAO (turbulence in altitude) and to determine the best DM conjugation altitudes for MCAO.

To evaluate the return sodium laser flux, it is important to measure the density of the sodium profile at 85-100km and its variability: seasonal variation, short term variation of the altitude/profile (Sporadic layers) and any variation from site to site. The amount of low altitude Rayleigh and Mie scattering is also an important parameter to be measured, in order to quantify the amount of laser scattered light entering the science FOV (in the visible) or to determine the additional noise produced by fratricide effect in multi laser tomography.

All the above parameters should be determined during the site testing and enough statistics (over at least two years) should be obtained to select the site, design the AO systems and predict the AO performance accurately.

During the operation all above parameters should be available on-line such as to organise the flexible scheduling and to optimise the AO parameters on-line.

4.3 On Instruments

Depending on the selected operations mode, the AO system relies on one or several natural guide stars plus possibly one to several laser guide stars. In general, the location of the guide stars overlaps with the field of view of the science instruments. This imposes certain requirements on the science instruments from the AO.

i) for infrared instruments (l > 1000 nm) and AO systems using visual guide stars (natural or LGS) a dichroic beamsplitter might be required in order to make the full field of view accessible both to the AO system as well as the science instrument. This mode of operation should impose the least restrictions and requirements on the science instrument.

ii) for infrared instruments (l > 1000 nm) and AO systems using infrared natural guide stars, grey and dichroic beamsplitters are required. Grey beamsplitters are required if the science target serves also as AO guide stars. In this case a certain fraction of the infrared flux is diverted to the AO system, leaving only a small fraction of the infrared flux for the science channel. Science instruments must be able to cope with the increase IR background due to the dichroic, and the reduced flux from the science target.

iii) for visual light instruments (l < 1000 nm) and AO systems using visual natural guide stars grey and dichroic beamsplitters are required. Grey beamsplitters are required if the science target serves also as AO guide stars. In this case a certain fraction of the visual flux is diverted to the AO system, leaving only a small fraction of the visual flux for the science channel. Science instruments must be able to cope with the reduced flux from the science target.

iv) for visual light instruments (l < 1000 nm) and AO systems using Sodium LGS, the science instrument must be equipped with a notch filter to suppress the flux from the Na 589nm line. A working assumption is that the brightness of the Sodium LGS corresponds to V = 9.0 mag. Similar restrictions apply in the case of a Rayleigh LGS .

5 LGS concepts

The opinion of the AO Working Group is that it will not be possible to fulfil the scientific potential of the proposed ELT using only NGS for AO. Sodium Laser beacons will be required to provide artificial illumination of the turbulent atmosphere, and they must be accommodated in site evaluation strategies, and telescope and instrument design constraints from the outset.

The simplest use of lasers is to generate one or more focussed spots, which, to first order at least, resemble NGS. The problem with focussed-spot laser "guide stars" is that they are NOT stars, and generally speaking, any similarity decreases with increasing telescope diameter. Unlike NGS, LGS are not at infinity (cone effect) and have non-negligible extension in the line of sight. Furthermore they do not measure tip-tilt, exhibit important focus variations during observation and are accompanied by substantial extraneous scatter of launch light at low-altitudes. The loss of tip-tilt information from LGSs (and the error on some low-order terms such as focus and astigmatism) means that this information must be recovered from one or more NGS, and this unavoidably limits the sky coverage of LGS systems. Mitigation is therefore crucial (see Appendix A).

It must be stressed that even if the tip-tilt, focus and low orders problem were to be completely solved, the monitoring of NGS, albeit at reduced bandwidth, would still be mandatory for the measurement of changing non-common-path wavefront errors between the LGS and science because of the different path of the laser light in telescope and instrument generating different aberrations compared to the scientific path. A number of schemes for aberration compensation involving the use of active optics shall be explored.

5.1 Multi-LGS issues on ELTs

Single sodium laser beacons are on the threshold of becoming an operational technology on several 8m class telescopes. In fact, the Keck laser system is now scientifically productive and around ten papers are available in a recent AAS issue. The VLT and Gemini beacons are currently undergoing commissioning and both represent significant technical advances: fibre feeding of sodium light and solid-state sum-frequency generation, respectively.

The multi-beacon technologies required for ELT operation have not yet been demonstrated in closed-loop operation. However there are a number of near-term developments which should provide experience of such systems and corresponding risk reduction. The Gemini-South MCAO system is a full-fledged, five sodium laser, star-oriented, scientific MCAO system. The VLT MAD system is not a laser beacon system but will explore both star-oriented and layer-oriented MCAO. Open loop multi-Rayleigh beacon experiments have already been conducted at the MMT by the CAAO and these continue. Both the VLT and Gemini have GLAO projects in progress, and the VLT has an LTAO project. All of the multi-beacon implementation projects are backed by extensive modelling, which either is, or soon will be, supported by detailed $C_n^2(h)$ data. The models are independent and have, in many cases, been cross-checked. Given all this activity, it is reasonable to assume that, with the exception of laser MOAO, multiple focussed-spot laser beacons will become well understood as an 8m technology during the earlier ELT design phases. The residual difficulties of extrapolation to an ELT (and the demonstration of laser MOAO) still remain, however, and these must now be addressed.

Preliminary modelling suggests that the number of beacons and the corresponding tomographic processing methodology are not the principal difficulties encountered when telescope diameter is increased. The number of beacons required for GLAO, MCAO, LTAO and laser MOAO seems weakly dependent on the telescope diameter. Rather, it is the increasing aberration and elongation of the individual component beacons with increasing telescope diameter, which raises the key technical challenge. Having said this, it must be stressed that LTAO and laser MOAO carry a very high scientific premium, arguably the highest of all the ELT science. It is very likely that such scientific imperatives will drive these techniques beyond their currently predicted performance levels, and that further extensive modelling will be required to understand their ultimate performance limits on an ELT. It is quite conceivable that this *would* engender a requirement for an increase in the number of lasers. Under such circumstances, technical trade studies with some of the novel laser concepts may be required (see Section 5.4).

5.2 Telescope aberrations with LGS:

The principal near-term difficulties which will be encountered with focussed-spot laser implementation on ELTs will be zenith-dependent aberrations. These are present also in 8m class telescopes, but with smaller extent. The aberration problem does not raise an extreme technical risk as such, but it certainly requires further analysis to understand how the problem may be best tackled to not compromise the final performance of the AO systems. The issues to be studied include:

- What is the magnitude of the aberration and its zenith-dependence?
- What are the low order modes appearing as non-common path errors between the laser and science focus?
- How does the aberration problem depend on telescope design?
- Can it be best addressed using a combination of a large static corrector and dynamic correction of any static residual error and the dynamic component from zenith angle variation ?
- What would be the initial alignment procedure?
- If residual non-common path aberrations between the lasers and the science focus are to be removed by closed-loop offsets, what are the limits and implications of doing this? (See the discussion of the virtual WFS below).

The aberration problem is discussed in appendix B. Further studies of the above set of questions are proceeding in the context of the FP6 novel concepts study.

Some 1st order requirements on the LGS aberrations through the telescope are given in section 4.1.

Although the uncorrected LGS-NGS non-common-path error may be several waves we do not anticipate that the design of correctors will be especially challenging. The correction is field- and therefore individual LGS WFS-dependent, but it is quasi-monochromatic and the sub-field for correction on each WFS is very small.

The remaining static and dynamic correction will be applied by closed-loop offset of the null-point of the LGS correction system. This implies an allocation of “extra” linear range on the LGS WFS and an extra allocation of stroke on the LGS corrector (or a separate semi-static corrector in the LGS WFS path). The term “extra” is used because the LGS WFS is already required to operate off-null in some multi-LGS schemes such as MOAO.

The dynamic removal of the changing non-common-path aberrations requires sensing of the evolution of the aberration with time. This can be accomplished through a combination of direct sensing of low-order modes from NGS and the monitoring of slow and therefore non-atmospheric changes to the time-averaged WFS signals from the LGS. There should not be a particular sky-coverage issue here as even if all the information had to be recovered from NGS, there would be a long integration time (at least 30-seconds) to remove the atmospheric component, and so faint, well-off-axis (and multiple) NGS could be used.

5.3 Spot elongation short term solutions

Laser beacon image elongation is a direct consequence of launch geometry, telescope size and the vertical extension of the focussed laser spot in the atmosphere. When elongation exceeds several arcseconds, as it very much will for a 30-60m ELT with central or peripheral laser launch positions, then it will cause significant WFS signal to noise ratio degradation and must be addressed. If the elongation exceeds the subaperture isokinetic patch size then the spot will not only be extended to a line but will become a wiggling line, hence compounding the WFS noise problem. A number of technical concepts exist for addressing spot elongation. These include:

- Increase of the power in a CW laser scheme to recover the SNR in the lateral subapertures of the WFS.
- Dynamic refocusing by opto-mechanical means. This has been shown to work by Steward Observatory/CAAO using a multiple Rayleigh beacon on the MMT. (The particular implementation, which uses a specific beacon geometry, could probably not be transferred unchanged to the ELT).
- Dynamic refocusing by electro-optical means.
- Temporal range-gating a pulsed laser to reduce the vertical extension. This implies some increase in laser power.
- Optical range gating (baffling) of the z-extended image.
- Use of optical or temporal range gating to split the extended line into several smaller spots which may be separately sensed.
- Use of a greater number of pixels in a (noiseless) WFS CCD or use of non-regular detector pixel geometry.
- Use of detectors where the charge-transport and readout systems have been specifically-engineered to provide an electronic equivalent of some of the benefits of optical dynamic refocusing of pulsed lasers.

- Direct optical processing of the vertically-extended image of the laser beacon. This is the PIGS concept and is discussed further in the appendix D.
- Use of the information contained in the spot elongation to resolve the Sodium layer and the differential cone effect, to be included in a full tomography algorithm for the command of the AO systems,

Whilst none of the above techniques is at the level of maturity that could be claimed to completely mitigate the risks associated with ELT-level laser image elongation, it seems very likely that some combination of a subset of them would do. A study of the relative merits of these techniques and options for combining these concepts will therefore shortly be initiated in the context of the FP6 novel concepts study. The appropriate optical configuration of the WFS relay, in particular the issue of image telecentricity, is also a subject for study.

5.4 Requirements for laser sources and laser transport

From the experience matured internationally so far, the following technological developments appear essential and are currently driving the ESO R&D strategy in this field:

- simplify, make possibly cheaper and ruggedize the laser sources at 589nm, to get 10W pulsed on air (15W pulsed in the lab), with a keys-on system. Fibre lasers would be the best choice.
- Propagate the laser beam up to the laser beam Launch Telescopes using single mode fibres, thus preserving the diffraction limited beam, avoiding mechanical vibrations to be transmitted to the beam, and avoiding stray lights in the telescope dome. If single mode fibre lasers are available, they will deliver the beam directly at the Launch Telescope, without the need for a relay fibre.

5.4.1 Laser sources

The progress with CW sodium lasers is encouraging; further development of pulsed lasers (desirably pulsed fibre lasers) remains highly recommendable for a variety of fundamental and practical reasons. The existing “macro-micro pulse” format would eliminate Rayleigh backscatter as a source of WFS measurement noise, thereby eliminating interference between guide stars in multi-LGS systems and enabling operation over a wider range of atmospheric conditions. Innovative formats with pulses 2 to 3 μsec in length and a 1-2% duty cycle would enable “dynamic refocusing” on the short 1-2km laser pulse as it transits the sodium layer (using dedicated custom CCD and/or other optical components, see section 4.2). Micropulses of less than 8nsec will be beneficial in case fibre transfer of the beam is necessary.

The Laser power requirements on ELTs will depend on the LGS concept and if the spot elongation increased noise problem is mitigated or not. This needs still detailed investigation. In case of CW Laser, so without dynamical re-focussing schemes, the upper limit fir required Laser power for a 30-m telescope is about 3 times (30-45 W) larger than for planned LGSs for 8-m class telescope (assuming 10-15 W in the sky). (Brent Ellerbroek presentation 2nd Backaskog Workshop on ELTs September 11, 2003). For a 42-m, this number doubles (~60-90 W (TBC)). For pulsed lasers with dynamic refocusing the required laser power (15-20 W for a 42-m (TBC)) should be only weakly dependent on telescope diameter.

5.4.2 Laser transport

Laser transport from the Laser room to the launch telescope might be performed either by fibre over 45-75 m (assuming they sustain the laser peak power, Stimulated Brilloin Scattering) or by optical relay with the adequate metrology. This problem disappears if pulsed fibre lasers can be used. The Laser Launch Telescope (LLT) can be unique (laser projected from behind the secondary) or multiple, laser emitted from the telescope centrepiece. In case of pulsed format, the fratricide effect may be eliminated by appropriate firing/sensing synchronisms. The LLT has a diameter of about 50 cm and a FoV necessary to create the required LGS constellation. LGS jitter removal may be done using the uplink laser beam, or using a steering mirror at the Wave-front Sensor itself. Diagnostics and aircraft avoidance system are integrated close to the LLT. For the monitoring of the mesospheric sodium density profile, of the Rayleigh scattering, an automated LGS monitoring facility using a small (40 cm diameter) side telescope should be implemented.

5.5 Advanced / less mature LGS concepts

A significant number of new and advanced concepts for LGS have been proposed to solve problems related to ELTs. These concepts involve either new Laser launch schemes or new WFS concepts or both. They are described in details in appendix D. The applicability of the various novel concepts to ELT-related problems is summarised below. A 'X' indicates that the problem is addressed.

	Elongation	Cone effect	Defocus wrt. NGS	Telescope aberration	STATUS	Features
PIGS	X		X	?	-Papers SPIE - Lab. (good matching res.) -Sky (controversial)	Launch system is conventional. Spot elongation is dealt with in a natural and static optical way.
SPLASH	?	X		?	-Simulations - Papers -Experiment planned	Laser is launched through multiple subapertures to make a Shack-Hartmann pattern on the sky, which is observed with the whole telescope.
Variable WFS	X			?		
Virtual WFS			X	X	- Preliminary experiment - To be presented in Orlando	LGS wavefront sensing in an upstream LGS focus of reasonable quality

						(to avoid aberrations in relay optics). Downstream sensing using one or more testsources in the upstream NGS focal plane, and combination of the LGS and test source wavefronts. -
P4	?	X	?		-Simulations - Papers -Experiment planned	Parallel full-aperture beam is launched and intensity evolution is monitored versus altitude in the Rayleigh scatter
ELLAS	X	X	?	?	Numerical simulations in progress	Creates a background layer at Sodium Mesosphere. Via layer shearing, solves the problem of cone effect, spot elongation, spot aberration. It can be used for extended fields. Promises also a solution for the tip-tilt determination.
LPSI	X	X			- refereed paper in A&A - Preliminary simulations - experiment planned	Full aperture launch of tilted laser beams and PSI technique delivers cone-free gradient measurement. Rayleigh and Sodium scattering can be used.
Background WFS	X	X	?			

6 Large deformable mirror(s) in telescope

Using Large Deformable Mirrors for an ELT presents several potential advantages which however can be compromised by the manufacturing complexity and cost of the Adaptive mirror itself. It is therefore reasonable to address this question carefully with a decision matrix for each additional deformable mirror added in the optical train of the telescope. The following matrices provides as far as possible, objective pro and cons for 1, 2 and 3 deformable mirrors.

Two first alternatives are possible for such DM technology. At this stage, a non-segmented 2 to 3 m large DM (~30 mm pitch) seems to be the less risky approach. A larger DM (4-5m) might be feasible using a segmented shell (6 segments for instance). This would potentially allow to reach higher number of actuators per square meter of entrance aperture. LBT technology has built-in capacitive sensors which would maintain the co-phasing of the different segments. However, this is more risky than a monolithic shell (see sections 7.1 and 7.2) and is not considered in the table below.

Adaptive Telescope with one DM		
Item	**Pro- cons**	**Remark**
Telescope high temporal aberrations and fast tracking errors produced by windshaking or from other sources	+	Although not yet confirmed by extensive telescope modelling, it is feared (see section 2.2) that high temporal errors (fast tracking error and fast low order aberrations) due to windshake of the telescope structure might not be correctable by the active optics and by the field stabilisation mirror. In that case, **large FOV** Adaptive Optics is necessary even for **seeing limited observations** and will require a large adaptive mirror in the telescope. Note however that, **multi LGSs & GLAO mode** will also be required to operate the telescope over a large fraction of the sky.
Large Field of View Adaptive Optics	+	Ground Layer AO and Multi-Object AO expected to deliver correction over a large FoV 3-6' (TBC) will be possible to implement only with a large deformable mirror already in the telescope optical train. Post-focal AO will require to re-image a technical FoV which is as big as 6-10' on for instance a piezo deformable mirror with a diameter of 800 mm (actuator pitch 10mm). The optical system able to do that looks out of reach and in any case will involve several additional optical surfaces (more than in the case of an Adaptive Telescope). The availability of the piezo DM with such characteristics **is also not proven**.
Adaptive Optics facility for Multi	+	An Adaptive telescope with one deformable mirror conjugated to the ground is able to serve all AO

focal stations		corrected focal stations: •SC-GL and LT AO •1st stage of correction for MC-MO & XAO
Telescope transmission efficiency and thermal background	~	The implementation of a DM in the telescope requires 2 additional optical surfaces. In the seeing limited case, assuming AO is not needed for the telescope operation, this reduce the transmission by TBD% and increase the thermal background by TBD% In all other AO modes, the implementation of a large DM in the telescope itself improves transmission and reduces emissivity. In the case of the Gregorian/Ritchey-Chretien telescope design, with an adaptive M2, transmission and thermal background are similar to a non adaptive telescope.
Cost estimate of Adaptive telescope versus post-focal DM	~	Linear extrapolation of the VLT DSM to a 2.5 m deformable mirror leads to a cost estimate of 30 M€ (without additional R&D cost). Cost of the laboratory Large DM test facility has to be added (no estimate at this stage). Telescope relay mirrors might be used for laboratory testing (if lab large enough..) Linear extrapolation of the 41^2 piezo DM + drive electronic for SPHERE to a 90^2 actuators (10mm pitch) is 6 M€/focal station (without additional R&D cost). In addition, the cost for the relay optics needs to be added as well as some laboratory test equipment (no estimate at this stage) Balance reached for 5 focal stations with AO In the case of a Gregorian/Ritchey-Chretien telescope the adaptive M2 is of 4 to 5 meters diameter and will probably be segmented. The estimated cost becomes about 40M€ (TBC) with the same number of actuators.
Risk: 2.5 m large deformable mirror versus piezo DM	-	Section 7.2.1 provides the status of the large DM technology. Risks are in the area of: thin shell production and handling, inter-actuator stroke, lateral shell constrain, heat dissipation, potential large stroke (>100µm at the edge) field stabilisation requirements. See also section 7.2 about thin shell manufacturing. 800-900 mm, 10 mm pitch, 20 µm stroke piezo DM: New development. Additional stroke to correct for telescope errors. Alternatively, implementation of 2 400-mm, 5-mm pitch DMs with 10 microns stroke (lower development required but more complex

		optomechanical design) In the case of a Gregorian/Ritchey-Chretien telescope the adaptive M2 is of 4 to 5 meters diameter and will probably be segmented. The risk related to the production of several off-axis aspheric thin shells is high and the co-phasing acquisition procedure needs to be studied.
Laboratory Testing of large DM versus post-focal DM	-	The laboratory testing of large DMs requires telescope simulator which usually involves large additional optics. However some telescope designs (5 mirrors solution) include these large optics in the optical train itself and might be used in the lab. for testing at low additional cost. If the 2-3 mirrors telescope solution is preferred the concave DMs (Gregorian telescope) are easier to test than convex DMs (Ritchey-Chretien). In the case of a post-focal DM, no major additional test set-up is required.

Adaptive Telescope with two or three DMs		
Item	**Pro- cons**	**Remark**
Multi-Conjugate Adaptive Optics FoV	~	At this stage the MCAO corrected FoV (at the diffraction limit) requested by the instrument and science cases seems to be about 1' in NIR with a goal at 2'. The corresponding technical FoV is therefore ~3-4'. A 2nd , 3rd DMs MCAO seems achievable with both the post-focal and the in-telescope approaches but design including multi LGS re-imaging needs to be proven before concluding on this. Post-focal AO will require re-imaging the technical FoV on for instance a piezo deformable mirror with a diameter of 400 mm (actuator pitch 5mm with a total stroke of 10µm). The availability of the piezo DM with such characteristics is an evolutionary upgrade of the present technology and consistent with TMT R&D
MCAO for Multi focal stations	-	At this stage, it is not clear from the science and instrumentation requirements that MCAO will be a widely multi-purpose facility on an ELT.
Telescope transmission efficiency and thermal background	-	The implementation of a 2nd and 3rd DM in the telescope at the optimum conjugation altitude requires additional optical surfaces. In the non MCAO mode this reduce the transmission by TBD% and increase the thermal background by TBD%

		In the MCAO modes, the implementation of a 2nd or 3rd large DM in the telescope itself improves transmission and reduces emissivity.
Cost estimate of Adaptive telescope versus post-focal DM	- - -	Linear extrapolation of the VLT DSM to a 3.5 m deformable mirror leads to a cost estimate of 30-50 M€ (without additional R&D cost). It is difficult at this stage to have a more precise cost estimate taking into account the unknown. Cost of the laboratory Large DM test facility has to be added (no estimate at this stage). Telescope relay mirrors might be used for laboratory testing (if lab large enough..) Linear extrapolation of the 41^2 piezo DM + drive electronic for SPHERE to a 90^2 actuators (5mm pitch) is 6 M€/focal station. In addition, the cost for the relay optics needs to be added as well as some laboratory test equipment (no estimate at this stage)
Risk: 3.5 m large deformable mirror versus piezo DM	- -	Section 7.2.1 provides the status of the large DM technology. Risks are in the area of: thin shell production and handling (flat easier), inter-actuator stroke, lateral shell constrain, heat dissipation and potential segmentation of the Large DM. 400mm, 10 mm pitch, 10 µm stroke piezo DM: Extension of present technology

From the above tables one can conclude the following:

- 1 DM in telescope is required if operation of the telescope in seeing limited mode needs AO or if a strong science case supports the GLAO and MOAO modes. In return cost of the large DM calls for an AO facility serving several focal stations, if not a postfocal AO might be less expensive
- 2-3 DMs in telescope will be expensive and risky. Unless Science cases and instrumentation request several MCAO systems, it seems more optimum to go for a postfocal solution (DM2 and 3) assuming the optical relay design is feasible.

7 Technology required to build the systems

AO systems foreseen for the ELTs are extremely ambitious and they can not be directly scaled from existing designs and currently available technologies. In particular the telescope diameter will clearly impact the AO complexity, in terms of number of actuators for deformable mirrors, number of pixels for wavefront sensors, computing power, laser guide stars, etc. There is therefore a need for new developments in various fields to enable the necessary key technologies. These new developments will involve contributions from a large number of research institutes and industries. They will ultimately validate or not the feasibility of the proposed AO systems. We review hereafter these key technologies, with their current status and required improvements.

7.1 Large Deformable Mirrors

Large Deformable Mirrors (aka Adaptive Telescope Mirrors, or ATMs herafter) are AO correctors that can replace one or more conventional ELT mirrors. Current 1m-class ATM technology (see appendix E) is able to provide ~30mm inter-actuator pitch with 0.1mm actuator stroke and ~1kHz bandwidth. The extension of current technology to 4m-class size (es. ELT secondary mirror, ~135x135acts) or 2.5m-class size (es. ELT post-secondary mirror, ~85x85acts) would provide the required correction (full or first stage) for all the AO configurations presented in Section 3. More then one ATM is also applicable (providing the suitable optical design) allowing a telescope integrated MCAO system. That is particularly attractive in case the MCAO would be an extensively used operative mode.

The usage of telescope mirrors as correctors gives several advantages with respect to conventional DMs as described in section 6. All foreseen AO systems for ELTs will benefit from the development of large deformable mirrors.

Current ATM implementation (see Appendix E) performs the wave-front correction deforming a thin shell of glass using electromagnetic (voice-coil like) actuators that are supported by a stiffer back structure. Because the voice-coil motors are force actuators, an internal position control loop (based on capacitive sensors co-located with respect to the actuators) allows to control the shape of the thin shell with respect to the stiff back structure. The internal control provides step responses with settling time less then 1ms.

The usage of electromagnetic actuators with internal metrology is allowed by the large format of the mirror and has the following advantages with respect to conventional DMs:

- ***larger stroke*** of electromagnetic actuators (~0.1mm) allows to use the ATM not only as atmospheric high-order AO corrector, but also as fast tracker (atmospheric tilt and wind-shaking corrector) as a single unit.
- ***no hysteresis***, due to the internal metrology
- ***low sensitivity with respect to actuator failure.*** Because electromagnetic actuators have no contact or, at least, very low intrinsic stiffness, in case of failure they can

be deactivated without keeping a frozen position. The neighbor actuators can drive the mirror in the location of the not working actuator.

However the particular location of the corrector with respect to the wave-front sensor and the large format of the thin shell have some drawbacks with respect to smaller post-focus correctors:

- ***more complex calibration with wavefront sensor.*** Convex ATMs usually require optical test-benches to pre-calibrate the interaction matrices (see Scimulator for MMT and ASSIST for VLT). The stability of influence functions is assured by the internal metrology. Concave ATMs can be optically coupled with wavefront sensor using small and simple optics/fibers directly on-telescope (see LBT solution), using accessible (non virtual) focal locations. The integration of those calibrating source in the telescope design/structure is advised.
- ***large thin shell production and handling is a delicate process.*** Production is discussed in the next section. Handling is solved by an adequate tool design as experienced in the current ATMs units. It should be noted that handling of large glass shells is routine operation in the glass industry.

The extension of current 1m-class technology to 2-4m-class ATM for ELTs is investigated in both USA (TMT, GMT) and Europe (FP6 ELT Design Study). Two directions of development have been taken: a tweeter (high order corrector) development (1.5-2mm thick shell with 25-30mm actuator pitch and ~1kHz bandwidth) and a woofer (low-order corrector) development (3-5mm thick shell with 50-100mm actuator pitch and lower bandwidth).
The main objectives of the FP6 studies are the development for:

- 2-4m-class thin shell manufacturing (addressed in the next section)
- increase the stiffness-mass ratio of the back structure to avoid the lowering of the resonance frequencies when the ATM diameter is increased
- increasing capacitive sensor dynamical range beyond the current 0.1mm limit to allow larger shell stroke for more efficient filed stabilization. An alternative solution is to use a “fast” positioning system of the whole unit to remove the large stroke/low bandwidth part of wind shacking effects. Three companies, for instance, answered to the ex-OWL-M6 call for tender proposing an acceptable solution for that and using different strategies.
- increasing actuator efficiency (including driving electronics) to increase inter-actuator stroke and/or reduce power dissipation
- alternative lateral support of the shell to replace current solution (central membrane) with a low stress distributed support (using central membrane the stress increases linearly with shell diameter $\propto$ shell weight/central hole circumference). Distributed support would also remove the need of a central hole in case of segmentation.

From the ATM internal control point of view, the de-centralized architecture of it (see Appendix E) allows to foresee scalability to 2-4m diameter units without critical developments.
Finally it can be noticed that the implementation of the 2-4m-class ATM can be obtained with different levels of successful development in case some level of segmentation is considered acceptable:

1. by segmentation using current LBT/VLT-like 1m-class units as segments (see GMT) without relevant development needed (but off-axis thin shells)
2. same as before removing the central hole (for the membrane) of each shell providing successful development of alternative lateral support
3. implementing a 2m-diameter back structure as common position reference for few 1m-class segments of shell
4. implementing a 2m diameter reference structure with a monolithic shell (providing successful development of 2m-class thin shells)
5. etc. for larger diameters.

7.2 Large Thin Shell Manufacturing

The manufacturing of a large (> 2.0m) glass thin shell is one of the major concerns of an ELT with ATM (Adaptive Telescope Mirror) technology. The current generation of adaptive secondary mirrors (MMT, LBT, VLT) has leaded to the development of ~1m size glass thin shells (from 0.64m for MMT to 1.12m for VLT) with thicknesses in the [1.7 – 2.0mm] range, allowing generating the required stroke with a 30mm inter-actuator pitch.

These recent developments have been made both in United States and in Europe with strong efforts toward the next size step necessary for ELT (TMT, OWL, etc.). These developments involve large optical companies as well as Universities laboratories. In Europe two optical manufacturing companies have demonstrated their capabilities to manufacture such glass thin shells and also participate to the FP6 programs, “JRA1 on Next AO Systems” and the “ELT Design Study”. Following these studies, and although a flat mirror is easier to realize, manufacturing a concave or convex 1m ∅ thin shell with aspheric shape does not appear to be a major difficulty.

The extension of the previous techniques, as well as new developments, for the manufacturing of larger mirrors is investigated in the FP6 frame work. Also, developments were made in Europe and United State for the manufacturing of flat or slightly curved 2m shells in the framework of NGST program. Although the manufacturing and handling difficulties increase with the diameter, it appears, with a good confidence, that a 2-3m ∅ thin shell could be manufactured in the next decade and integrated in an adaptive mirror within an ELT. Various shapes can be considered for such a 2-3m thin shell with increasing complexity and cost: concave, flat or flat aspheric and convex. (see table 1)

A flat aspheric (with an $-Ar^2 + Br^4 + Cr^6$ figure) would be useful in the case of a telescope design with a parabolic primary mirror. The manufacturing and the testing of such an aspheric flat could be close to the ones for a simple flat.

A larger diameter (4-5m ∅) thin shell, for a large ELT secondary mirror, is however difficult to foreseen due to the highly risk of breakage of such a thin shell during manufacturing or handling procedures. A solution to overcome this limitation could be to use a segmented thin shell assembled from ~2m segments. At the moment, Mirror Lab at University of Arizona is developing a technique for the manufacturing of off-axis thin shells with 1m ∅. The main drawbacks of this solution are the complexity and the higher cost (~10 times) associated to the manufacturing of N (4 or 6) aspheric off-axis 2m thin shells comparatively to a single flat (or flat aspheric) one.

Thin shell	**Manufacturing**	**Testing**	**Cost**
Concave	+++	+++	+++
Plane	++	+	++
Plane aspheric	++	+	++
Convex	-	- -	- -
Off-axis aspheric	- - -	- -	- - -

Table 1: Advantages and drawbacks for each type of thin shell, with increasing complexity from +++ (easy) to --- (difficult)

7.3 Tip-tilt mirrors

Because some of the systems, such as the XAO, MCAO and LTAO systems, will require high performance, it will be necessary to implement in the post focal optical train a dedicated tip tilt mirror in order to achieve high temporal bandwidth, especially when using the large DM in the telescope. Such component will have to be developed in close relation with the concerned instruments. On an ELT, the required dynamics on such a component is well above the one currently achieved on a 10 m class telescope.

7.4 Piezo deformable mirrors

Recent development of Piezo-Stack DM technology has been supported for a variety 8m telescope AO projects and for TMT:
- Gemini-South MCAO project: two DMs from CILAS with 21x21 and 25x25 actuators, 5mm pitch and 7 μm stroke;
- ESO Planet Finder project: a DM from CILAS with 41x41 actuators, 4.5mm pitch and 8 μm stroke;
- TMT MCAO system: a feasibility study by CILAS of 61x61 and 73x73 actuators DMs with 5 mm pitch and 8 μm stroke (goal 10 μm).

Increased stroke seems to be achievable with a longer actuator, as well as operation at low temperature with acceptable hysteresis: -35C has already been demonstrated with current actuator material. A 9x9 actuator DM prototype is in progress for TMT. ``Modular'' DM actuator designs have been developed by Xinetics with 1 mm to 2.5 mm inter-actuator pitch. This approach may also be appropriate for very high order DMs, but the small stroke of these actuators implies that they would need to be used in conjunction with a second large stroke, low order deformable mirror such as an adaptive secondary.

The effort must be first centred on the development of a ~100^2 actuators DM with 4-5 mm pitch and 10 µm stroke (TBC). A Piezo DM with characteristics close to these is being developed by OPTICON with ~40^2 actuators for SPHERE. The development could be schedule in a number of successive steps to properly mitigate the risk. In a second time, another interesting component could be a ~200^2 actuators DM with ~1 mm pitch and a few µm stroke (TBC) for XAO.

This technology will be especially well suited to the MCAO (100^2 actuators and 10 µm stroke) and XAO (200^2 actuators and 1-2 µm stroke) systems but could also be of interest for the LTAO and MOAO systems for instance.

7.5 Micro- deformable mirrors

The production of small, relatively low cost, deformable mirrors will allow more flexibility in the design of AO systems for the extremely large telescopes, in particular by reducing the size and therefore complexity of these systems. These devices are of particular interest for the MOAO and XAO systems, although they can also be used for other concepts such as MCAO. The current design of the MOAO system for instance requires one deformable mirror per science object with typically 50^2 to 100^2 actuators, placing a premium on the cost and size of the deformable mirrors, while XAO requires only one deformable mirror but with a very large number of actuators (200^2 with 1-2 µm stroke) difficult to obtain with classical techniques, ie. based on piezo-stack technology, at a non prohibitive cost. In any cases, the use of these micro deformable mirrors (MDM) will require a first stage large deformable mirror (woofer – tweeter approach). Also of specific interest for the MOAO system is the fact that the technologies used in the development of MDMs (electrostatic or magnetic based actuation) provides more predictable and repeatable actuation than the piezo-stack actuators used in conventional DMs, which suffer from intrinsic hysterisis. This property therefore enables the open-loop operation which is required by the MOAO concept.

Several approaches have been followed for the development of MDM, based on either electrostatic or magnetic actuation principles. These devices are also attractive for applications in other fields, such as vision science, telecommunications, laser beam shaping, etc. and for the same reasons (size, cost).

Electrostatic MDMs are already commercially available through different manufacturers (OKO in the Netherlands, Boston Micromachines in the USA) with the number of actuators varying from 19 up to 30^2 for Boston Micromachines. In principle these MDM devices can scale to a large number of actuators at much lower cost than conventional technologies. A 64^2 device is in preparation at Boston Micromachines and plans exist also from other sources, for instance in France in the frame of Opticon JRA1. One of the current limitations of these components is their relatively limited mechanical stroke, typically 1 μm, but efforts are also invested to improve the stroke. It has to be emphasized that, if the final cost of the individual components will be much lower than for their classical piezo-stack counterpart, the development phase will continue to require significant funding efforts. The electrostatic approach seems the more promising for the considered applications on ELTs.

Magnetic MDM are also commercially available (Floralis in France), currently with 8x8 actuators. This actuation principle allows for a much larger stroke (typically more than 15-20 μm) but at the expense of the bandwidth, limited to a few hundred Hz. It is therefore not anticipated that this approach will be followed very far for applications in the field of AO systems for the ELTs.

One could also consider the development of MDM based on micro piezo actuators, although this approach would probably also suffer from the hysterisis problem and would therefore not be adequate, at least for MOAO.

The micro-deformable mirrors will be of particular interest to the MOAO (50^2 to 100^2 actuators) and XAO (200^2 actuators with 1-2 μm pitch) systems. MCAO systems can also benefit from this technology.

7.6 Visible detectors

Efficient detectors (visible or infrared) for wavefront sensing are crucial for the performance of any AO system. High frame rate, high QE, low readout noise (RON), and PSF response (i.e., charge diffusion) are usually the critical parameters.

The recent development of nearly zero-noise detectors in the visible based upon an Electron Multiplication CCD (for instance from E2V) seems promising for AO applications requiring extremely low readout noise (RON). This is an important step toward the development of a detector for a NGS AO system on an ELT, where a pixel format as large as 512x512 pixels may be required.

The “zero” RON technology for visible wavefront sensor detectors uses register amplification to reduce the apparent RON well below $1e^-$ at readout rates as high as 1.5 kframes/second. However, amplification or ``excess" noise effectively increases the photon noise by a factor 2. But the gain in performance is still really substantial for wavefront sensing because it is the RON which limits the magnitude with conventional CCD. The development of a 240x240 detector using 8 parallel readout registers has been

funded in the frame of Opticon JRA2 for the VLT SPHERE project. Testing and actual performance of this technology will be known in 2007.
For ELT, larger format will be necessary (600^2 pixels, TBC). An increase of the QE and sharper PSF response are also of prime importance. All foreseen AO systems for ELTs will clearly benefit from improved wavefront sensor detectors. For XAO applications, frame rates as high as 2-3 kframe/s will be required.

7.7 Infrared detectors

As explained in the possible AO system description, it is necessary to sense at least the tip-tilt, focus and astigmatism to break the degeneracy caused by atmospheric quadratic modes, which are imperfectly sensed by LGSs. To maximise sky coverage for multi LGSs systems (LTAO, MCAO, GLAO), this should be performed in the NIR assuming a fast low readout noise IR detector is available. The number of pixel for this application is small (32x32 maximum).

For SCAO and XAO, there is a need for a full fledge IR detector for wavefront sensing either to perform wavefront sensing in highly embedded objects (for instance for the Mid IR instrument) or to reduce the chromatism problem for XAO. For these cases a low noise fast readout 256x256 IR detector is required with a frame rate of 1kHz-4 kHz.

Some time ago, CALTECH and the infrared detector group of ESO have teamed up to launch a program at Rockwell Scientific for the development of a CMOS AO sensor which can be hybridized to both HgCdTe diodes for the infrared spectral range (2.5 micron cut-off wavelength) or Si-PIN diodes for the visible, the so-called CALICO sensor. Both a bare multiplexer and a HgCdTe infrared sensor have already been delivered to ESO. The CALICO detector is a 128x128 pixel prototype sensor, which has 8 parallel video outputs which can be used in parallel to read out each of the 7 different unit cell designs implemented on the same chip. Each design comprises 128x16 pixels. The first unit cell design, which is being evaluated at ESO is the LnPix3 structure, which has a separate capacitive transimpedance amplifier for each pixel. The detector board for the LnPix3 structure has been manufactured and tested. New high speed 38 MHz off-chip cryogenic preamplifiers have been implemented and are operational. After initial set-up problems first light images have been obtained with the bare multiplexer. However, the analog bandwidth of the video output which should operate at 7 MPixels/sec, is still too slow. The predicted readout noise at frame rates of 2.7 KHz is 3.7 e^- rms for the optical Si-PIN diodes and 7.7 e^- rms for the HgCdTe infrared array.

Recent discussions have been going on with AURA-TMT-MPE-MPIA to form a funding consortium to share the development of the future 256x256 IR detector for AO and interferometry (Fringe tracker). Both Rockwell and Raytheon are interested by this development and feel they can meet the following top level requirements:

- 256x256 pixels
- 40 micron pixels (CTIA)

- 0.8 to 1.9 micron or 2.5 micron cutoff wavelength
- High speed readout - up to 1 kHz frame rate (goal 2kHz) of the full 256x256 pixels / up to 4 kHz frame rate for window of 128x128 pixels
- Readout noise of 3-5 electrons at 1 kHz frame rate (goal).
- Reading at slower speed may provide lower noise.
- Analog-to-digital converters on-chip (digital output)
- Maximum degree of freedom to program the readout modes and develop the best clocking schemes.

7.8 Adaptive Optics buttons and miniaturized optics

An effort should be made in this field in order to significantly reduce the litter and the cost of the AO systems. It is obvious for the DM with the MEMS, but it should be investigated for the WFS. Buttons for MOAO are one design solution to be addressed for instance. Coupling the light in fiber optics bundles could bring helpful tools to transport the detectors and their electronics away from the crowded focal area. Fiber bundles could be also a solution to segment the image pupil on a number of CCD avoiding the development of large format detectors.

7.9 Real-time computers

Currently no single-board computer is capable of processing the amount of real-time data required to run the AO systems for an ELT. Extreme AO (XAO), Multi-conjugate AO (MCAO) or simply Multi-Target Ground Layer Correctors will require about one thousand of actuators for 8m class telescopes like the VLT running at a Kilohertz rate or more and up to a few tens of thousand actuators and around 2 Kilohertz frequency for an ELT. The new Adaptive Optics Real Time Computers will have to be based on multi-CPU multi-board computers in order to achieve the required computational power. The complexity of each of these systems and their number raise concerns about the complexity of their development, their reliability and their maintenance.

The solution is a common standard platform that can achieve all the goals of the AO systems. This is SPARTA, a standard platform that provides both a hardware and software common infrastructure in which all the previously mentioned applications can run. By using a common design approach, several AO systems for the ELT can be implemented by simply using technology that is either ready today or already in the industry pipeline and that will be ready in one or two years.

The main problem to face while designing such big AO controllers is not the total computational power, which can be easily reached by piling up a considerable number of CPUs, but, instead, the critical factor is the latency. It is in fact relatively simple to process gigabyte of data per second, given a pipeline of CPUs which is long enough. What is difficult is to ensure that the computation completes in the shortest possible time and the total available time is measured in hundreds of microseconds. SPARTA uses FPGAs to reduce the latency to the minimum the current technology's hardware allows, CPUs and DSP to process the data. Such architecture, properly scaled to the timeframe of an ELT, is able to deal with several of the AO systems for an ELT.

The challenge is the Extreme AO system, where the number of actuators and the loop frequency pose significant challenges to the RTC. The expected throughput and latency of the system described above is not enough. Four areas need improvement:

Technology	**200x200**
Input/output communications. Today it is based on a 2.5 Gb/s serial communication. The 10Gb/s is becoming available and it has been used as the baseline for the other designs. Here we need 2 lines at 50 Gb/s or 4 lines at 20Gb/s.	8
Faster processing elements, faster CPU-to-CPU busses, faster memory.	10
Integer arithmetics. FPGAs perform faster if integer arithmetic is used. By observing that input data (pixels) are integers and output data (control voltages) are as well, one could think of arranging the computation in integer arithmetics. Study is required here. However, performance gain is already known.	2
The sparseness of the interaction matrix of an XAO system is very high. However a control matrix (the inverse) is not. Smart algorithms will be able to take advantage of the sparseness of the IM and require less processing power.	10

The table gives the improvement factors required for a 200x200@2KHz XAO based on Shack-Hartmann, starting from today's technology.

The first two areas are technological and within the allotted timeframe of 10 years they seem reasonable and well achievable. Famous Moore's law predict an increase of computing power in 10 years by a factor 100, so the highest value we used, 10, is not so aggressive. The room for improvements that are expected from the FPGA technology is certainly higher than what standard CPUs can do, since they reached the limit with the 5GHz barrier. CPU manufacturers are now trying to improve of the computing power of a single chip by adding more cores to the same chip. DSPs are not evolving with the same pace, but the availability of new fast busses could revamp their development and performance. **The key to success here is to establish a partnership with an industrial partner to steer the development of very high performance SBC tailored to the need of the RTC for the ELT so that it contains the right might of computing hardware (CPU, DSP, FPGA) and the fastest memories and busses.**

The other two areas are more of theoretical research. On the one hand, both DSPs and FPGAs perform faster if integer arithmetic is used. By observing that input data (pixels) are integers and output data (control voltages) are as well, one could think of arranging the computation in integer arithmetic. Study is required here, but preliminary prototypes show interesting results. On the other hand, smart algorithms will be able to take advantage of the very high sparseness of the XAO interaction matrix and require less processing power. Preliminary results on this subject are promising.

7.10 Algorithms

In most of today's AO systems, the inverse-problem of reconstructing the wave-front is based on vector-matrix multiplies, which will become impractical for future systems since the complexity of computing the reconstruction matrix by using standard methods scales as $O(n^3)$ whereas its application (done in real-time) requires $O(n^2)$, with n is the dimensionality of *a (command vector)*. Upcoming systems must undergo further analysis focusing on the criteria: (1) computational power required, (2) memory used, (3) ability to pipeline, (4) exploitation of parallel computing and (5) performance achievable (exact or almost exact solutions are required as to keep system accuracy and errors below a predefined level).

Recent developments on efficient algorithm implementation have gone through four main directions: Sparse direct, iterative, Fourier-domain and Hierarchical methods. All these methods explore different aspects of reconstruction but none copes perfectly with the criteria used to evaluate them. A trade-off between the advantages and drawbacks of each method has to be carried through. Nested implementations can be sought as to benefit more substantially from their advantages.

The trends are given for the most common algorithms studied.

Method/gain	98x98	250x250	500x500	Precision	Gain = f(D)
Direct sparse	1-50	7-340	10 - 1300	Perfect	$\propto \frac{D^2}{k \cdot \alpha}$
Iterative MG-PCG	1-30	4-200	15-800	High	$\propto \frac{D^2}{N_{iter}}$
Fourier-domain	230	1250	5000	High	$\propto \frac{D^2}{\log(D^2)}$
FD-PCG (Iterative)	10	60	250	High	$\propto \frac{D^2}{N_{iter} \cdot \log(D^2)}$
Local and hierarchic	~600	~3700	~15000	Low	$\propto D^2$

Table 7-1: Expected gain factors with respect to the standard VMM (vector-matrix multiplication), for systems with 98x98, 250x250 and 500x500 WFS sub-apertures. The gain is also indicated as a function of the telescope diameter, D, the sparseness fill-in factor, k, and the Cholesky fill-in factor,α, when the spatial-resolution is constant, i.e. D/N=constant, with N the number of WFS sub-apertures across the diameter. The FD-PCG values take into account the fact that four FFTs are done per iteration, for a average number of slopes of 10.

Results obtained under realistic operation mode have to be merged with available information on hardware performance to have a deeper insight on algorithmic applicability. Optimization of algorithm accuracy must undergo further studies, namely the study of the impact of using integer arithmetic's.

Fourier-domain methods will likely reach great development becoming the strongest candidates for the reconstruction process in future AO systems.

In any case, these algorithms should not compromise the expected performance of the very complex AO systems which all require the implementation of tomography or complex wavefront reconstruction in the AO control to get rid of the severe limitations like cone effect, large FoV for high Strehl MCAO, WFE in XAO…

Developments in the field of dedicated algorithms computing power reduction will benefit to all AO systems for ELTs.

7.11 Laser technology

The performance of continuous wave (CW) sodium guide star lasers has improved dramatically in recent years, with the Starfire Optics Range demonstrating on home-made system output powers of 50W in the lab and approximately 35W on the sky.

A commercial supplier (Lockheed-Martin Coherent Technologies, or LMCT) has provided a 12W quasi-CW laser to Gemini North, and it is now under contract to provide a system with higher power for the Gemini South MCAO system.

Figure 8: Starfire Optical Range. 35W of a sum-frequency laser at 589nm have been propagated to the Mesosphere

The Gemini North laser is suffering still from the Non Linear Crystal performance, limiting the output power to 6W, but it should be solved within reasonable times.

To produce one laser guide star of sufficient power for 0.25 m^2 sub-apertures it is necessary to have 9 W of equivalent laser power in air. For a conventional laser, this means typically 15W equivalent power at the laser output. For fibre lasers, this means typically 10W equivalent power at fibre output, on the Launch Telescope. The required power would increase by as much as 50% (TBC) if the LGS elongation problem will not be appropriately solved on an ELT.

For ELT, where 5-9 LGS are foreseen if a classical LGS-AO scheme is adopted, which would mean to have either 5-9 lasers, each coupled to its own telescope, or a single, very powerful laser with light distribution. The latter scheme is less preferable in terms of laser cost, complication, single point of failure in operation, and light losses in the splitting optomechanics.

Further development of these laser systems to improve their reliability and maintainability is very important, however. It must be stressed that pulsed laser at 589nm, with powers of at least 15W and pulse formats desirable for ELT do not exist yet. It will take 3-5 years of development to bring them on the market.

Fibre lasers seem definitely the way to go for the second generation laser sources, and for ELTs. They are much more reliable and robust than discrete component free space resonators, they deliver diffraction limited beams, the fibre can reach up to the Launch Telescope routing anywhere on the telescope, and their cost is 5-10 times less than the cost of discrete components solid state lasers. Fibre lasers with powers of hundreds of watts are commercially available, but not at 589nm.

ESO has followed the fibre Raman laser solution together with industry, and collaborated with Lawrence Livermore Nat'l Labs for a sum-frequency fibre laser approach. The in-house activities have brought to find a path to produce a fibre Raman laser at 1178nm, which is frequency doubled at 589nm. The ESO fibre Raman laser name is AFIRE (Advanced FIbre Raman Emitter) and it is foreseen as CW laser to be used on the 4LGSF project. The first unit will be available in 2008. This laser will have the size of a 19 inch VME rack, servo-controlled in frequency, and deliver the beam via a single mode fibre.

The design of a pulsed format version of the current ESO AFIRE CW laser can be sought via a contract with industry. A first assessment of the feasibility to obtain such a pulsed format from AFIRE is very promising.

R&D towards lasers with this pulse format is starting in the community, although still at a fairly early stage. Two AODP projects at LMCT and Lawrence Livermore National Laboratories (LLNL) are progressing, with lab demonstrations of systems with interesting powers and flexible pulse formats now scheduled within a year or two. Their timescale however is not firm. On the European side, an effort to push the laser technologies for pulsed formats optimized towards the ELT systems is highly recommendable.

Depending on the scheme which will be selected by the AO systems (conventional LGS with or without spot tracking, or non conventional coneless LGS schemes) the lasers for ELT will have to be pulsed or CW, the latter at higher powers than currently available.

A development phase of a few years is still necessary to secure the appropriate ELT lasers, but the needed technology is well in reach and evolving in the right direction, spontaneously driven by the laser market. To speed up the pulsed laser ELT formats requires a concerted strategic effort, to be started soon, e.g. in the frame of FP7.

Laser technology will be used by all AO systems on ELTs, except for the SCAO and XAO systems.

The following table summarizes the situation presented above.

Type of Laser	Power per LGS	Application on ELT	Comment
CW	Up to 15W, < 2GHz	Not enough	The spot elongation requires significant power increases (TBD) for an ELT. This power level is not sufficient. Commercial laser at these power levels are on sight in the next 3 years.
CW	More than 20W, <2GHz	Same configuration as current LGS-AO on 8m telescopes	The extra power is needed to compensate the spot elongation effect. The US air force has developed a 50W CW system, not commercially available. It could nonetheless be cloned with R&D and technology transfer to US companies.
Pulsed	Up to 15W equivalent power	Spot tracking and refocusing methods	This power level is sufficient in case of the ELT for conventional and non-conventional LGS schemes (TBC). The pulse format required is not the easiest. Fibre lasers promise a good outcome. R&D is in progress for both free space resonators and fibre lasers, it needs a boost in speed, to obtain a feasibility assessment in the next two years.

7.12 Laser transport

The laser beam needs to be relayed up to the Launch Telescope for propagation.

In case fibre lasers are used, there is little if any need for beam relay, as the single mode fibre can deliver a diffraction limited beam directly at the Launch telescope.

In case solid state, more conventional lasers are used in the ELTs, there is the need to relay the laser beam. A single mode fibre relay is to be preferred in this case, since it delivers a diffraction limited beam, removes problems of vibrations in the telescope, light pollution, turbulence in the air path and complex optomechanical systems to relay the beam while the telescope moves. The needed length of the fibre relay is on the order of 45-75m for a 30-60m class ELT

As the preferred laser for most of the current concepts is pulsed, depending on the format and power chosen conventional fibres are probably inadequate. Non linear effects in solid core fibres may occur, such as Stimulated Brillouin Scattering (SBS, which causes a backpropagation of the laser beam), Stimulated Raman Scattering (SRS), to name the most important ones.

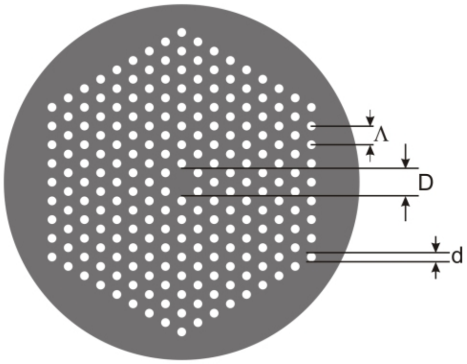


Figure 7-2 *Solid Core PCF with the holey pattern. These class of fibres are index-guided, and can used to make Large Effective Area Fibres reducing by ~25 times the non linear effects at high laser powers*

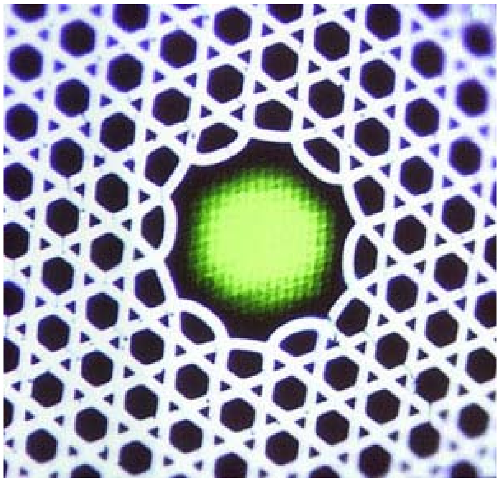


Figure 7-3: Example of an Hollow Core PCF from Corning. These specialty fibres use the Bandgap effect to propagate photons in their core, and have very little sensitivity to macrobendings. They are the ideal candidates for high power beam transport; the non linear effects are almost non-existent

In recent years Photonic Crystal Fibres (PCF) have emerged in the photonics community, and attracted the attention of the laser physicists for their special properties. PCF or holey fibres exist in versions with Solid core and with Hollow core.

The former is a class of index guided fibres, where the Mode Field Diameter in the core can be made 3-5 times larger than conventional single mode fibres, creating a Large Effective Area Fibre. One of these fibres was developed by ESO with industry, and is used e.g. in the ESO LGS Facility installed in Paranal to relay a 10W CW 589nm laser beam.

The HC-PCF is a Photonic Bandgap fibre, and having the mainstream power propagated in the air of the Hollow Core, has almost non-existant non linear effects for the power ranges and pulse formats required for the ELTs.

Although at Telecommunication wavelengths (1.3-1.5 microns) HC-PCF exists with extremely low transmission losses, the existing HC-PCF have inacceptable losses at 589nm. A development program with industry is under way to develop high laser power fibre relays with HC-PCF.

The HC-PCF numerical aperture is 0.11 at 589nm, with a core Mode Field Diameter of 4.3 micron. Targeted losses levels are 20 dB/km. The HC-PCF development is running at the time of this writing at ESO in collaboration with industry, in a timescale of two years it should be completed.

8 Demonstrators and path finders

8.1 Existing and Planned demonstrators and path finders

The implementation of various AO techniques and systems depends critically on the ability to demonstrate that they work, both by selected laboratory demonstration and full-system on-sky demonstration. The following laboratory and on-sky systems are currently available or planned. (see also appendix G for details)

System	Short Description	Status (Year Operational)
MAD	ESO's Multi-conjugate Adaptive optics Demonstrator aims at demonstration in the lab and on-sky of GLAO 'LTAO' and MCAO techniques at IR wavelengths using NGS.	Operational (Now)
HOT	ESO's High-Order Testbed aims at demonstration of various XAO techniques at VIS/NIR in the lab, including wavefront sensor techniques and demonstration of the Woofer-Tweeter concept.	Under Construction (2006)
SESAME	The SESAME test bench at the Observatoire de Paris was build as a laboratory demonstration of various aspects of MCAO in the visible, including LGS aspects.	Operational (Now)
BOA	The BOA test bench at ONERA is used for validation of new AO techniques and devices, both in the lab as on-sky. Systems include XAO, MCAO and MOAO, while also system calibration, control algorithms, and WFS concepts are addressed.	Operational (Now)
HOMER	ONERA's Hartmann-Oriented Mcao Experimental Resource aims at GLAO and MCAO demonstration in the lab.	Design Phase (2007)
AOF+LGSF	ESO's VLT AO Facility and Laser Guide Star Facility aims at providing an integrated facility for instruments on one of the UTs. It is currently foreseen to include a deformable M2, 4 Na LGS, Real-Time Control system SPARTA and two instrument GLAO/LTAO modules.	Design Phase (2011)
SPHERE	ESO's SPHERE is a Planetfinder instrument aiming at detection and characterization of Exo-planets using an XAO system combined with differential imaging and spectroscopy in the NIR.	Design Phase (2010)
WHT	ING's 4.2-meter William Herschel Telescope is an operational telescope on La Palma featuring both the operational AO system NAOMI (to be upgraded with a LGS) and a Nasmyth platform available for external	Operational/ Considered (Now/2007?)

	experiments. Several (LGS) techniques have been demonstrated and a dedicated (LGS)-AO test environment is currently being considered.	
ASSIST	Leiden's Adaptive Secondary Setup and Instrument Stimulator is the test bench for the AOF, specifically for testing the large convex adaptive M2 mirror for the VLT. Furthermore, ASSIST will be a full Adaptive Telescope and atmosphere simulator for testing instruments using the AOF+LGSF.	Design Phase (2008)

Table 8-1: Existing and planned demonstrators and pathfinders

8.2 Additional demonstrators

The main demonstration projects for the ELT can be divided in three categories:

- Demonstrators for LGS concepts. With only a few applications where LGS systems will not be used, but only a limited number of on-sky operational systems, it must be demonstrated that the various challenges can be overcome.
- Demonstrators for the operation of the various AO systems in a number of configurations. Currently only SCAO has been extensively demonstrated in on-sky operation, but also other techniques need to be demonstrated before they can be confidently implemented in ELT instrumentation.
- Demonstrators for AO components and related techniques are required for the demonstration of specific components which do not directly fall in the above categories.

In the next three sections the already existing demonstrators are compared to the required demonstrators.

8.2.1 LGS concept demonstrators

The operation of an AO system featuring one or multiple LGS gives unique challenges as compared to NGS AO, while many of the currently proposed AO system will rely heavily on the availability of a working LGS infrastructure. The known limitations in the current implementation of laser guide stars will pose even more severe challenges in the application of laser guide stars on ELTs. On-sky demonstrators, showing that these challenges can be overcome, are required. A summary of specific techniques for overcoming, e.g., spot elongation and the cone effect, and the various concepts in Section 5.3 is shown in Table 8-2.

LGS-AO Concept	Laboratory Demonstration	On-Sky Demonstration
Dynamical Refocusing/ Radial CCD	*required*	WHT-LGS bench?
Laser scattering/ Fratricide	*?*	WHT-LGS bench?, LGSF-AOF
Multi-LGS (See also AO system demo's)	*required*	LGSF-AOF (WHT-LGS bench?)

Novel LGS Concepts on-sky		WHT-LGS bench?
• PIGS	YES	WHT
• P4	Planned	WHT-LGS bench?
• SPLASH	Planned	WHT-LGS bench?
• LPSI	*required*	WHT-LGS bench?
• Virtual WFS	Preliminary	WHT-LGS bench?
• ELLAS	*required*	WHT-LGS bench?
• Other	*required*	WHT-LGS bench?

Table 8-2. Overview of LGS concept demonstrators currently on-sky or planned.

The AO Facility and Laser Guide Star Facility are currently the only on-sky facilities planned for multi-LGS operation but it is currently not foreseen that advanced schemes for mitigation of spot elongation and cone effect will be included. The WHT-LGS test bench is a concept currently being investigated as a proposal for the EU FP7 framework and would offer a flexible infrastructure for (LGS) AO experiments. This test bench is envisioned to allow for on-sky demonstration of the various concepts summarized in Section 4.3 and others. Furthermore, valuable operational experience is expected from the PARSEC LGS system.

8.2.2 AO system demonstrators

The already planned demonstrators cover most of the direct demonstration of the various AO systems, as laid out in Table 8-3.

AO System	Laboratory Demonstration	On-Sky Demonstrator/System
SCAO	MAD/SESAME/BOA	NAOS/MACAO/
GLAO	MAD/SESAME/HOMER	MAD(NGS only)/AOF+LGSF
LTAO	MAD/SESAME/BOA	MAD (NGS only)/AOF+LGSF
MCAO	MAD/SESAME/HOMER	MAD (NGS Only)/LINC/NIRVANA (NGS Only)
MOAO	SESAME	*required*
XAO	HOT/BOA	SPHERE

Table 8-3.Overview of the current laboratory test setups, on-sky demonstrators and on-sky operational systems before the ELT.

Table 8-3 shows that currently most AO systems will have demonstrators both in the laboratory and on sky, with the exception of MOAO. There are several regions where (additional) demonstration experiments might be desired:

1. On-sky demonstration of the GLAO and LTAO concept using LGS. MAD will be able to demonstrate the concept based on NGS, but this will not yet demonstrate the challenges connected to LGS operation of GLAO and LTAO. The AOF+LGSF will allow for full demonstration of both systems, but only in 2011 and earlier results might be desired.
2. On-sky demonstration of the XAO system. The demonstration again might be covered by targeting risk mitigation in laboratory, including the concept by itself (see phase A study of SPHERE). On sky demonstration of the full instrument will take place with SPHERE, in 2010. Furthermore, one or more test benches might be

modified to allow for rapid development of the key technologies and components required for the ELT application.

3. Demonstration of these concepts at visible wavelengths. MAD currently has a ‘science’ wavelength in the K-band, but is not equipped for demonstration at the shorter wavelengths due to limitations in the number of actuators. The complexity of this wavelength warrants more specific studies, which in part are also addressed by the AOF and SPHERE.
4. Extended testing of (LGS) MCAO on-sky. MAD can only address a limited set of MCAO parameters, and an additional test bench addressing other aspects, like varying conjugate heights and LGS MCAO is required.

Demonstration of LGS MCAO will also be done at GEMINI with the advent Gemini-South Adaptive Optics Imager (GSAOI), the currently being developed MCAO system. This is expected to be the only multi-LGS system in operation on-sky until first light of the LGSF and the option of demonstrator experiments on GLAO, LTAO and MCAO on GEMINI should be explored.

8.2.3 AO component demonstrators

The AO components can be divided in two separate elements; physical hardware, like DMs or CCDs, and integrated components, like various WFS schemes or reconstruction schemes. The following hardware components are required:

- Small-stroke micro DMs with a large number of actuators ($50\text{-}200^2$), required for XAO and MOAO and associated drive electronics
- Medium-stroke (piezo) DMs with a large number of actuators ($100^2\text{-}200^2$) for MCAO and XAO
- Large 2.5 – 4 meter deformable mirrors for integration in the telescope optical train
- Fast low-noise CCDs. The exact specifications are partly given by the outcome of the LGS studies
- (Na) Lasers
- Real-Time Control Architecture

The feasibility of these various hardware developments can generally be demonstrated without specific test benches and have been extensively discussed in Section 7, and integration of these elements into the AO systems will demonstrate their suitability for AO and LGS-AO on an ELT.

The integrated components do need specific testing of the concept. Some of these concepts can be fully demonstrated in the lab, while for others an on-sky demonstration is desired or even required to verify applicability in facility AO systems. Table 8-4 gives an overview of these different ‘integrated AO components’.

AO Component	Laboratory Demonstration	On-Sky Demonstration
WFS		
Pyramid	PYRAMIR, MAD, HOT	MAD,LBT
Spatial filtering in SH	HOT	SPHERE
Chromatic effects/ADC	HOT	*desired*
Extended Objects	HOT, BOA, SESAME, HOMER	LGSF-AOF
Focal plane WFS	HOT (?), BOA	*desired*

Alternate WFSs	SESAME	*desired*
WFS pupil matching	MAD (?)	LGSF-AOF
DM		
Woofer-Tweeter concept	HOT	*not required*
On-sky DM calibration	SESAME	LGSF-AOF
Cryogenic operation of DMs	*desired*	*not required*
Non-linearities in DMs	MAD	MAD
Algorithms		
Fast reconstruction algorithms	*required*	*required*
A-priori reconstructors based on atmospheric knowledge (like tomography)	*required*	*required*
Interaction AO—Segmentation	*desired*	GRANTECAN-Keck (?)
AO Calibration	MAD/HOT/SESAME/BOA	MAD
Matching WFS & actuators	MAD (?)	LGSF-AOF
Interaction AO & instrumentation		
XAO Differential Imaging	HOT (?), BOA	SPHERE
XAO polarimetry	HOT (?)	SPHERE
AO Buttons	SESAME	*required*
LGS background levels	?	LGSF-AOF

Table 8-4. Overview of integrated AO components which are, or need to be, demonstrated either in the lab or on-sky.

9 Roadmap

ELT will place high demands on Adaptive Optics in order to keep the promise of high angular resolution. Compared to AO capabilities in operation today the expected performance and the resulting complexity of AO for ELT are challenging. The 2nd generation of AO systems being developed by several observatories in Europe (VLT, LBT, GTC) is essential to fill this gap. In addition, a significant sustained effort is required to actively prove the necessary new concepts, to enable the key technologies and to develop these new capabilities. It is worth noting that the telescope diameter impacts dramatically the AO complexity and ultimately its feasibility: number of DM actuators, DM diameter, number of wavefront sensor pixels, computing power, complexity of the laser implementation, etc… We believe that SCAO and possibly GLAO with realistic performance at least for 1st light can be achieved with aggressive evolutionary upgrades of existing concepts and component technologies. The other systems like LTAO, MCAO, MOAO and XAO, which are scientifically very attractive, are more challenging and will require substantial qualitative advances through a well planned development strategy reducing the risks.

Therefore the roadmap of the development of AO for ELT shall include both the implementation / upgrade of AO concepts / systems on 10m class telescope and in parallel the development of the particular concepts, technologies and components for the ELT. We think that a first phase, lasting about 4 years of conceptual studies and technology feasibilities with the first two years dedicated to concepts and technologies selection, should be planned before starting real detailed designs.

We subdivide the effort in three main topics which cover the overall problematic of AO in ELT. The first one concerns the Laser Guide Star concepts and issues, the second the relevant systems to be studied and the third the dedicated components to be developed.

9.1 LGS Technologies and Concepts

Because of the high sky coverage requirement coming form the Science, the LGS approach is mandatory in the future AO systems foreseen in the ELT. We have to underline, that even with this approach it is not possible today to give confident figures because of the number of parameters involved. But we know that the sky coverage will be significantly increased when compared to the one obtained with NGS conventional AO.

In the LGS approach, NGS are still required, first to measure the tip tilt but also some unseen low order modes in the case of the MCAO. In addition, the Na density distribution introduces errors in the focus provided by the AO system driven by the LGS, leading to the requirement for a “true” sensor on NGS (this could be the active optics sensor, TBC). Moreover, the differential aberrations between the LGS path and the scientific field in the telescope and instrument optics, require to implement some calibration of these aberrations directly on NGS. Hence NGS wavefront sensors are necessary but with relaxed specifications when compared to the one in a pure NGS AO, allowing larger sky coverage.

Note that due to the number of physical limitations in the LGS concept, this approach can not be used for XAO where the wavefront error budget must be extremely minimized.

9.1.1 Cone effect

This is one of the major limitations of the AO performance with LGS on ELT.

9.1.1.1 Multi LGS concept

The conventional approach is to implement a multi LGS scheme, allowing tomography of the atmosphere and reconstruction of the wavefront in the scientific FOV. Up to now, this concept has not been demonstrated on sky. The Gemini MCAO system will contribute significantly to the validation of the concept. We recommend to perform intensive numerical simulations on this subject (see AO system subsection). Elementary laboratory tests should be performed mainly to validate the tomography approach and the expected performance. MAD and/or SESAME could be the test benches for that. Such activities, in advance to the AOF operation, should give sufficient answers to the different issues linked to the approach. They will also prepare the implementation of the AOF on the VLT. In this plan, the AOF is a key milestone to acquire the full control of the operation of such a complex system.

9.1.1.2 Advanced concepts

Such concepts have to be analysed to bring new solutions to the cone effect problem, hopefully with better performance than the conventional multi LGS approach. Research and development should be pursued: first through the FP6 ELT DS. The plan (on typically 4 years) is to extensively study the concepts through numerical simulations, in particular including turbulence propagation modeling, and then through laboratory tests to validate a number of key issues. Finally, on-sky tests should complete the feasibility. At each step, reviews should take place to select the most promising approaches for the next phase.

9.1.2 LGS spot elongation

It is mandatory to start as soon as possible the investigations by a detailed analysis of the performance degradations due to the spot elongation through intensive numerical simulations. The noise impact on the wavefront sensing and through the reconstruction must be quantified. Conventional models based on extended sources can be used for that purpose.

The second contributor is the anisoplanatic effect linked to the size of the spot (several arcsec) imaged by the pupil border subapertures. A question is the level of accuracy to be considered in the simulation of this effect. It should be underlined that true light propagation model could be required, allowing to evaluate the coupling of anisoplanatism and scintillation for such lateral subpertures. It could also be helpful to quantify the differential cone effect due the thickness of the Na layer and it impacts on the tomoagraphic wavefront reconstruction.

For the noise error reduction a number of scheme have been proposed and should be investigated with high priority in order to limit the required laser power. These schemes lead to the use of pulsed lasers in order to be able to "track" the passage of the light through the Na layer. The possible schemes are :

- dynamic refocusing (pulsed-synchronized oscillating membrane refocusing the LGS) which seems a promising approach with relatively affordable technology. Prototyping (already advanced at Steward Observatory USA) should start as soon as possible in Europe with first laboratory tests and then on-sky performance demonstration using dedicated launch telescope placed at typically 20 m away form the observation telescope. The feasibility shall be demonstrated in 3 years.
- Radial CCD (pulsed-synchronized charge transfer in radial pixels of a dedicated CCD) which is a bright idea but requiring important technology developments. It must be noted that the US AODP has funded the program for such dedicated CCD, which shall become available in two years

For the anisoplanatic error, the only way to reduce it, is to develop appropriate control algorithms taking into account all the effects linked to the thickness of the Na layer (~20% of layer latitude) including differential cone effect (including spot elongation) and variability of the Na density. Indeed a specific tomographic approach has to be studied accounting for the different altitudes of the contributors to the LGS, it could also solve the spot elongation problem. This should be studied in the first phase of the project.

9.1.3 Laser emitter and components

There are no technological problems related to the Launch Telescope systems for LGS. They should be integrated early in the Telescope Project to allow adequate servicing space and installation.

Laser sources stability and reliability has to be improved, the developments are in progress and should be sustained. The choice of Continuous Wave or Pulsed laser developments should be decided depending on the technical solution for the LGS spot elongation.

9.1.3.1 Laser of sufficient power:

During the preliminary phase of conception of the telescope, let say 2 years from the start of the project, feasibility studies shall be completed. Then an additional phase of conception and prototyping (2 years) must be started to finish by a laboratory demonstration of the component. It concerns:

- pulsed solution to be investigated in first priority in terms of power and pulsed format in order to mitigate Rayleigh backscattering and spot elongation issues,
- continuous (CW) solution but with higher power to bring a sufficient SNR even with spot elongation,
- fibre laser as the first technology to be considered, but in the same time a backup solution has to be defined based on the on-going developments around the world.

At the end, on-sky tests for the selected solution are mandatory to fully validate the approach and quantify the real performance. Again the ESO AOF will be an important step.

9.1.3.2 Laser transport and launch:

The already considered solutions for VLT must be consolidated during the first years of the project. In particular fiber relays, together with fiber lasers, are strategically important developments.

9.2 AO concepts and Systems

Based on our present knowledge of the AO concepts and the available technologies, our group suggests to consider the following schedule in the development of the AO systems:

1. SCAO as a possible first light system,
2. GLAO with LGS, because of the low performance required,
3. LTAO close to GLAO concept but with much higher performance,
4. MCAO and MOAO because of the higher level of complexity of these systems,
5. and finally XAO because of the challenge to achieve the performance.

Note that this schedule is not linked to any scientific priority. This should be done as soon as possible in the next phase.

For all the systems, the studies must be performed in complement to the ones already started in FP6 ELT DS. In addition, the proposed plan fully includes the present VLT 2^{nd} generation AO instruments as key achievements for the ELT.

For all the systems, extensive numerical simulations have to be performed in order to explore the whole parameter space, including the number of DMs, the number of actuators and subapertures, the DMs stroke, the number of LGSs, the number of NGSs, the control algorithms… and considering relevant observing conditions. These simulations should help in the conceptual phase (2 first years) and should be done in close cooperation with the telescope design and instrument studies. These simulations should also help in the definition of the laboratory tests in order to partially validate the simulation results and the selected concepts.

These tests should be dedicated to the analysis of critical components or particular subsystem issues. Benches like MAD and SESAME should be used for that purpose. In particular, the tomography to mitigate the cone effect must be the first priority, as the tip tilt compensation scheme in a large FOV based on NGS sensing. The goal finally is to demonstrate the performance achievable by such approaches. We underline that in our plan, the MAD tests at the VLT on NGS is the very first step to be completed as soon as possible.

In a subsequent phase, we think that an on-sky demonstration of the multi LGS (at least 2!) concept using one DM in LTAO mode is mandatory to fully validate the real performance and acquire the full control of such a complex system. This should be done well in advance when compared to the delivery of the AOF at the VLT. Parts of MAD could be reused for that. An alternative solution could be to have an access to the Gemini LGS MCAO system under development in order to perform experiments with it. Then in a second time, AOF will really be a very important key milestone for the multi LGS and GLAO implementation at ESO.

Particular tests should also be foreseen for the two systems MCAO and MOAO, after intensive validations in laboratory. On-sky demonstrations could be prepared with dedicated prototypes to be installed at the Cassegrain focus of the telescope which will be equipped with AOF by 2011. The schedule should be to obtain the first light of the prototypes in 2012. For MCAO an alternative could be once again to use the Gemini system.

For XAO, the proposed plan is to perform simulations and laboratory tests using HOT and BOA. We would like to underline that the VLT instrument SPHERE is the key milestone in the development of the high contrast technique at ESO. In 2010, it will provide on-sky performance results and the crucial operation experience, required for the development of an ELT instrument. In parallel, research and development on new concepts (residual speckle suppression, very high quality optics…), in order to achieve much higher contrast than SPHERE (presently $\sim 10^{-6}$), are mandatory for the ELT application.

9.3 Tomography and control algorithms

A large number of critical issues have to be addressed through the development of optimal phase reconstruction and temporal control algorithms: the tomography with LGS, the tip tilt compensation, the reduction of the telescope vibration impact, the control strategies for GLAO, MCAO, MOAO and XAO… Laboratory demonstrations of the algorithms are mandatory with benches like MAD, SESAME, BOA. The optimal control of ELT AO systems is a major point to obtain the maximum return in performance from the investment cost.

9.4 Components

The following table summarizes the principal key technologies to be developed versus the AO systems considered in this document, as already identified in Section 3. The technologies are detailed in the following sections.

Key Technology	SCAO	GLAO	LTAO	MCAO	MOAO	XAO
Large Adaptive mirror	2-3 m with 30 mm pitch, $\sim 85^2$ (~6000 actuators), 100 μm stroke					
Piezo-DM			possible	100^2 10 μm	possible	200^2 1-2 μm
MEMS				possible	50^2-100^2	200^2 1-2 μm
VIS WFS detector **IR WFS detector**	**High red QE**, <<1e- RON, 600^2 pixels, 0.7kframes/s **High QE,** <5 e- RON, 128^2; 0.7kfr/s					256^2 - $1K^2$ 2-3kfr/s
Processors Algorithms	New algorithms avoiding explicit matrix-vector multiplies Optimized control algorithms including tomography…					
Lasers		~15-20 W pulsed - ~60-100 W CW (TBC)				
LGS WFS		Dynamic refocusing or custom CCD / pulsed laser				

For the development of the critical components, we underline that both the JRA1/JRA2 of Opticon and the ELT DS contribute to the studies of the different technologies which could be selected in an ELT. These activities are very important and are integrated in our plan. These should be continued in the frame of FP7.

9.4.1 Large DM

At least one deformable mirror should be integrated in the telescope optical train in order to minimize the number of surfaces and to reduce the complexity of the post focal instruments and to offer a GLAO capability and first stage compensation for other more complex systems. It might also appear, because of windshaking, that the concept of adaptive Telescope is necessary even for seeing limited operation. It seems today that a size of 2 to 3 m is a maximum for the thin mirror to be manufactured as a single dish. This key component should be studied with a high priority as soon as the telescope concept is selected. At least two competitive feasibility studies should be launched in order to evaluate different potential technologies. In addition, experience acquired during the development of the AOF secondary DM will also be of great benefit in the study of the large DM for ELT.

9.4.2 Piezoelectric actuator DM

Piezoelectric actuator DM is one of the potential technology for the high order DM to be implemented in the systems like MCAO, MOAO or even XAO. The first priority is the study of a DM with 80^2 to 100^2 actuators, 5 mm pitch, 10 microns stroke. A competitive feasibility study should be launched as soon as the conceptual design of the instruments is started. In a second step, another feasibility study could be for XAO a DM with a small pitch (~1 mm) and reduced stroke.

9.4.3 Micro DM

This technology is of great importance for the future generation of AO systems in order to substantially reduce their volume and therefore their cost. The first step will start in the frame of the JRA1 with the development for a first prototype of ~2000 actuators. Then in a second time, a feasibility study should be launched to analyse the solutions for the specific requirements of ELT systems like MCAO, MOAO and XAO.

9.4.4 Tip tilt mirror

Specific components will have to be studied in close relation with the instrument design.

9.4.5 CCD

The current development supported by the JRA2 of Opticon at EEV is of prime importance to enable the use of Electron Multiply CCD technology (no noise, fast read out) in AO. Future developments should be envisioned to improve the performance like the point spread function, the quantum efficiency… Larger format could also be necessary. Original CCD detector architectures addressing the LGS spot elongation issue

(CW laser) or the dynamic refocusing issue (pulsed laser) needs to be studied and developed.

9.4.6 NIR detector

Low noise fast readout NIR detectors will be essential to either provide AO correction on embedded objects (for instance for a MiD IR instrument), or to sense the low order modes on a Natural Guide Star in NIR while using Laser tomography. The latter will help to meet the sky coverage expectation thanks to the partially corrected NGS in the NIR. The on-going discussion for such development should be pursued.

9.4.7 Real Time Computer

Computing power required for AO evolves like the fourth power of the telescope diameter. For complex AO capabilities on ELT the normal evolution of the Moore law will probably not be sufficient to meet the required computing power. It is therefore crucial that new algorithms –involving heavy mathematical tools - aiming at reducing the computing power requirements are studied. This has started in the frame of the FP6 ELT Design Study. This effort should be reinforced and active collaboration with the mathematical institutes should be investigated. For the real time computer architecture, the fast evolution in this field should be taken into account before to select any final solution.

10 Conclusion

In this report, the ELT AO WG has summarized the possible AO systems to be considered in an ELT fulfilling the assumed science requirements. The risks and critical issues have been analysed, no major showstopper has been identified today. A roadmap is proposed for the development of the key systems and relevant technologies. Constraints on telescope design have been listed, in particular its optimisation for the LGS technique is crucial. It is worth noting that the telescope diameter impacts dramatically the AO complexity and ultimately its feasibility, as the seeing conditions.

It was not possible, in the time allocated to establish this report, to address the problem of cost estimation. It was partially done for the large DM to be integrated in the telescope (Section 6). A basis for cost estimate could be to take the already foreseen instruments of the second generation of the VLT and to apply a certain multiplicative factor linked to their physical size, the number of actuators of the DMs, the overall complexity and the expected performance (FoV, Strehl): not including R&D, at least a factor 4 to 5? (TBC)

Because no significant feedback from the other ELT WG was included in this document, the AO WG wants to strongly underline the necessity to perform a careful cross-check and overall synthesis with the other WG reports in order to converge to a truly consolidated plan for the ESO ELT project in the next months.

A significant sustained effort will be required to actively prove the necessary new concepts, to enable the key technologies and to develop these really new capabilities in astronomy. The manpower and the funding required to develop all the mandatory AO technologies correspond to a very huge amount which is not presently available in our community, firstly because of the already existing important projects like SPHERE, MUSE, HAWK-I, LINC-NIRVANA, VLTI 2nd generation... It will necessitate a substantial effort of ESO and to obtain significant supports from EU through the different research programs (joint research projects, research training networks…), to hire young researchers (doctorates and post-doctorates) and engineers and to establish strong collaborations between the European laboratories, active in the field of AO. The members of the ELT AO WG would like to express their willingness to take up the challenge by involving their laboratories in this major development, through R&D, feasibility studies and instrument designs.

11 Appendices

(see the other document)

A. Introduction to LGS problematic

B. Some thoughts about the use of Laser Guide Stars in ELTs

C. ‘Classical’ methods to solve spot elongation on focussed Sodium beacons

D. Advanced LGS concepts

E. Large deformable mirrors

F. Segmentation and high contrast imaging

G. Existing demonstrators and path finder

Appendices

to the ELT Adaptive Optics Working Group report

28th February 2006

1 Appendix A: Introduction to the LGS problematic

The opinion of the AO Working Group is that it will not be possible to fulfil the scientific potential of the proposed ELT using only NGS (Natural Guide Stars) for AO. Laser beacons will be required to provide artificial illumination of the turbulent atmosphere, and they must be accommodated in site evaluation strategies, and telescope and instrument design constraints from the outset.

Conceptually, the simplest use of lasers is to generate one or more focussed spots, which, to first order at least, resemble NGS. These spots, generally referred to as Laser Guide Stars (LGS), may be created either by Rayleigh scattering in the lower atmosphere (up to say 20km) or by resonant scattering from mesospheric sodium (up to around 90km). The Rayleigh method is not practical for ELT use as the lower altitude gives rise to a large focus anisoplanatism, or cone effect (see below). Dense arrays of Rayleigh laser beacons might be conceived, but it is in general recommended that fewer and appropriate sodium lasers are used with an ELT. Sodium beacons require a wavelength of 589nm and linewidths of 0.5-1 GHz to achieve efficient return. Naturally, Rayleigh return is always present whether exploited or not, but the (lower-altitude) Rayleigh scatter which accompanies a sodium beacon may generally be eliminated optically.

The problem with focussed-spot laser “guide stars” is that they are NOT stars, and generally speaking, any similarity decreases with increasing telescope diameter. Unlike NGS, laser guide stars are not at infinity and have non-negligible extension in the line of sight. Furthermore they do not measure tip-tilt, and are accompanied by substantial extraneous scatter of launch light at low-altitudes.

The inability to measure tip-tilt reliably with conventional LGS schemes arises from there being a nearly reciprocal global atmospheric phase gradient applied to the beam on its upward and downward path through the atmosphere. Fortunately this does not apply to higher-order mode measurement from a single laser guide star as the laser light is scattered rather than reflected. The effects of higher-order phase distortion induced on the upward path are therefore erased from the return wavefronts themselves. It is only the position of the return wavefront emission which is affected by the induced global tilt and spot distortion on the upward path. There is, however, an implication for the measurement of higher-order modes when multiple laser guide stars are employed. This is because the reciprocity applies to the tip-tilt of each beacon separately and the tomographic information obtained from them is therefore incomplete. This effect is described in the following section on multi-LGS issues. A further uncertainty affects the lower temporal bandwidth component of focus measurements from sodium guide stars, which are affected by fluctuations in the vertical distribution of sodium density.

The loss of tip-tilt information from LGSs (and the error on some low-order terms such as focus and astigmatism) means that this information must be recovered from one or more NGS, and this limits the sky coverage of LGS systems. Mitigation is therefore crucial and the following considerations require evaluation:

- Some of the wider-field multi-LGS systems provide their own partial mitigation. Even though the recovery of full tomographic information for, say, MCAO requires multiple NGS, the extended "clean-up" of a larger field by the action of the LGS system means that instantaneous NGS imaging can be much improved, and the required minimum brightness for wavefront sensing much ameliorated. There is also a possibility of correcting the NGS field(s) with separately-targetted LGS AO systems in situations where the NGS does not benefit from correction of the science field. This approach, originally suggested by Rigaut and Gendron {ref} for single sodium guide stars on smaller telescopes, has never been implemented, presumably on the grounds of cost and complexity. However, when considering the enormous scientific premiums of full-performance LTAO on an ELT, or the fact that an ELT laser MOAO system provides much of the required complexity anyway, the case for this type of system should be re-opened.
- The tip-tilt power may not follow a simple extrapolation of turbulence measurements on smaller telescopes because of the effects of the outer scale of turbulence. However the stringency of tip-tilt correction required to preserve short-wavelength diffraction-limited performance on an ELT will ensure that this will only be a partial mitigation, although undoubtedly one requiring supporting site data for evaluation. Unfortunately an ELT will be likely to induce extra tip-tilt power of its own through wind-shake.
- The effect of uncorrected tip-tilt (and other lower-order) modes is not equally decisive for all forms of science and AO system. Some scenarios, such as a medium-performance GLAO system feeding pixels or IFU elements, which are larger than the diffraction limit, will suffer much less from extraneous tip-tilt. This is because the relevant scientific performance metric is included energy and this will be much less affected than say the Strehl ratio of a near-diffraction-limited system in similar conditions (Ellerbroek et, JOSA A, 1994)
- Tip-tilt measurement systems can be improved. In particular, lower-noise high-speed infrared NGS WFS detectors could markedly improve sky-coverage. {ref technology section}
- All of the above systems an considerations, provide only partial mitigation or relief and would still leave statistically-degraded performance within, say, thirty degrees of the galactic pole, and virtually no performance in small individual areas of scientific interest. The ultimate technical remedy for the conventional LGS scheme problem of tip-tilt determination is the polychromatic laser guide star, which provides a multi-wavelength return and therefore the possibility of deducing the tip-tilt from differential measurements of the LGS itself (Foy et al. A&A, 1995). This system has not been demonstrated in the past years and some theoretical objections still exist. It is advancing towards scientific demonstration, with a system for CFHT now under consideration. Under these circumstances the polychromatic LGS development should be monitored and as for other

novel concepts proposed in this document encouraged. Should the pending theoretical issues and simulations be positive, it should be encouraged for on-sky demonstration. Unfortunately even the polychromatic conventional LGS schemes would not measure telescope induced tip-tilt, the control of which remains a high priority. Fortunately at least its effects are completey aplanatic, and, providing a large enough technical (or even auxilliary) field is available, an error signal might be extracted from multiple separated bright NGS.

It must be stressed that even if the tip-tilt problem were to be completely solved, the monitoring of NGS, albeit at reduced bandwidth, would still be mandatory for the measurement of changing non-common-path errors between the LGS and science, although other schemes involving the use of active optics will be explored. This requirement is discussed below.

The finite range of the laser guide stars means they illuminate a conical sample of the atmosphere, and therefore incompletely sample and miss-project higher-altitude turbulent layers. This is the cone-effect, or focal-anisoplanatism, and its effect on uncorrectable wavefront variance proceeds as D5/3, where D is the telescope diameter. The magnitude of the effect also depends on turbulence distribution and wavelength, and it can be about 5-9 times worse for Rayleigh than for sodium guide stars. The D-dependence of the cone effect means that single sodium stars, which can give useful correction in the near-IR on 8m telescopes, will not give useful correction on an ELT. Multiple focussed spots will therefore be required in order to illuminate the turbulent volume sampled by the science field. If such a constellation, whether laser or natural, has a suitable angular distribution, then atmospheric turbulence tomography is possible, allowing the correction to be applied at multiple vertical conjugates. Alternatively the tomographic information may be used to restrict correction to one particular turbulence concentration, normally the ground layer. In either case, the goal is to increase the corrected field of view, and the stability of correction across that field. In the case of ground-layer AO, this stability is achieved at the cost of the level of correction. Laser guide star constellations suffer from there being no tip-tilt information available from any of the individual beacons. This means that some low-order modes, whilst they can be detected, cannot be assigned to any particular turbulent layer. This information must be derived from NGSs.

A further application of the mitigation of the cone-effect using multiple LGS is the correction of a single line of sight or small field of view to a high degree, essentially approximating NGS high-order AO, but without the need for a bright NGS. This is referred to as Laser Tomographic AO (LTAO). A multiplex version of this, in which several small but independently position-able sub-field are corrected independently, is called Multi-Object AO (MOAO). This latter technique has been studied theoretically as an NGS technique, but an LGS variant is required scientifically and modelling of this has begun.

The vertical extension of focussed laser beacons, when combined with their finite range, means that a line rather than a point source is observed off-axis. This effect scales linearly with the lateral distance from the launch position to the point in the pupil where the beacon is observed. This in turn scales with D for laser launch from the centre or side of the telescope. For an ELT, this problem is severe. There will be at least a requirement to track, or somehow compress, a highly elongated source. If the elongation exceeds the isokinetic patch size for the observing sub-aperture, then the shape of the line will fluctuate.

The finite range to the laser beacon means that its image in a telescope optimised for infinity will be aberrated and needs corrective optics. This effect depends upon focal ratio, but if the ELT, as seems likely, has a focal length which is more or less independent of its diameter, then the aberrations will scale aggressively with diameter. This will be as bad as D4 in some cases (see appendix 1). Moreover the aberrations, and the corresponding corrective prescription, will not be constant, but vary with slant range to the beacon, and therefore with zenith angle for a sodium beacon.

There are also advantages as well as disadvantages in using laser beacons compared to working with NGS. We control the power and angular distribution of laser beacons, and the fact that they are monochromatic, and possibly pulsed, opens up a number of additional options for separating them from the science beam, and for subsequent processing. Furthermore we also control the optical properties of the beam and we are not obliged to try and emulate NGS at all.

The use of unfocussed beams addresses a number of the effects of telescope diameter on focussed-spot systems. With parallel laser beams the problems of the cone effect and spot elongation, which get increasingly important with telescope diameter, disappear. Such schemes are less technically mature than focussed-spot schemes, which exist in 8m class implementations, either commissioned or in progress. Accordingly, we separate our discussion of the more mature schemes, which are likely to affect early instruments and scientific capabilities, from the novel concepts. It must be stressed that should the coneless parallel schemes be proven to work, there might be a great simplification and increase in performance of laser AO. We will include amongst the novel concepts those schemes, which though based on focussed-spot beacons, use new and experimental approaches to dealing with their associated problems.

All of the coneless schemes require further numerical simulation and laboratory evaluation, and, where this is positive, they will require evaluation on-sky. The same is also true of techniques required to mitigate the problems of the more conventional focussed LGS systems when they are applied at the ELT scale, and of polychromatic LGS schemes. We therefore recommend a coordinated and energetic exploration of all these technologies, and provide further details of the requirements in the sections which follow.

2 Appendix B: Some thoughts about the use of Laser Guide Stars in ELTs

2.1 General remarks

The main driver for constructing an ELT is both to increase the number of collected photons and to deposit them in extremely sharp diffraction-limited images. It has long been realized that to achieve this both active and adaptive optics should be an integral part of such a telescope. The purpose of this so-called live optics is dynamically to correct for image degradation induced by atmospheric index fluctuations, wind shaking, gravitational sag and thermal effects. Some of these error-sources are deterministic and their effects may be eliminated performing tabulated actions, but others are stochastic and require dynamical wavefront sensing. One of the key factors of wavefront sensing is that it requires one or more guide stars for sensing the wavefront errors to be nulled by the corrective optics or by mechanical adjustment of the telescope optics structure. Conventional AO systems make use of natural guide stars (NGS) for this purpose, but the limited number of NGSs of adequate brightness in combination with the restricted neighborhood (the isoplanatic patch) for which good correction is possible results in rather poor sky coverage. Invoking multi-conjugate adaptive optics (MCAO) will/may increase the isoplanatic patch, but it requires access to more than one NGS (the actual number depends on the number of corrective mirrors), and so we are back again with the original problem.

For this reason the prospects of using LGSs is currently under heavy investigation. Two schemes for creating LGSs seem feasible: In the first one Rayleigh scattering creates the stars in the atmosphere (up to around 15 km height above ground level increasing to 30 km for 60° zenith angle). The other one relies on creating the stars by elastic backscattering from atoms in the mesospheric sodium layer. This layer is located at a height of around 90 km and has a thickness of about 10-15 km (increasing to a height of 180 km and a thickness of 20-30 km along the line of sight at 60° zenith angle). The finite height of the LGSs creates some very fundamental problems, the consequences of which on image quality must be carefully evaluated. In the following I'll only address the issue of sodium beacons, but we should maybe also take up Rayleigh guide stars in the work group(?) Listed below are some of the main problems, which should be addressed:

1) The LGS foci changes with zenith angle.

2) Since the telescope is optimized for infinite conjugates, the LGS images are always aberrated.

3) The cone effect: What is the proper sampling of the atmosphere?

4) Perspective elongation and isoplanatic limitations.

2.2 Effects of focus changes and aberrations

The first and fundamental effect of the finite altitude of LGSs is that the focus will be longitudinally shifted from that of the natural stars. For the case of sodium beacons, the shift may for a typical ELT with a focal length around 600 m be several meters at zenith, decreasing with increasing zenith angle. As a consequence the wavefront sensor must be continuously refocused when tracking a science target.

The second effect is the inevitable aberrations contaminating the LGS images. Strangely enough only optical designers seem to realize that since the telescope design is optimized for infinite conjugates, it will show aberrations for all other imaging geometries. The severe ones will be field independent spherical aberration growing with the fourth power of the telescope diameter, field proportional coma growing with the third power of the telescope diameter and maybe astigmatism proportional to the squared field angle and growing with the square of the telescope diameter. Changing zenith distance will also change these aberrations. It should be realized that this results in a "floating zero" for the wavefront sensor when relating the wavefront measurements to natural stars. This may affect both the accuracy of the wavefront measurement (if the floating zero is not well known or fluctuates) and the required dynamical range of the wavefront sensor. To illustrate the magnitude of the problem, the sodium beacon RMS wavefront error for the Gregorian part of the Euro50, for the OWL, and for the Salinari/Goncharov telescope (S/G) presented in Glasgow 2004 is shown as function of field angle in Figures 1, 2 and 3 respectively.

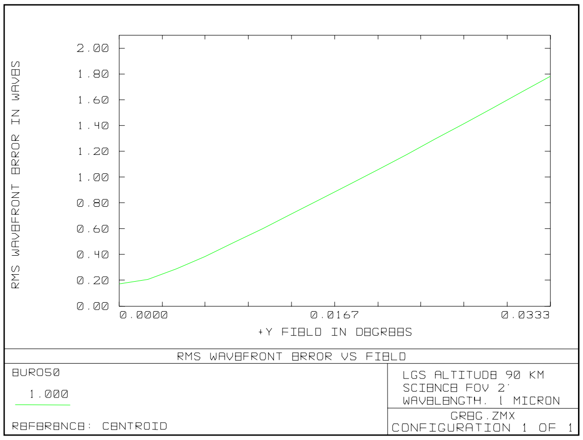


Figure 1a: LGS RMS error versus field. Euro 50

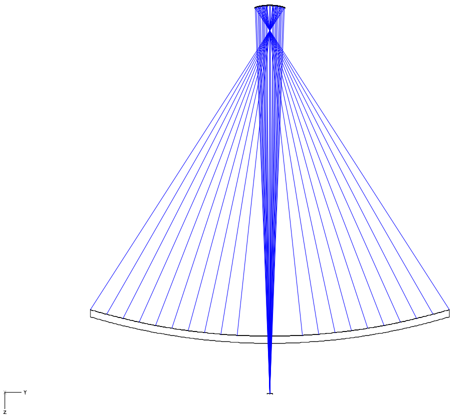


Figure 1b: Gregorian part of the Euro 50

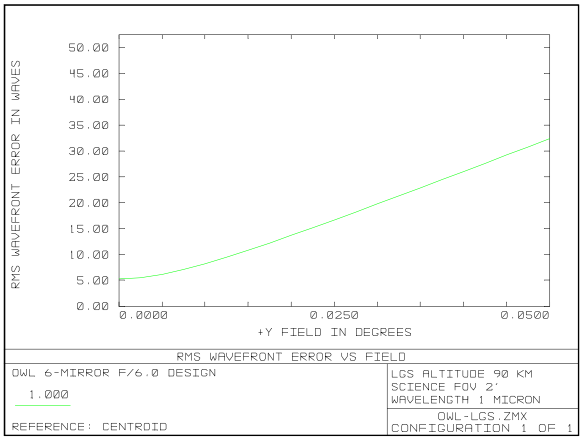


Figure 2a: LGS RMS error versus field. OWL

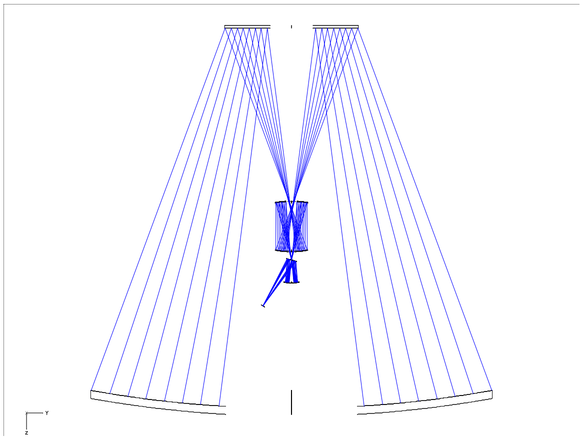


Figure 2b: OWL optical layout. 100 m aperture

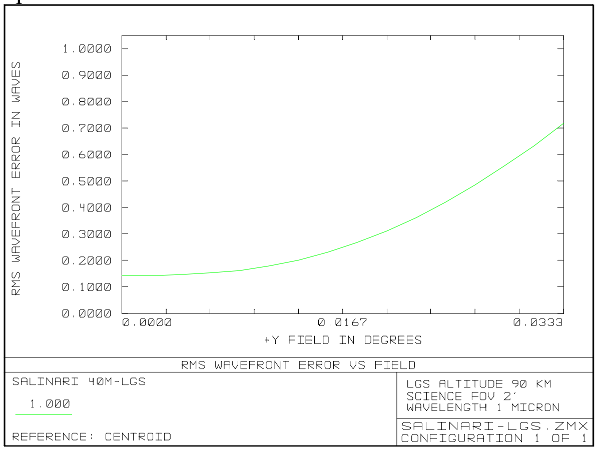


Figure 3a: LGS RMS error versus field. S/G

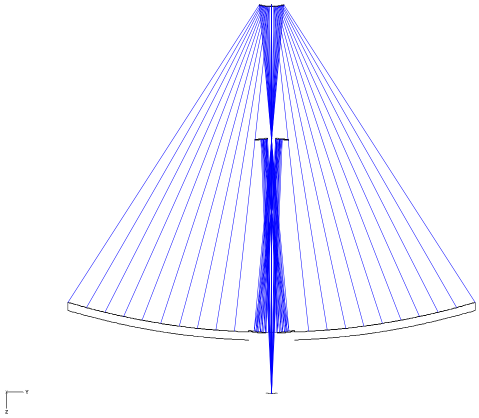


Figure 3b: S/G optical layout. 40 m aperture

Note that the different maximum field angles on the RMS plots are chosen to ensure that the atmosphere is adequately probed by the LGSs, that is:

$$\mathrm{FOV}_{\mathrm{LGS}} = \mathrm{FOV}_{\mathrm{Science}} + \frac{D\cos(\varsigma)}{H}$$

where D is the telescope aperture diameter, H is the height of the LGS and ζ is the zenith angle. Note also that since the wavelength has been chosen to 1 micron, the RMS values for the purely geometrical (non wavelength dependent) aberrations are also in microns. All of the RMS curves have been calculated under the best possible conditions, i.e. refocusing the telescopes to best focus optimizing the shape of the image surface and taking the RMS relative to the centroid. Comparing Fig. 1, 2 and 3 one should not draw the conclusion that the S/G optical configuration is superior to the Euro50 configuration, again being superior to the OWL configuration with respect to LGS imaging. The difference in RMS magnitudes mostly reflects the fact that spherical aberration goes with the diameter in the fourth power, coma with the diameter in the third power and astigmatism with the diameter in the second power. Since the focal lengths of the telescopes are almost the same, a “fair” comparison requires that the diameters be rescaled to the same value (e.g. 50 m), and the performance be compared at a common field angle (e.g. 0.033^{o} = 2'). Noting that OWL and Euro50 predominantly suffer from spherical aberration and Coma, and the S/G predominantly suffers from spherical aberration and astigmatism, the three configurations seems to be compatible with respect to LGS aberrations when scaled to the same aperture.

When evaluating the effect of the floating zero-point calibration, the magnitude of the RMS wavefront error should be compared to the expected atmospheric RMS wavefront error fluctuations. Assuming Kolmogorov statistics (pessimistic) and an achromatic atmospheric index variation, the RMS of the atmospheric OPD (which is independent of wavelength) will be given by

$$\mathrm{RMS} = \frac{\lambda_0}{2\pi}\left(\frac{D}{r_0 \cos(\varsigma)}\right)^{5/6}$$

where r_0 is the reference Frieds parameter at the reference wavelength λ_0. D is the telescope aperture diameter. Taking $r_0 = 0.2$ m @ $\lambda_0 = 0.5$ microns, this RMS is shown as function of D in Figure 4

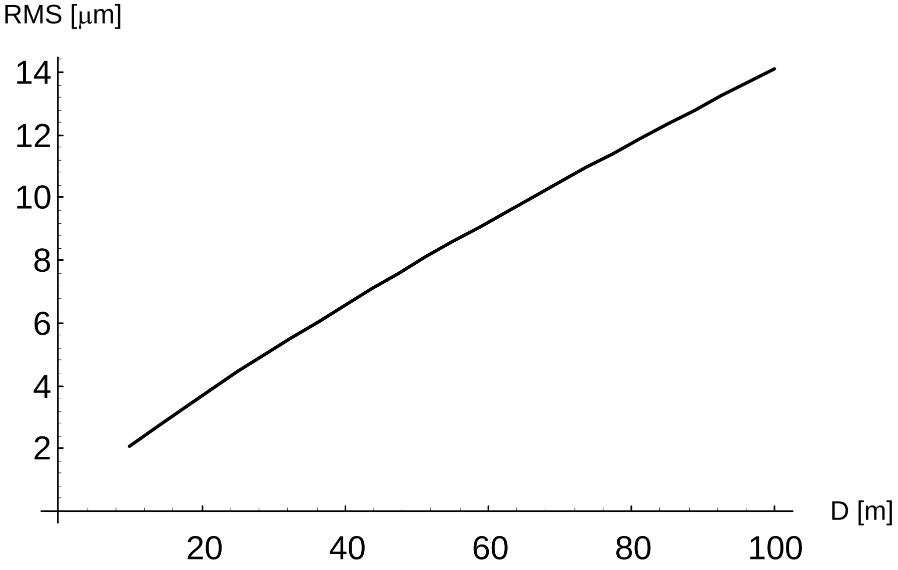


Figure 4: Atmospheric RMS error as function of telescope diameter D. Valid for all wavelengths

Comparing Figure 4 to Figure1a, 2a and 3a, it is seen that, taking the marginal LGS, the atmospheric fluctuations to be corrected will be significantly larger than the aberrations for the Euro50 and the S/G, whereas they will be significantly smaller for the OWL. Taking into account that the goal of the correction should be a residual RMS error of around λ/10, this indicates that planning for sodium beacon wavefront sensing, the diameter of the telescope aperture may well be a showstopper regardless of the optical design. It should also be pointed out that the telescope aberrations for Rayleigh beacons will be much worse since they are located further away from the ideal conjugation condition for the telescope.

Although one may, from the above considerations, draw the (cautious) conclusion that, for a given diameter, the actual optical design of an ELT may not affect the level of the LGS aberrations, and hence the expected AO performance, care should be taken here in relation to the complexity of the design. The aberration induced RMS errors, and hence the needed zero point calibration, are calculated for a perfectly aligned telescope. In practice the telescope will be dynamically aligned and may very well end up in a (changing unknown) configuration, which may differ from the ideal one. Taking the Gregorian configuration of the Euro50, the secondary may decenter resulting in field homogeneous coma. Typically this will be counteracted by rotating the secondary around its center of curvature resulting in no change of pointing. As a result the telescope will end up in a configuration where the conical foci of the two mirrors coincide, but where the optical axis has a kink at this focus. There is no guarantee that this situation will result in the same LGS aberrations as the ideal situation – in fact since the circular symmetry of the telescope is broken, it most certainly will not. For the OWL and the S/G configuration the situation is much more complex. Here we have at least three corrective mirrors, which should be aligned with the primary. Decentering or tilting any one of these surfaces will result in coma, which may be compensated by rotating either one of the remaining ones around its center of curvature. Tilt of the OWL flat secondary will also result in coma. The possible end configurations (corresponding to kinks in the optical axis at the intermediate foci) resulting in good image quality for the natural stars, but different LGS aberrations – and hence different (unknown) zero point wavefront calibrations are numerous. Before settling for a given ELT configuration, the *variations in the magnitude of the LGS aberrations between different alignment situations should be investigated, since they depict the final wavefront error for the natural AO corrected stars. Going for a correction down to a level of $\lambda/10$ requires that the LGS aberrations are known to that level.*

2.3 The cone effect

Normally the cone effect is associated with the fact that parts of the atmosphere contributing to the wavefront error experienced by a natural star is not probed by the LGSs created at a finite height and therefore cannot be corrected, or to put it another way, parts of the atmosphere seen by the natural stars are not seen by the LGSs. The obvious solution is to choose a number of LGSs in an arrangement sufficient to cover the uppermost atmospheric layer in a height of 15 km. This way all relevant parts of the atmosphere should be covered by probing rays and its effects on natural stars could be evaluated. However, whereas this is obviously a necessary but minimal condition for good AO correction it is not obvious (at least to me) that it is also a sufficient condition. Since the atmosphere is a continuous entity, the directions and the number of probing rays crossing a point in the atmosphere must also be relevant. This can be based on two arguments: *First* it has been known for long from medical applications of transaxial tomography that the resolution in an image point depends on the number of probing rays crossing through that point. The more crossing rays the better will be the resolution. In relation to AO this means that we may have to demand that relevant atmospheric points should be crossed by more that one ray (that is illuminated by more than one star), resulting in a larger number of LGSs than sufficient for just covering the atmosphere. Luckily the geometry is such that the atmospheric points close to the aperture associated with the smallest r_0 and therefore requiring most resolution in the tomographic mapping will also be crossed by more rays than the upper atmosphere. *Second* there already exists a wealth of both analytical calculations and simulations (the latter ones for "small" ELTs of about 30 m) of the expected MCAO performance. Most of these estimations are based on probing the atmosphere by natural guidestars, which ensures perfect atmospheric coverage. They do however show that separating the guidestars by more than a few isoplanatic angles will result in a Strehl being "pulled" by the guide stars and deteriorated performance in between the guidestar positions. The actual number of needed guidestars is of course dependent on the characteristics of the atmosphere as is the consequences of arranging them with a mutual separation larger than some isoplanatic angles. *Hence the needed number of LGSs should be the subject of heavy investigations employing both analytical and simulation tools. Adequate atmospheric coverage may not be sufficient and there might be a maximum tolerable angular distance between the stars.*

Given the LGS wavefronts, the optimal control strategy for using them to correct the NGS wavefronts should also be studied. There seems to be two options: One can either use them to perform tomographic mapping of the atmosphere in an appropriate number of layers and then derive the DM deformations correcting optimally for this number of layers, or one could get rid of the cone effect by synthesizing NGS wavefronts from LGS wavefronts and correct these wavefronts optimally. Both methods suffers from the lack of knowledge of the global tilt information.

2.4 Perspective elongation

Perspective elongation stems from the fact that assuming an on axis LGS launcher, the finite thickness t of the sodium layer will result in the created star looking elongated when observed in a radial distance R from the axis. The angular elongation ε is given by:

$$\varepsilon = \frac{t\,R\cos(\varsigma)}{H^2}$$

where H is the height of the mesospheric sodium layer. Fig. 5 shows the zenith elongation as function of the distance from the axis.

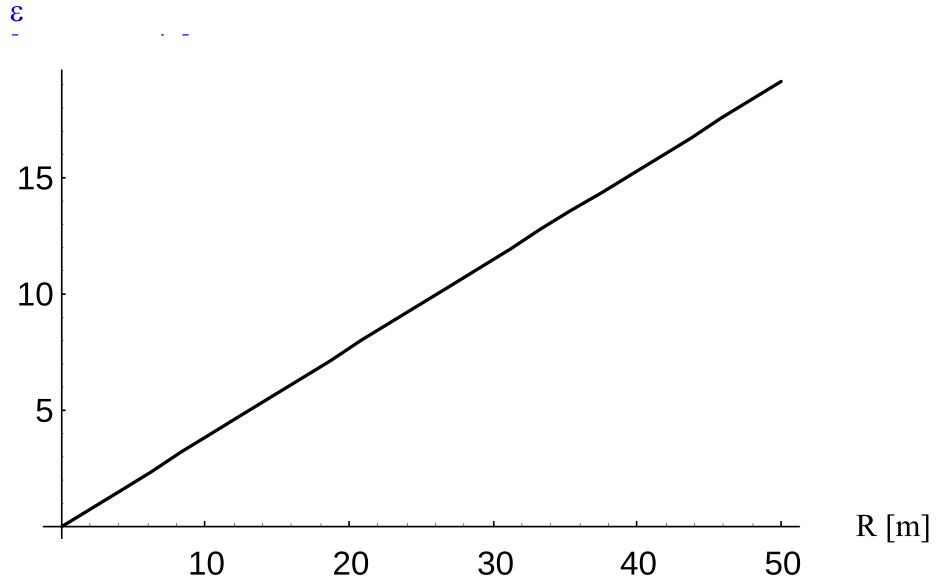


Figure 5: Elongation ε as function of axial distance R assuming an axial launcher. Zenith angle $\zeta = 0$

Elongation is harmful for the uncertainty σ_s of the wavefront slope measurement which assuming Poisson noise is given by

$$\sigma_s = \frac{\alpha}{\sqrt{N}}$$

where α is the angular extension of the spot along the direction of the slope component in question and N is the total number of photons collected in the spot. The uncertainty can be decreased (precision increased) either by "compressing" the spot or by collecting more photons.

Since the elongated spot is due to photons arriving from different heights within the thick sodium layer, schemes based on tracking (refocusing) a travelling a bullit star created by a pulsed laser have been proposed. One approach (Angel et al) is based on using a deformable mirror with oscillating focal length and another one (Beckers et al) consists of using birefringent binary optics in combination with fast polarization switches. A third approach (Keck) relies on special CCDs capable of shifting the charge synchronous with the pulse propagation through the sodium layer. *Some of these proposals should be tested out in practice.*

One important issue should however be realized: The isoplanatic angle puts an upper limit to the tolerable spot elongation. If the elongation becomes larger than the isoplanatic angle, the elongated spot will no longer move as a "rigid body" in the Hartmann images, it will wiggle like a worm preventing reliable determination of the local wavefront slope. One may argue that the relevant angle should be the isokinetic angle, but the Hartmann spots are detected in subapertures with a width of r_0, which means that the dominant aberration is tilt resulting in the isoplanatic and the isokinetic angle being identical. The isoplanatic angle α_{iso} is for Kolmogorov statistics given by

$$\alpha_{iso} = \alpha_0 \left(\frac{\lambda}{\lambda_0} \right)^{6/5}$$

where α_0 is the reference value at the wavelength λ_0. Taking α_0 = 2.5” @ λ_0 = 0.5 microns, the isoplanatic angle is shown as function of wavelength in Fig. 6.

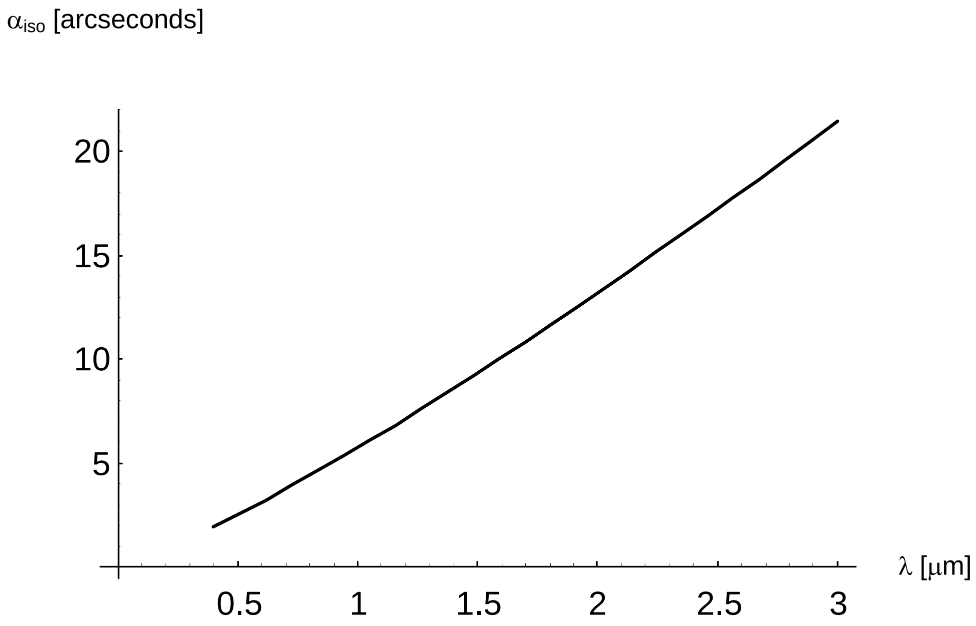


Figure 6: Isoplanatic angle α_{iso} as function of wavelength λ

Comparing Fig 5 and Fig 6, it is seen that for a 50 m telescope the above described methods to overcome perspective elongation will not be applicable for wavelengths below 1.5 microns and for a 100 m telescope the wavelength limit will be 2.7 microns. However, the motivation for overcoming effects of perspective elongation lies in the wish for saving laser power by utilizing the yield from the full thickness of the sodium layer, so if the claim on the ELT is to provide reliable AO correction down to visible wavelengths, then *efforts should be directed towards construction of pulsed lasers sufficiently powerful to allow for gated detection* thus locking the LGS to a fixed altitude at the moment of detection.

3 Appendix C: ‘Classical’ methods to solve spot elongation on focussed Sodium beacons

In this appendix we present some of the so-called ‘classical’ methods to solve spot elongation. The adjective classical is to be used here in the sense that these methods permit to use the usual scheme of star-oriented tomography with existing WFS concepts (Shack-Hartmann in general) in GLAO, LTAO, and MCAO. The advanced concepts presented in the next appendix need for most of them to consider new approaches for wave-front sensing and tomography as well of course for the LGS itself.

All the approaches presented in this section need pulsed lasers (<~ 10 KHz) to avoid overlapping of spots as viewed from the telescope as they travel though the Sodium layer. The pulse duration should be a few microseconds so that the extension of the spot in the vertical dimension is roughly equal to the seeing. The 3 concepts describes here are:

- Range gating
- Tracking the spot on the detector
- Optical dynamic refocusing

Range gating implies a loss of photons and thus requires an increase in Laser power for ELTs wrt. to current technology on 8-m telescope. The two other methods, actually solve the spot elongation problem (but not the spot anisoplanatism) and don’t need an increase of Laser Power on an ELT.

3.1 Range gating

Range gating is the simplest method to deal with spot elongation. Its purpose is simply to reduce the spot elongation by allowing only parts of the photons to reach the WFS detector. The gating can be done temporally, using a gated CCD for instance, or optically. The main drawback of range gating is that a certain amount of photons are wasted and thus lasers with high power are needed. However there are some advantages in range gating:

- a smaller number of CCD pixels is required.
- the noise variance of centroiding is inversely proportional to the number of photons and is proportional to the square of the spot size. Hence using gating, the noise component due to spot elongation should decrease faster than the noise increase due to the loss of photons. Some preliminary calculations show that the optimum spot elongation after gating should be around 2 times the seeing spot.

The laser power needed would be about 5 times more than the one designed for 8-m class telescopes. Without gating (so keeping all the photons but having a larger spot elongation) about 8 times more power would be needed.

3.2 Spot tracking on the chip

The Adaptive Optics Development Program (AODP) at NOAO proposes to develop a new generation of WFS detectors that could solve the spot elongation problem using pulsed lasers at about 10 kHz with 1-2 µs pulse duration. Two main upgrades permit to make spot tracking on the chip:

- The format of the pixel layout is adapted to the spot elongation in a given sub-aperture: one of the main axis is oriented in the direction of the spot elongation. For LGS launched from behind the secondary this results in a radial geometry of the pixels.
- The charge across the array in a sub-aperture is clocked such that it tracks the spot as it transits through the Sodium layer. Like this one can integrate several pulses before the read-out.

No increase in Laser power is thus needed because there are no light loss and the spot size always appears seeing limited without elongation

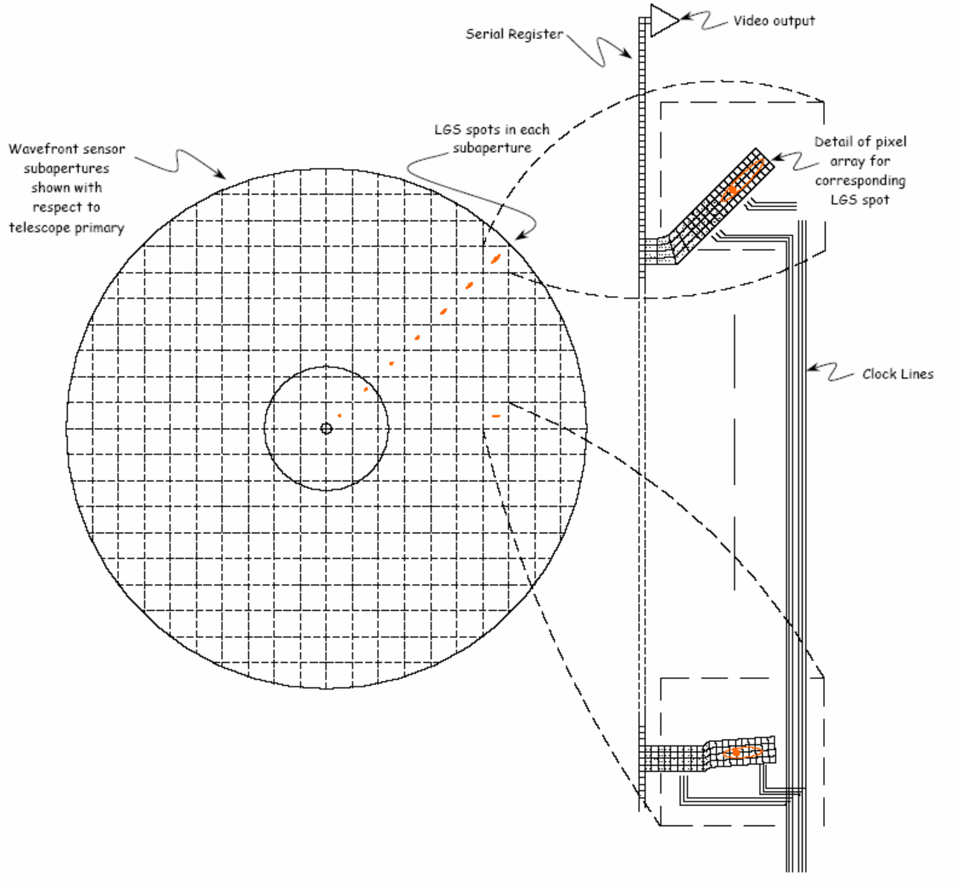


Figure 3-1: Concept of radial CCD with pulsed laser spot tracking on the chip.

The current plan of the project is to demonstrate one quadrant of a radial format CCD array designed for 602 subapertures with 1000 Hz frame rate.

3.3 Optical dynamic refocusing

Using conventional CCDs several methods have been proposed to refocus dynamically the Laser spot as it travels vertically through the Sodium layer. The basic principle is described in the figure below for a Rayleigh beacon (the same principle applies to Sodium beacon):

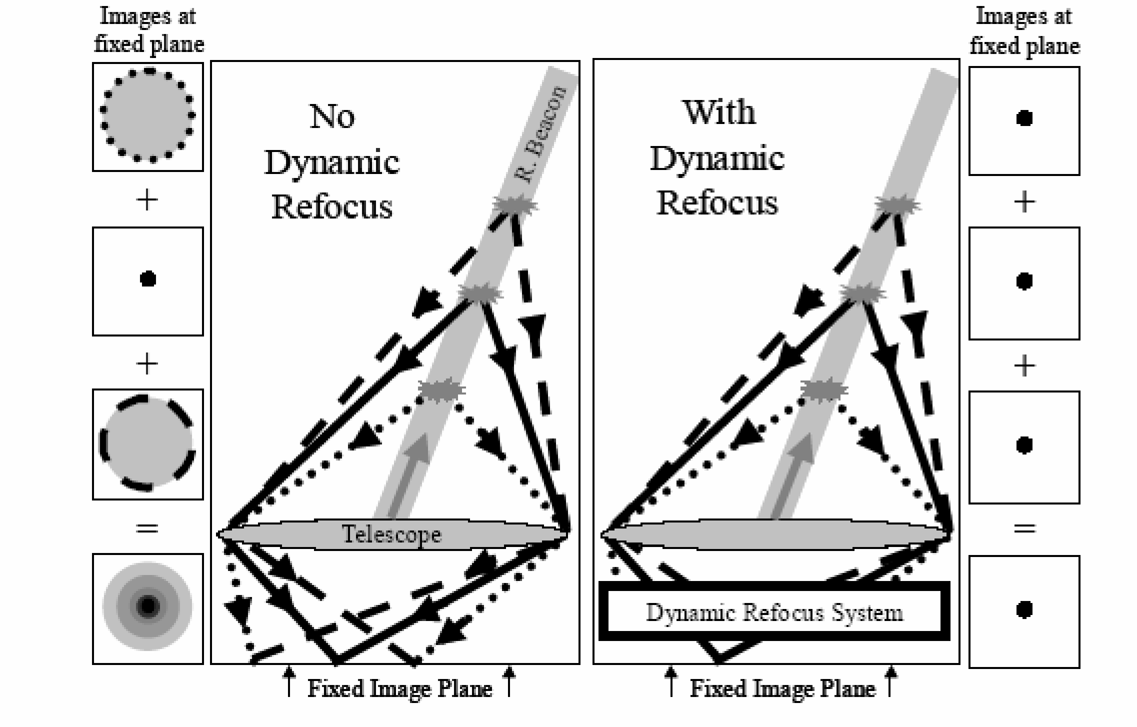


Figure 3-2: Dynamic refocus principle

Without any correction device, the rising spot goes in and out of focus at a fixed image plane. With a dynamic refocusing system, the spot stays always in focus. (from J.A. III Georges et. al. SPIE 5169 2003)

The dynamic refocus systems proposed so fat are of 2 main types:

- opto-mechanical systems, moving optics
- electro-optical systems

The MMT Rayleigh LGS dynamic refocusing system:

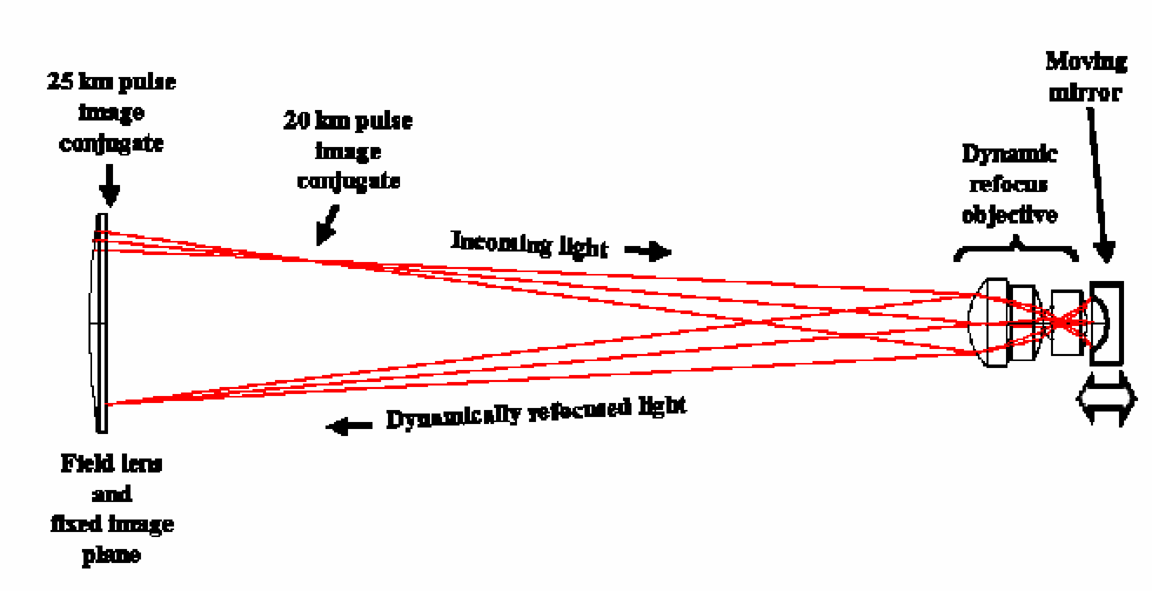


Figure 3-3: The MMT dynamic refocusing system using a tapered resonator (from J.A. III Georges et. al. SPIE 5169 2003)

Dynamic refocusing has been demonstrated on the Sky at the MMT with Rayleigh LGS. Their system is based on:

- An objective that creates an F/0.6 fast beam to reduce the distance between 2 external images of the spot.
- A movable mirror glued on a resonator vibrating at 5 kHz. The amplitude of the movement of the mirror is 160 μm.

This system was proven to work on the sky as it can be seen on the following images:

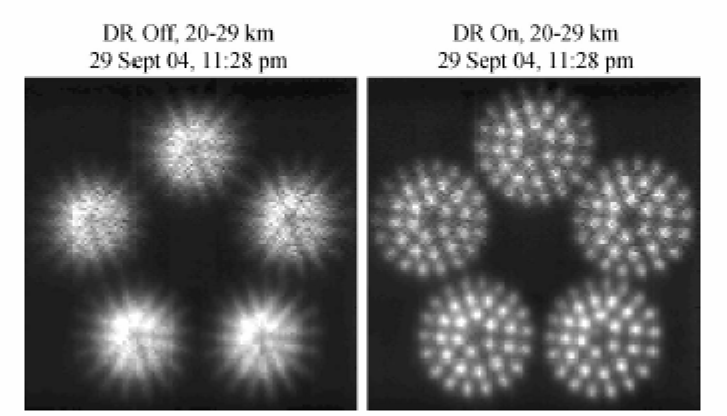


Fig. 1. Shack–Hartmann images of five Rayleigh LGSs at the MMT without (left) and with (right) dynamic refocus. The range gate in both cases was 20–29 km. Each image is an average of approximately 20 s of data recorded at 50 Hz.

Figure 3-4 Dynamic refocus images at the MMT (from Baranec C. et al. Optics Letter 2005).

The fast beam and the high acceleration of the moving optics (8000 g in the case of MMT) makes it impractical for an use at an ELT.

Another concept proposed by Baranec C. et. al. Optics Letter 2005, uses a segmented MEMS device to make the refocusing. The MEMS device is segmented such that each segment corresponds to one sub-aperture and is composed of a steerable mirror. Like this the spot is tracked and kept in the center of the sub-aperture. The concept can be adapted to multiple LGS when the MEMS device is placed in a pupil plane (see Fig.)

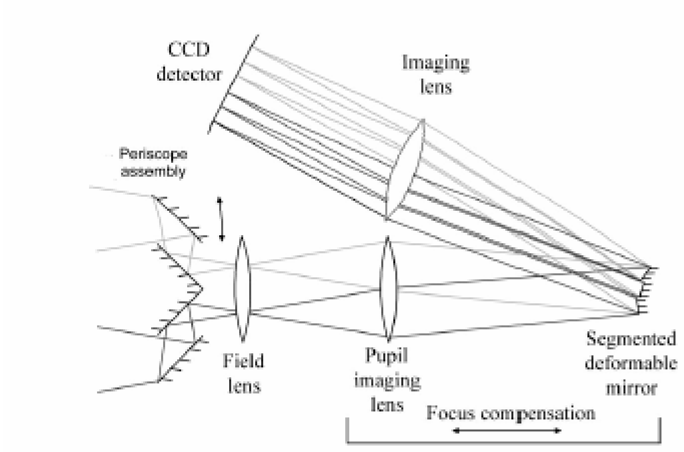


Figure 3-5: Dynamically steered WFS for LGS refocusing

The main adavantage of this concept as compared to the MMT one is that one doesn't need to create a fast beam and the acceleration of the individual mirrors is much less (about 100 g instead of 8000)

The electro-optical device proposed for Euro-50.

Instead of using a moving optical element, Beckers et al. (SPIE 5159, 2003) propose to design an optical device that can vary very fast its focal length with the speed needed to track the LGS spot. In their concept they use 4 lenses made of bi-refringent materiel and 4 polarization modulators permitting to control 16 different focal length states.

The main advantage is that there is no moving part. A drawback is that half of the photons usually lost in the polarization selection (some polarization effects of the LGS return flux remains to be studied to possibly implement a system permitting to use a polarized LGS saving thus some light). The performance for the polarization modulator in speed for the switch between to states is still not clear.

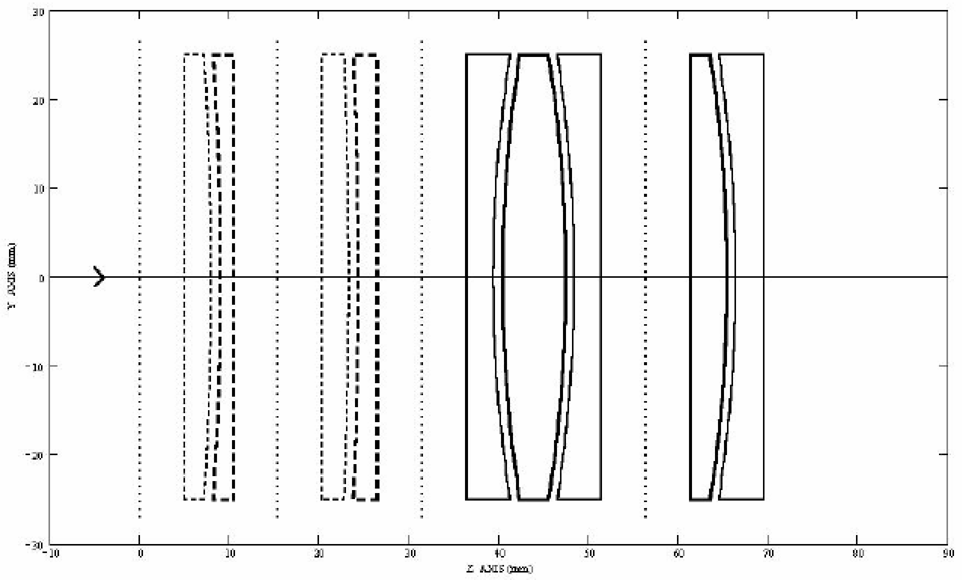


Figure 3: Proposed birefringent lens assembly. It consists of 4 units of the type shown in figure 2 with radii R (from the left) of 293.7 mm (L1, Calcite doublet, dashed lines), 587.3 mm (L2, Calcite doublet, dashed lines), 124.43 mm (L3. Quartz triplet, full lines) and 123.43 mm (L4, Quartz doublet, full lines). The vertical dotted lines are the polarization modulators (M1 to M4).

Figure 3-6: Electro-optical system for dynamic refocusing at the EURO-50 from J. M. Beckers et al SPIE 5169 (2003)

4 Appendix D: Advanced LGS concepts

4.1 PIGS: Pseudo Infinite Guide Stars

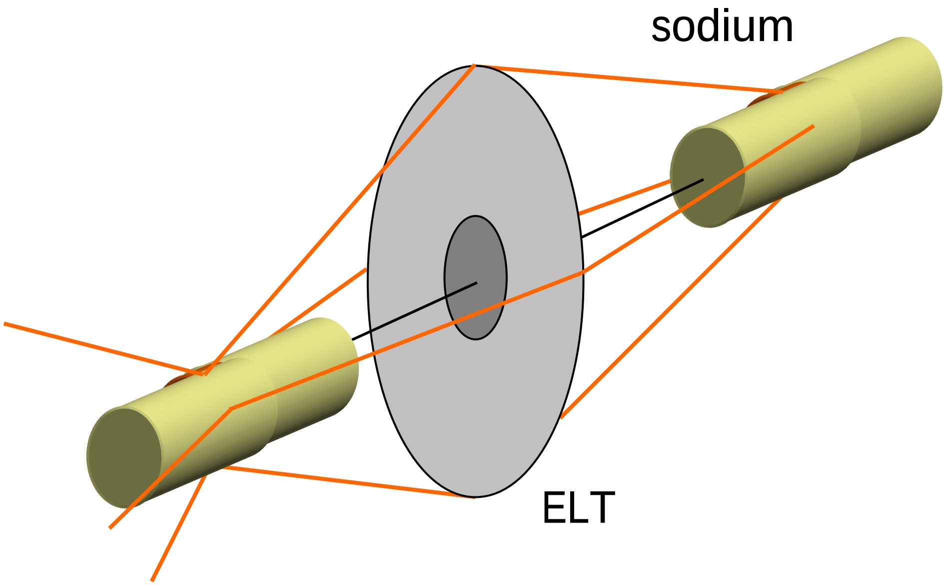


Figure 4-1: The PIGS rod WFS

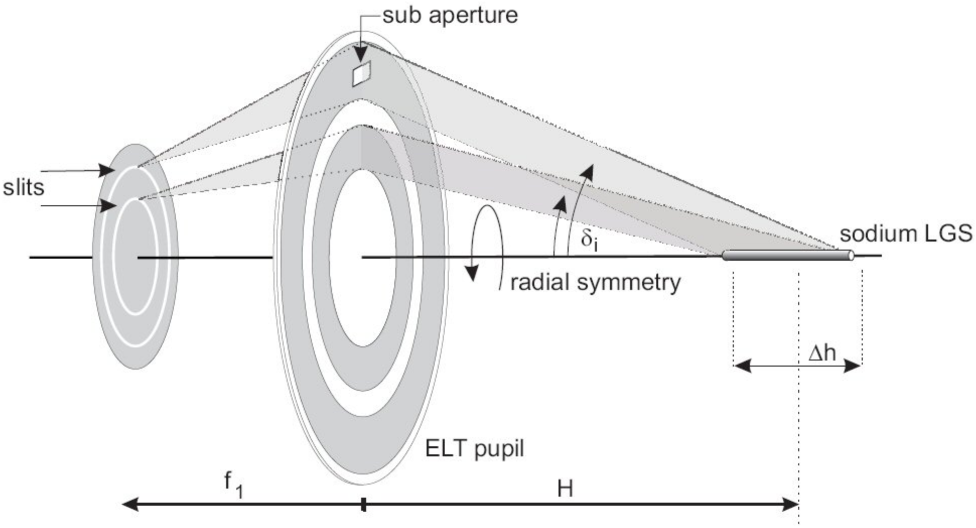
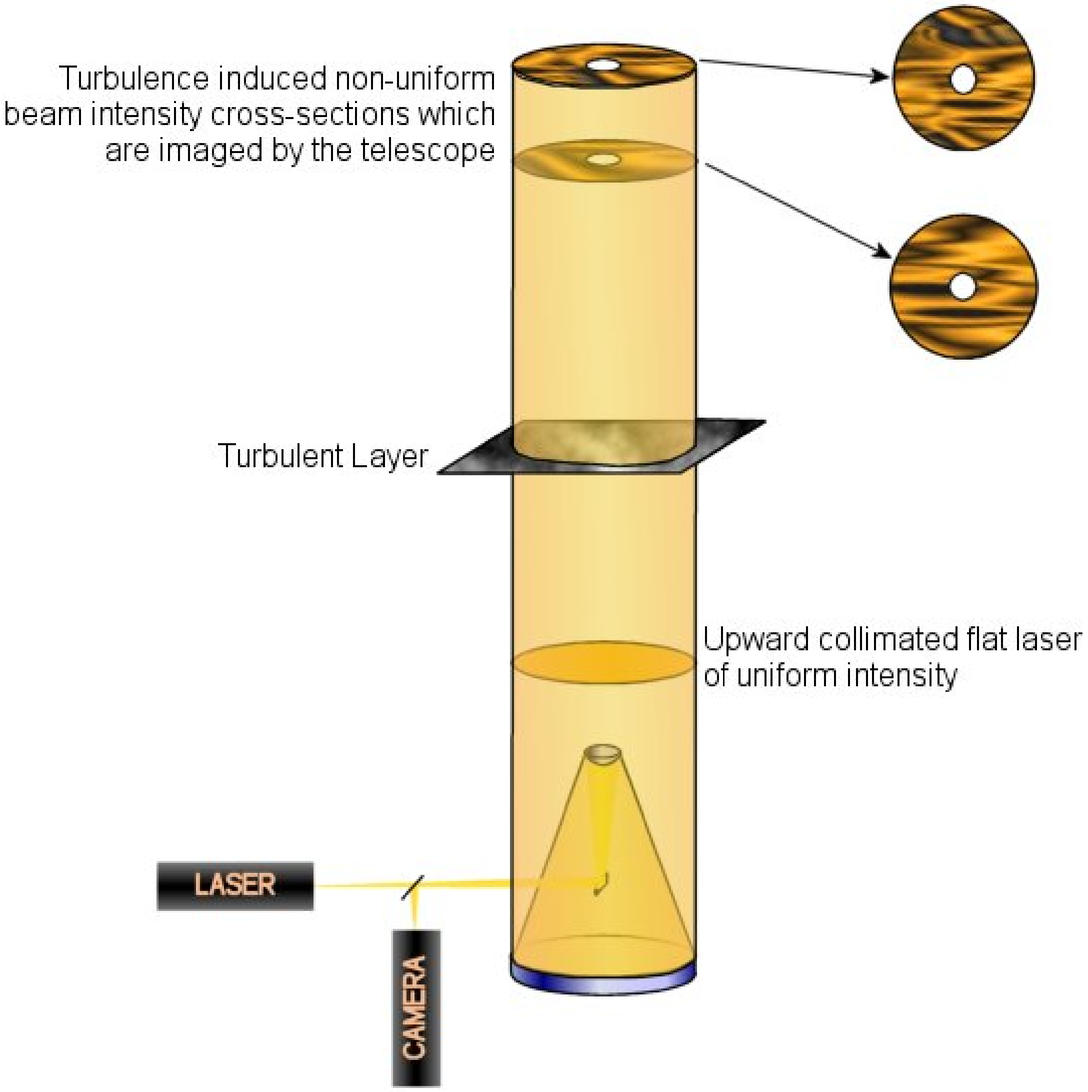


Figure 4-2: The PIGS circular slit WFS

The PIGS concept is a way to deal with spot elongation in the case of focussed Sodium Beacon by using a specialized WFS. The pupil illumination is perturbed by the cylindrical rod and by the circular slit in a way to give an high-sensitive Laplacian Signal on the pupil plane. It is a sort of curvature Roddier-likeWavefront sensor, but for axial sources instead of point ones. The Laplacian actually operates on the polar rather than Rectangular coordinates on the pupil.

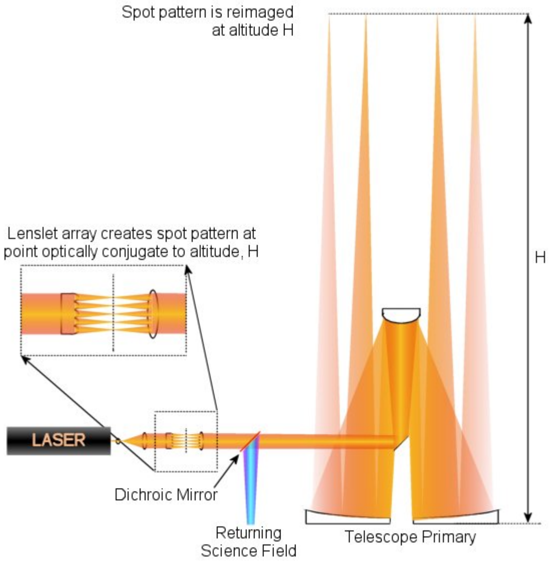
4.2 Project Pupil Plane Pattern: P^4

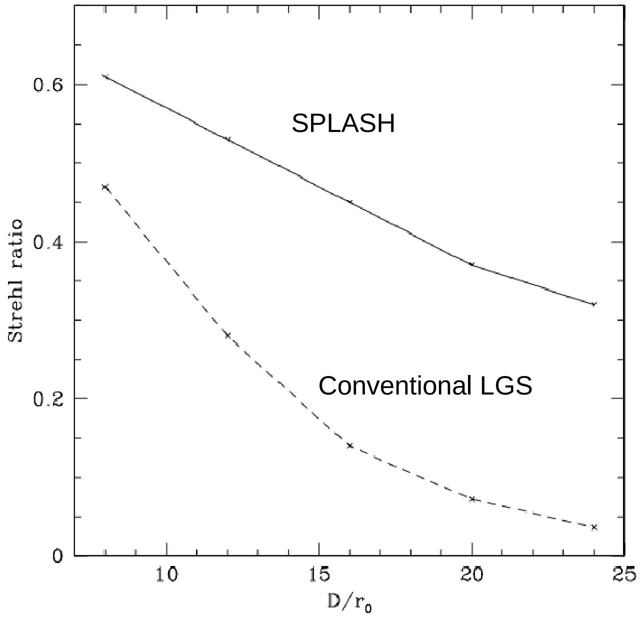
Classical AO assumes that light is negligibly diffracted by passage through atmospheric phase aberrations. Scintillation shows that this description is not fully valid above a ground-based telescope. It then becomes possible to envisage sending a collimated laser beam with known initial intensity through the turbulent layers of the atmosphere and to determine the refractive index changes by the changes in the beam intensity at altitude. The focal anisoplanitism problem is avoided as the signal is created during the upward propagation of the beam, which measures the phase within a cylinder. The method of wavefront sensing is analogous to that of Curvature Sensing, where the phase aberrations at the pupil of imaging optics evolve into intensity aberrations by diffraction in the Fresnel regime. The concept proposed here, Projected Pupil-Plane Pattern, is to emit a collimated laser beam from a telescope primary and then collect the light back-scattered (via Rayleigh or Mie processes) from various altitudes. Pairs of layer intensities are then used to determine the phase aberrations between them, up to the height where the diffraction effects move from the Fresnel to the Fraunhofer regime. The back-scattered intensity can be, in principle, collected by any telescope because the signal is created by the diffraction on the upward path. This significantly relaxes the field of view requirements and, in principle, a small survey-type telescope with large field of view and camera at prime focus could be used for imaging the layer intensities. The need for knowing a priori the distance between layer intensities and phase aberration layers is a problem which reduces the accuracy of the method and encourages imaging as many layers as possible.



4.3 Sky Projected Laser Array Shack Hartmann

A conventional LGS beacon projected from a telescope primary mirror has an upward propagation path identical to that downward, so the overall tilt measured by the spot (beacon) position using the same telescope mirror is zero. This is tilt reciprocity. If instead an array of beacons is projected from the telescope mirror, each from an individual sub-aperture, then imaging the array of resultant spots using the whole mirror will show a distorted array. Alternatively, each spot has a relative position offset, caused by the tilt aberration above its sub-aperture. The spot positions are then, as for a Shack-Hartmann WFS, a measure of the local tilts less the global tilt and used as the wavefront signal. As the spot array covers the same area of sky as the telescope aperture, the focal anisoplanitism from the cone of a single laser guide star is reduced to that of several narrower cones parallel to each other. Hence focal anisoplanitism is reduced, rather than removed. Furthermore, as the field of view increases, such as with larger telescope diameter, the downward propagation of each spot becomes less correlated. The scheme then no-longer measures the local tilt relative to the global tilt. Finally, turbulent layers close to the spot array height are poorly sampled so the measured positions are biased toward lower layers.





4.4 Laser guided adaptive optics with on-sky phase shifting interferometry

The method proposed here, uses the coherent superposition of tilted laser wavefronts over the whole aperture of the telescope as indicated in figure 1. With applying methods of laser phase shifting interferometry (LPSI) one can retrieve a local phase difference that can be used in the adaptive optics system like the gradients retrieved from a usual Hartmann sensor. The details of the proposed scheme are outlined in Rabien et al. 2006. Here we summarize the principle in short words:

With a laser pulse split in two flat coherent laser wavefronts leaving the telescope- one tilted slightly in respect to the other- an interference pattern is created at any distance. When reaching a certain height in the atmosphere, both waves will have collected local phase changes. Due to the tilt in the wavefront, the path through the atmosphere to the point (x,y,H) of each wave is slightly different. The collected phase differences due to the atmospheric turbulence structure modulate the intensity of the interferogram that is written in the sky. With a gated wavefront camera the scattered light from this pattern can be imaged with the use of the full telescope aperture.

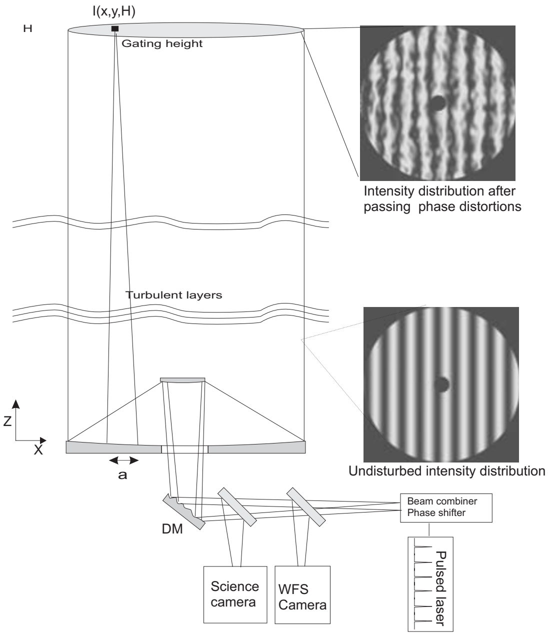


Figure 4-3 Basic principle of measuring atmospheric turbulence with phase shifting interferometry. A pulsed laser beam is split in two beams and tilted in respect two each other. To one of the beams a known phase shift can be applied. The scattered fringe pattern which is formed in the atmosphere at height H, can be viewed with a gated camera over the full telescope aperture. In a set of laser shots a known phase difference is added to the beam in each pulse. Depending on the algorithm used for the phase retrieval, a set of three or more laser shots will allow the local phase difference to be measured.

Using now several laser shots on timescales which are short compared to the coherence time of the atmosphere and applying known phaseshifts between the launched wavefronts, allows to retrieve the atmospheric induced distortions.

The resolution of the sensing can be chosen freely with the amount of tilt added to the beams to adapt to different conditions. Detecting the light scattered from low altitude will result in a ground layer correction. Extending the system to multiple detections at different heights or two beam systems with more deformable mirrors a complete sampling of the turbulent layers in the atmosphere is possible. Therefore high Strehl ratios are reachable and multiconjugate adaptive optics correction with an extended field of view is possible.

Compared to usual guide star systems, the lasers are available commercially. In general a pulsed system with 1-5kHz repetition rate and sufficient power to be detected at high signal-to-noise will be necessary. The power demands for the laser will decrease if a dynamical refocusing device is used, as proposed by Angel 2000. Beam quality issues for the proposed scheme are totally relaxed, due to the full aperture launching of the laser.

References:

Angel R., in „Science with the LBT“, ed. Herbst, T., Neumann Druck, Heidelberg, Germany, 2000
Rabien et al., A&A accepted, 2006

Prospects of LPSI:

Cone effect free measurement of the turbulence
High strehl applications possible
Extension to wider field or MOAO possible
Necessary lasers available today
No extra beam relay and launch telescopes required

Status:

Theory and first performance simulations developed
Laboratory demonstration in progress
On sky demonstration can be done with smaller telescopes

4.5 Virtual Wavefront Sensing

The use of LGSs for AO presents the following problems:

1) Changing from Zenith to 60° Zenith angle the LGS focus in an ELT may move several meters and the corresponding telescope aberrations will change accordingly. They represent a bias contribution to the measured LGS wavefronts, which must be subtracted in order to relate these to NGS wavefronts. The bias must be known with the same precision as is required for the resulting nominally nulled NGS wavefronts.

2) In order to correct a certain science FOV, the LGS FOV must be several arcminutes larger to ensure full atmospheric coverage.

3) Shack-Hartmann LGS spots suffer from elongation due to the non-zero thickness of the mesospheric sodium layer.

4) Due to the cone effect, the atmosphere is sampled along directions, which are not relevant to wavefront mapping for infinite stars.

5) LGSs cannot measure tip/tilt.

In connection with AO and MCAO, where some or all of the DMs are incorporated in additional relay optics normally significantly smaller than the core telescope optics, the two first problems may be severe. Propagating the LGSs through off axis relay optics they will be far from the optimal conjugation location and will require the optics to "open up" to transmit the needed FOV. Virtual wavefront sensing addresses this problem. The idea is that before a piece of relay optics is entered, the LGS wavefronts including the action of possible upstream DMs are measured. One or more test sources are then located in the relay entrance focal plane associated with NGSs, for which the relay is designed to be optimal. The wavefronts for these sources monitoring the DMs in the relay are then measured after the relay. Knowing the aberrated LGS wavefronts entering the relay and the test star wavefronts after the relay, which should be zero for "flat" DMs, it is possible to calculate the "would be" LGS wavefronts – socalled virtual wavefronts – which should be observed if the real LGS wavefronts could propagate through the relay system. The concept may be useful in connection with a two-mirror telescope having one DM conjugated to near the ground level followed by a relay system comprising a second DM conjugated to a high altitude layer in the atmosphere. Poking actuators on the upstream DM will affect the measured LGS wavefronts and poking actuators on the relay DM will affect the test source wavefronts. The combined effect on the virtual wavefronts can be estimated forming an interaction matrix for the virtual wavefronts. A reconstructor can then be formed. Assuming that the bias LGS aberrations in front of the relay are not too severe and can be reliably subtracted, both the LGS bias aberration and the LGS focus problem can be addressed. It should be noticed that neither the LGS nor the test source wavefronts would operate in a null seeking mode. The feasibility of the concept is currently under test in Galway in a laboratory experiment.

4.6 The Concept of ELLAS

The ESO proposed method is called ELLAS (Eso Laser Layer-oriented Advanced Sensing). It is based on the fact that illuminating an area extended as much as the telescope (or more for MCAO) on the mesospheric layer, using a pulsed laser, the mesospheric area which is backscattering has spatially coherent patches of the order of r_o when reaching the ground.

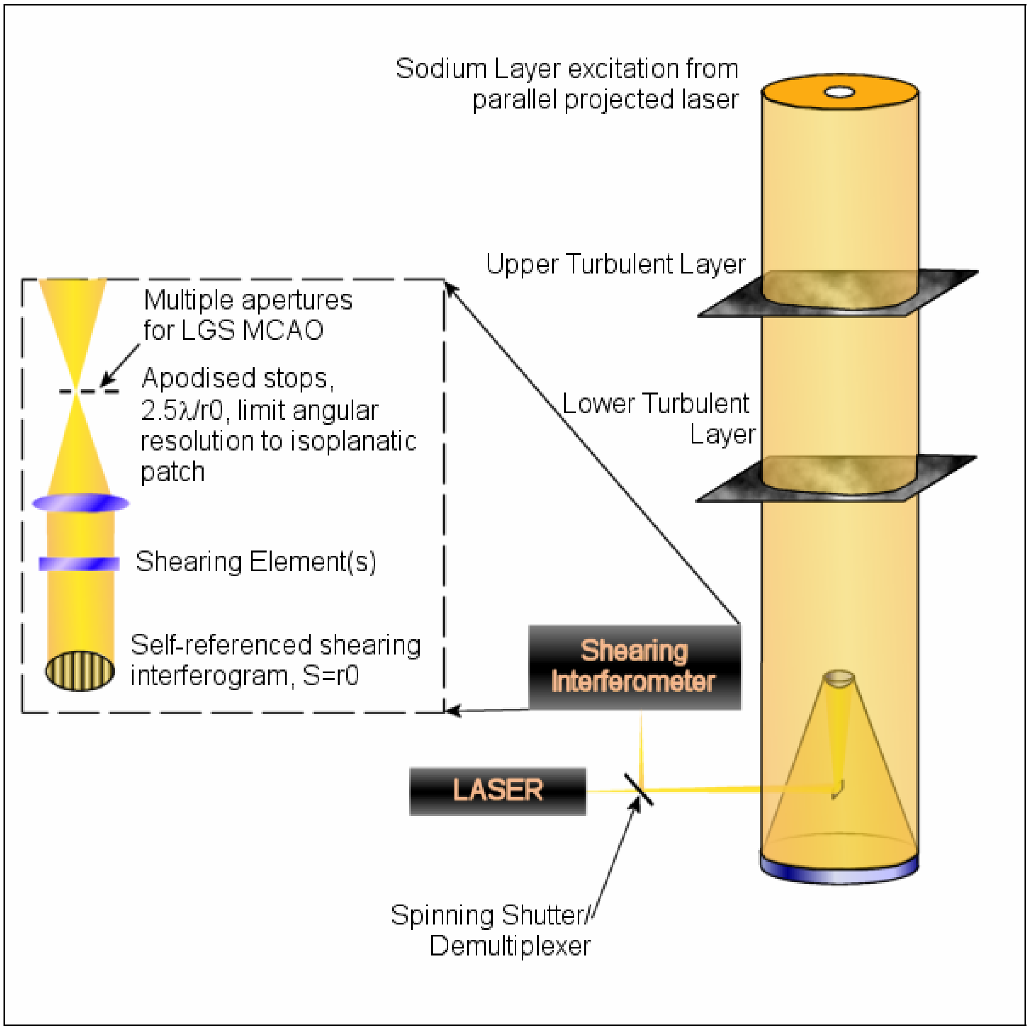


Figure 1: *Simplified coneless sensig scheme with Pulsed laser, and a Shearing WFS. The mesospheric layer area can be illuminated from the full telescope aperture or even by the side. The layer image will be spatially filtered to limit the angular field of view subtended by each subaperture, and thus allow its spatial coherence.*

In other words, the subapertures of the AO system, if dimensioned appropriately, have sufficient coherence in their part of the wavefront to use shearing interferometry (i.e. a self-referencing method) and determine the local tilts. This method implies the use of 589nm lasers. The degree of coherence is demonstrated using the Van Cittert-Zernike theorem below. This is because the field from a incoherent source acquires spatial coherence with distance.

The design we show is applicable to any size telescope, and it is cone-effect-free. The design is made to correct at the same wavelength of the pulsed laser, i.e. it is also suitable for corrections in the visible with ELTs.

If an apodized field stop appropriately located selects the returned beam angular extent equal or smaller than the isoplanatic patch (Figure 1), then the wavefront spatial coherence is sufficient to have e.g. a shearing interferometer wavefront sensor, with shear $s \sim 0.2 r_o(\lambda_{las})$, with λ_{las} the emitted laser wavelength.

For Multiconjugate operations, multiple apertures may be used, isolating isoplanatic wavefronts coming from different directions and feeding corresponding Wavefront Sensors.

The advantages of a shearing wavefront sensor with monochromatic light are similar to those reported for curvature and pyramid sensors: gain tunability in closed loop, full aperture advantage. The latter means that if the WFS senses a diffraction limited wavefront at its operating wavelength, these type of sensors have an advantage coming from the full aperture imaging. Moreover the Shearing wavefront sensor is self referencing, i.e. it uses the wavefront itself to reference relative tilts across the shearing distance s, and does not need an image of the source. We can thus use the mesospheric layer image itself to interfere.

The Shearing Wavefront sensor works at best with monochromatic wavefronts, such as those provided by Laser Guide Stars. It has been already successfully used with Rayleigh lasers guide star systems (at 532nm) by Dave Sandler et al. at Thermotrex Co. for the US Navy .

The Shearing Wavefront Sensor

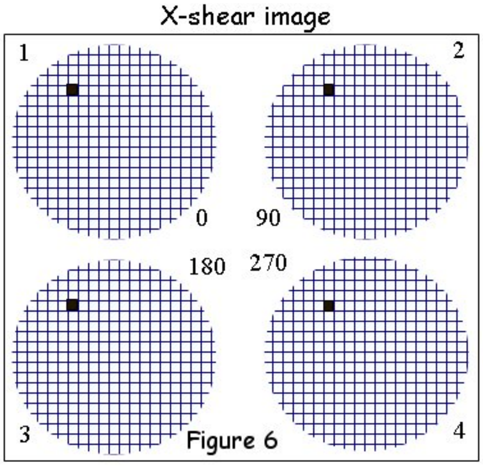

X-shear image

Figure 6

We want to use the four-bucket scheme [J.C.Wyant, Applied Optics, **14**, 2622, 1975], whereby the shear is $s=0.2\ r_o(\lambda_{las})$, and $d=0.8\ r_o(\lambda_{las})$ corresponds to a sampled subaperture of the deformable mirror. The shear value will be variable in the experimental setup to optimize fringe contrast. Fringe contrasts between 0.6 and 0.9 have been reported experimentally, with a 532nm Rayleigh pulsed laser beam [D.G. Sandler et al., JOSA A , **11**, 858, (1994)].

We use symmetric later shears of $\pm s/2$ for the two interfering beams, for two orthogonal axes, x-y. For each axis four sheared beams are created with phase shift steps of 90°, giving four images of the sheared layer (Figure 2). The corresponding pixels in each of the four images will conjugate to the deformable mirror subaperture of size d. They are used to compute the single-axis tilt in each subaperture, as defined by the pixel size.

A linear combination of the four pixels intensities gives the wavefront slope t_{ij} across the subaperture ij (Eq 1). The shear extent s can be tuned in closed loop, thus optimizing the WFS gain for the larger effective r_o. Variable sinusoidal lateral shearing (heterodyne) have been used in the past, to increase the stability and the performance of the Shearing

WFS. We do not plan to use it since the closed loop tilt residuals will automatically smooth the wavefront sensor gain response over the different Zernike terms. Hence the concept uses a dc adjustable-shear interferometer.

$$t_{ij} = \frac{d}{s} \cdot \tan^{-1}\left[\frac{I_{ij}^{(2)} - I_{ij}^{(4)}}{I_{ij}^{(3)} - I_{ij}^{(1)}}\right]$$

The error budget

The arctan term in Eq 1 gives the phase difference measurement. Differentiating it we get the expression for the subaperture wavefront sensor tilt variance (x and y summed)

$$\sigma_{pd}^{2} = \frac{2}{\alpha^{2} N} + \frac{8\sigma_{ccd}}{\alpha^{2} N^{2}}$$

where σ_{ccd} is the sensor rms readout noise, N is the total number of photon counts per subaperture summed over the four pixels of the sheared beam images, α is the fringe visibility. The computation of the latter is dealt with in the next section.

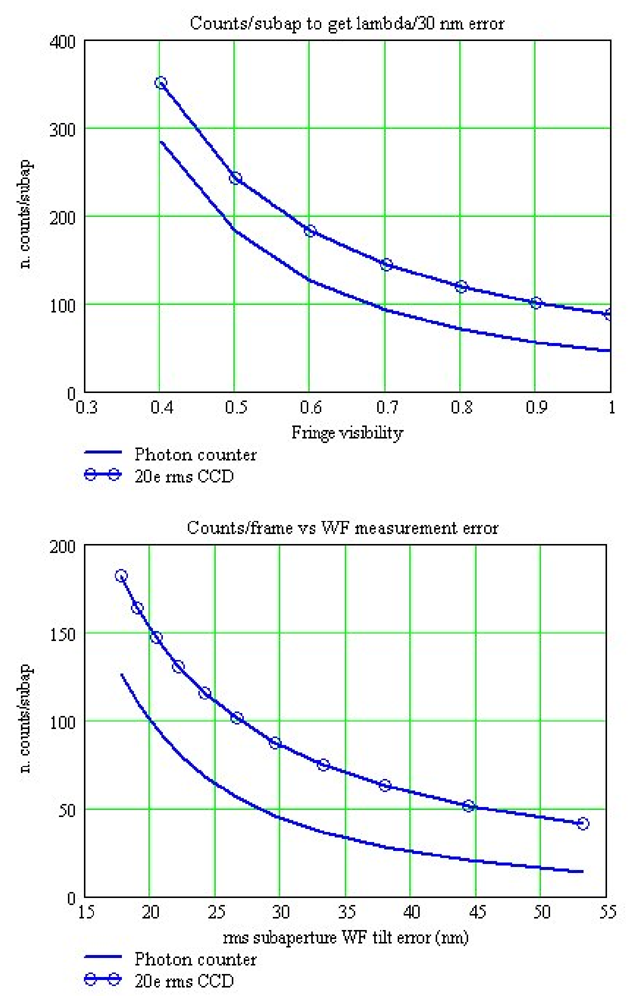


Figure B-2 top: number of counts/subap/frame necessary to make a subaperture tilt estimate rms error of λ/30 (17nm), vs Fringe Visibility. **Bottom:** for a fringe visibility of 0.6, dependence of the subaperture rms tilt error from the number of counts per subaperture (bottom).

Similarly to other wavefront sensors, the contribution of the detector read-out noise to the phase measurement error is very significant. This and the use of pulsed laser favour significantly, in future systems, the nanosecond-gated photon-counting parallel detectors, such as the Single Photon Avalanche Diode Arrays under development at Politecnico of Milan.

Solving *Eq 2* for N, targeting $\sigma_{pd}= \lambda/30$, $\alpha=0.6$, λ =589nm, we get e.g. N=127/frame for read-out noise free detectors, and N=182 for a 20e$^-$ rms read-out noise detector. The dependence of N from the fringe visibility is indicated in the plot Figure 3, bottom.
By projecting a 589nm pulsed laser one can gate the return flux and link it with the altitude in the mesospheric layer. This can be done using a membrane mirror re-imaging, in a similar fashion to what is done with curvature AO systems, as will be explained in section 4. The membrane mirror allows to keep fixed the image size of the propagating beam, and always conjugated to the CCD sensor.

The fringe visibility in the subapertures

The detector samples the 4 sheared parallel beams, produce the signal on the subaperture pixels (4 pixels per axis). The tilt measured in the single subaperture is used to rebuild the wavefront.
In previous LGS-AO systems with shearing interferometers made for the US Navy, it has been experimentally demonstrated that by projecting a polarized laser beam the Rayleigh beacon has a degree of spatial coherence in the subapertures well sufficient to produces fringe visibilities between 0.6 and 0.9 at optimal shear distaces.

Now this value depends on the projection-sensing geometries and the seeing. The modulation depth α,or fringe visibility, equals the value of the total optical system MTF at spatial frequency $s/$ (λ_{las}), using the same notation of section 3.1. The modulation depth α is given by a product of factors:
$\alpha \approx \alpha_{shear} \cdot \alpha_{samp} \cdot \alpha_{opt} \cdot \alpha_{atm}$ where

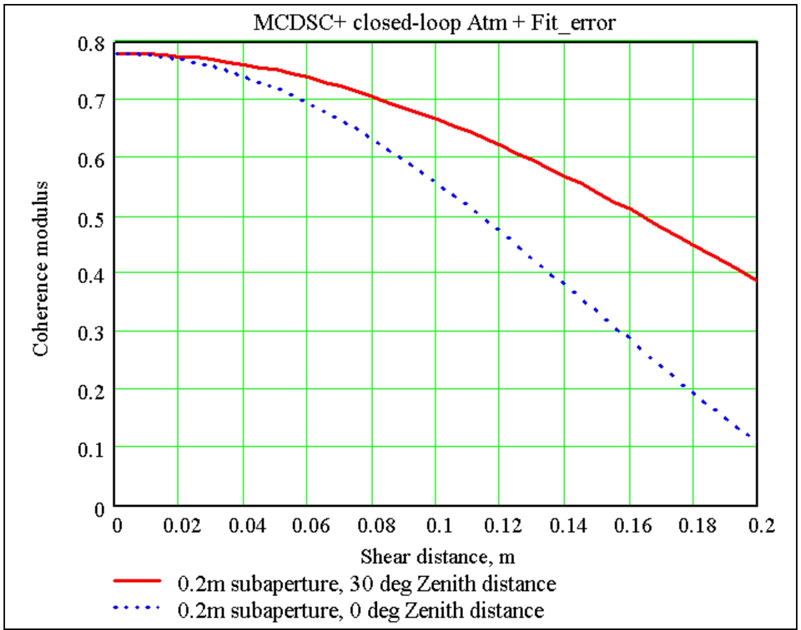


Figure B-3: The fringe visibility α has been computed for a 21cm subaperture on a ground telescope, a closed-loop 20x20 subap system on a 4.2m telescope, including the WF sampling error. The shear values are those projected on the telescope primary mirror. Optimal shear distance values s~0.2d have been reported with LGS-AO, where d=0.21m in our case, hence s~0.04 in the plot above.

α_{shear} is given by the modulus of the complex degree of spatial coherence [see A.S.Marathay, *Elements of Optical Coherence Theory,* John Wiley & Sons Pub., ISBN 0-471-56789-2];
α_{opt} is the system optics MTF value at spatial frequency *s/* (λ_{las}). We disregard this term, as it is ~0.98 for s=0.2d;

α_{atn} is given for Kolmogorov model atmospheres by exp[-3.44$(s/r_o)^{5/3}$]. In closed loop a larger, effective $r_o(\lambda_{las})$ has to be used. This is typically a factor 4 larger than r_o in our case, in closed loop operation. Finally
α_{samp} is given by exp($-\sigma_{fit}^2$), related to the fitting error variance of the wavefront sampling, $\sigma_{fit}^2=0.17(d/r_o)^{5/3}$.

The expected value of *α* for different WFS beam shears is shown in Fig.4. The increasing distance of the scattering layer with Zenith distance is due to the increasing degree of wavefront spatial coherence with distance.

Conclusions

- A novel method for parallel beam sensing of a laser reference beam is proposed
- Numerical analysis is under way
- Once completed succesfully, a feasibility field experiment should be attempted

5 Appendix E: Large deformable mirrors

5.1 *Current status of large deformable mirrors*

ATM technology based on electromagnetic actuators has been proven for 6-8m-class telescopes with the existing Adaptive Secondary Mirror (ASM) for MMT (Mt. Hopkins-Arizona, 64cm-diameter, 2.0mm-thick convex shell, 31mm actuator pitch, Fig. 1). This unit has performed several AO technical and scientific on-sky runs with success (Brusa et al., 2004). Two more adaptive secondary mirrors are under construction for LBT (Mt. Graham-Arizona, 91cm-diameter, 1.7mm-thick concave shell, 31mm actuator pitch, Fig. 2) and a 112cm-diameter unit is in the design phase for VLT (29mm actuator pitch, Fig. 3). In these systems the back structure is built using thick (5-8cm) Zerodur/ULE shells or SiC/Zerodur lighted structure as position reference surface. Gemini is also investigating the possibility of implementing an adaptive secondary mirror on one of their telescopes for a LGS GLAO system. Extension of this technology to mirror diameters between 2 to 4 meters is now being investigated for ELTs in both the US and in Europe.

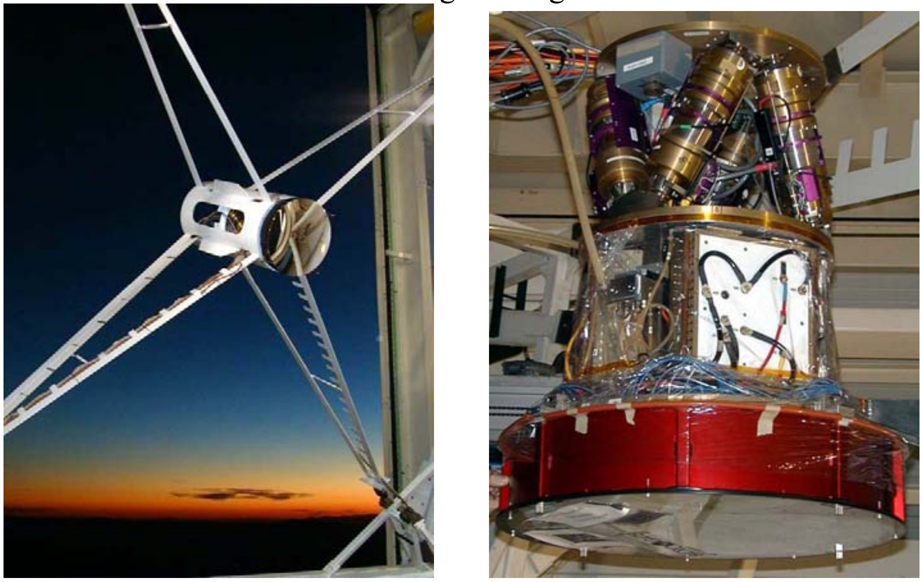


Fig. 1. MMT Adaptive Secondary Mirror unit. Courtesy of CAAO/MMTO.

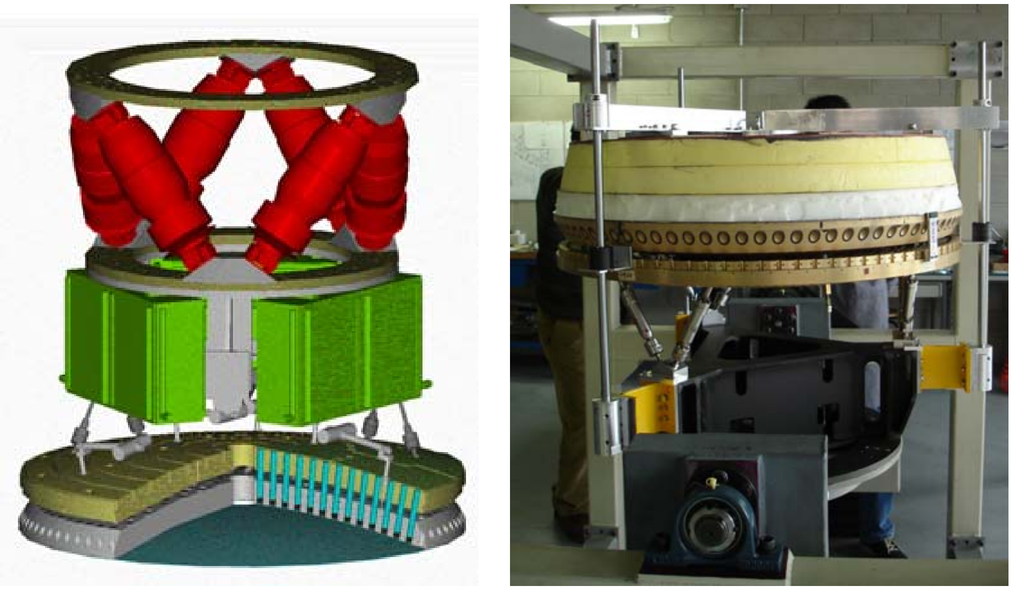


Fig.2 Left: the LBT adaptive secondary unit. Right: the unit in assembly phase. Courtesy of ADS.

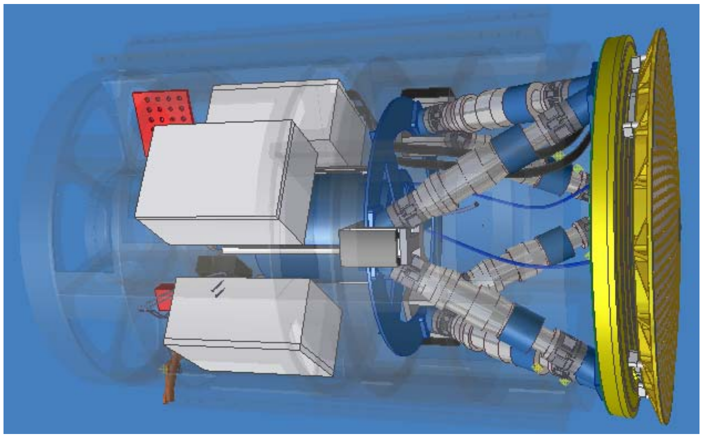


Fig.3. The VLT Adaptive Secondary Mirror. Courtesy of ADS Int.

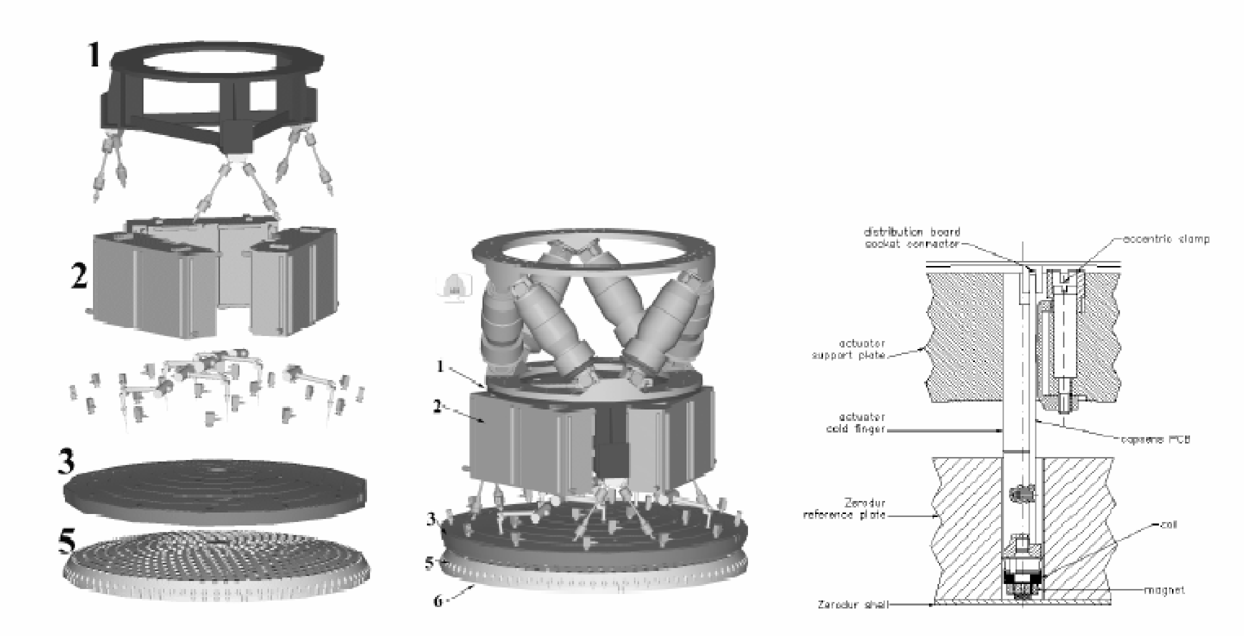


Fig.4: Relevant components of an ASM (LBT unit in the example). See text for a description.

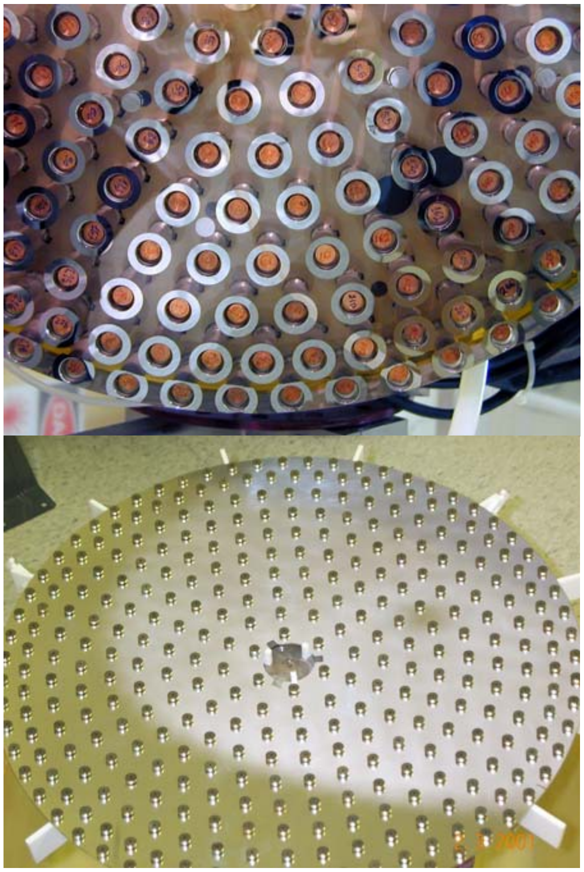


Fig. 5. Left. front surface of reference plate (MMT unit). Capacitive sensor rings are visible around each actuator coil. Right: back surface of the thin shell (MMT unit) with glued magnets and common capacitive sensor armature for reference signal injection.

Fig.4 shows the main six components of an ASM unit. In particular the exploded view of the LBT system is shown:

1. ***an hexapod*** that provides a fine mechanical alignment of the unit;
2. ***cooled boxes for the control electronics***. Each box contains DSP boards for the control and the diagnostics of the electro-magnetic force actuators using the capacitive position sensor feedback. The crates contain also communication boards for fast command transfer (currently ~4Gbit/s) and separate lines for diagnostics. In the VLT system the crates are located above the hexapod in order to reduce the moving mass and increase the first resonant frequency of the unit;
3. ***a cooled aluminum plate (cold plate)*** that provides support and cooling for the actuators. In the VLT system this plate is connected directly to hexapod to increase system stiffness;
4. ***the electro-magnetic force actuators***. A coil is placed on the aluminum cold finger tips that are faced to the corresponding magnets bonded on the back of the thin mirror. On each actuator there is a board providing the contacts to pick the capacitive sensor signal and the related pre-amplification and de-modulation electronics. The analog signals are converted to digital on the DSP boards. The conversion rate is 40-80kHz;
5. ***a thick (50~mm) Zerodur glass plate*** (*reference plate*) with bored holes, attached to the cold plate through a fixed hexapod and a set of astatic levers. This plate is used as a position reference for the thin deformable mirror. The more recent design of VLT ASM considers a 50-60% light-weighted Zerodur or SiC reference plate. The coil cold-fingers, supported by the cold plate, pass through the bored holes on the reference plate to reach the deformable mirror. The mirror position is sensed using the co-located capacitive sensors, monitoring the local gap between the back of the thin shell and the front of the reference plate. The capacitive sensor armatures are obtained with a deposition of an electrical conductive coating ring around each actuator hole on the reference plate side (Fig.5) and the common armature (where the reference signal is injected) given by the coated back surface of the thin shell;
6. ***a deformable (~2mm thick) Zerodur shell*** (*thin mirror*) having magnets glued to its back surface in correspondence of the coils. The front (optical) surface matches the concave (LBT) or convex (MMT/VLT) aspheric figure. The back surface is spherical to match the front surface of the reference plate. The shell has a central hole to which a membrane is attached to provide lateral and in-plane rotational constraint (movements not controlled by actuators) leaving free motion in tip-tilt and piston. When the mirror is not active (coil forces switched off), passive magnets installed in each actuator body push the shell against the reference plate assuring a safe rest position.

The internal fast (40-80kHz) control loop is de-localized, i.e. the actuator force is computed as a function of its own capacitive sensor reading. That avoids centralization for the control law computation and the resulting communication bottleneck that introduces an unacceptable delay in the loop. De-centralized control assures the scalability of the current control strategy when increasing the number of actuators.

However, in order to assure the controllability of shell modes (few hundreds) inside the target bandwidth, the de-centralized scheme requires the introduction of viscous damping in the control loop. In particular the bandwidth of the system is proportional to the ratio between the actuator damping [N/(m/s)] and the mass per actuator. In the MMT system the damping was introduced by the viscosity of the air trapped between the reference plate and the thin shell. The required damping (i.e. bandwidth) is assured with a gap of 40-50μm, giving the corresponding stroke limitation (±20μm) in the MMT system. In the LBT unit electronic damping has been introduced allowing a larger working gap and providing larger bandwidth and stroke (±50μm). Currently the limitation on the electronic damping level is given by the amplification of the high frequency coil-capacitive sensor cross-talk.

The following table summarizes the main parameters of the ASM current developments.

	MMT (6.5m)	**LBT (2x8.4m)**	**VLT (8.2m)**
Project status	on-sky since Nov 2002	in assembly phase	CDR passed. Starting Preliminary Design Phase
No. of actuators	336	672	1170
Diameter	0.640m	0.911m	1.120m
Shell thickness	2.0mm	1.7mm	1.8-2.0mm
Optical figure	convex hyperboloid	concave ellipsoid	convex hyperboloid
Actuator geometry	concentric rings	concentric rings	concentric rings
Actuator pitch	31mm	31mm	29mm
Pitch on M1	31cm	28cm	21cm
Reference plate	50mm-thick Zerodur	50mm-thick Zerodur	Light-weighted Zerodur or SiC
Total mass (without hexapod)	130 kg	250 kg	180 kg
First structural resonance freq.	33 Hz	20 Hz	54 Hz
Settling time	1.7ms	0.7-0.9ms (measured on 45-act proto)	0.5ms (goal spec)
Shell damping	Air trapped in gap	Electronic (control)	Electronic (control)
Working gap and position PtV stroke (AO configuration)	40μm (stroke: 40μm) (limited by required air damping)	70μm (stroke: 100μm) (limited by high freq. disturb. amplification in electronic damping)	>70μm
DSP architecture	16bit integer, 1ALU, 80Mop/s	32bit floating point, 400Mflop/s	32bit floating point, >400MFlop/s
No. of actuators per DSP	2	4 (WF reconstructor on-board)	8
Communication link (AO real-time commands)	Fiber link 160Mbit/s	Fiber Channel 2.1Gbit/s	Fiber Channel 2-4 Gbit/s
Diagnostics link	No	Gbit ethernet	Yes
Capsensor reading	40kHz	70kHz	80kHz
Actuator current drivers	linear	linear	non-linear (under development)
Power dissipated in electronics crates	4.7 W/act	3.8 W/act	0.96 W/act
Power dissipated at actuator level (cold	0.41 W/act	0.21 W/act	0.27 W/act

plate)			
Power dissipation computed for median seeing (r0=12.1cm@V) correcting all the available modes			

5.2 References

Lloyd-Hart, 2000, "***Thermal Performance Enhancement of Adaptive Optics by Use of a Deformable Secondary Mirror***," PASP 112, pp. 264

Riccardi et al., 2005, "***Fitting error analysis for the VLT Deformable Secondary Mirror***," Arcetri Report 2-2005 aka VLT-TRE-OAA-11250-3642 Issue 4, 7 Sep. 2005. http://www.arcetri.astro.it/pubblicazioni/Reports/05/2_05.html

Mcguire et al., 1999, ``***Full-system laboratory testing of the F/15 deformable secondary mirror for the new MMT adaptive optics system***,'' *Proc. SPIE* **3762**, pp. 28-37

Riccardi et al., 2003 ``***Adaptive secondary mirrors for the Large Binocular Telescope***,'' vol. 4839 of *Proc. SPIE*, pp. 721-732

Brusa et al., 2004 `` ***MMT-AO: two years of operation with the first adaptive secondary***,'' vol. 5490 of *Proc. SPIE*, pp. 23-33, 2004

6 Appendix F: Segmentation and high contrast imaging

Segmentation of the primary mirror has important impacts on high contrast imaging since it creates static features in the PSF that will impact the ultimate contrast achievable by differential methods.

- **The influence of gaps size** is to scatter light in the FOV of the coronagraphic PSF. Amount of scattered light goes with the square of the gaps size.
- **The shape of the segments** is also very important since it determines the distribution of light in the field of view.
    - An hexagonal shape creates an array of bright peaks.
    - A petal shape permits to distribute more smoothly the scattered light and thus would be preferred.

In Figure 6-1 are shown two very different segmentation scenarios illustrating the gain one can obtain by changing segments shape, diminishing the gaps size and increasing the segments size.

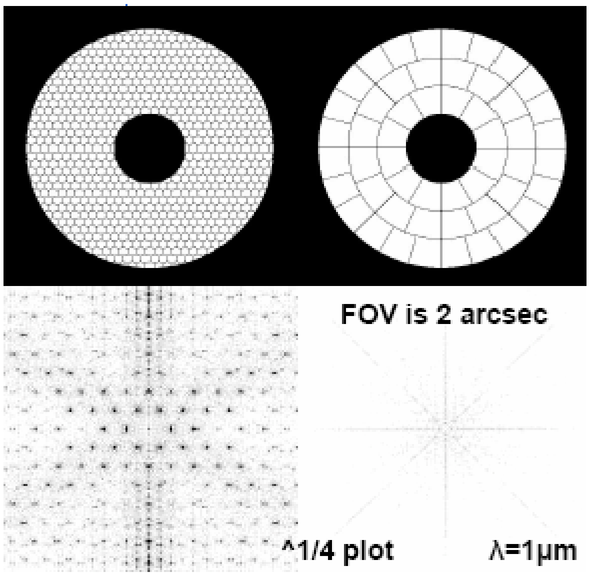


Figure 6-1: Impact on coronagraphic PSF for 2 different segmentation scenarios for a 42-m telescope: left: hexagonal shape, 1.5-m flat to flat, gaps size 10-mm. Maximum of peaks at 10^{-6} to 10^{-5}. Right: 'Petal' or 'keystone', ~5-m size, 2-mm gaps size: more diluted scattered light with maximum $< 10^{-9}$.

- The segments size has also an importance especially when considering differences in reflectivities between individual segments due to ageing and re-coating process (see Figure 6-2). Larger segments permits to concentrate more the scattered light in a smaller area. In any case differences in reflectivity should be minimized and frequent cleaning of mirrors should be foreseen.

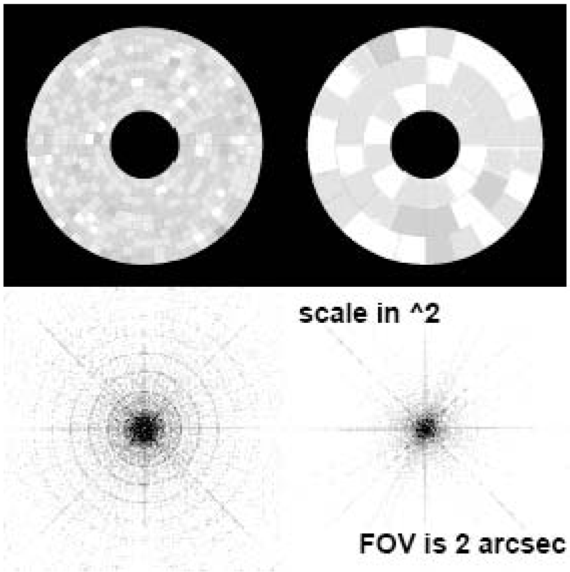


Figure 6-2: Impact on coronagraphic PSF for 2 sizes of segments (‘petal’ shape case), in presence of difference in reflectivity between segments. Left 1.5-m segments size. Right: 5-m.

Special requirements on co-phasing from XAO:

The wave-front control of an ELT includes three main units. Each unit is meant to correct for the different components of the distorted wave-front:

- **adaptive optics**: corrects the wave-front distortions induced by atmospheric turbulence
- **active optics :** corrects the misalignments of the telescope mirrors and their deformation
- **phasing:** corrects the misalignment of the individual segments in the segmented primary

The corresponding control loops run independently and the disentangling of the components is performed using the difference of their temporal and spatial bandwidth.

Each wave-front control unit is affected to some extend by the total wave-front. This fact defines the requirements of one wave-front control unit on another. Thus the partial correction of the wave-front aberration due to the segments misalignment by adaptive optics decreases the wave-front RMS and improves the image quality.

The requirements of AO on phasing system can be split in two principle levels.

- A first level of requirement: in the presence of residual phasing errors the AO system must be able to perform a closed loop on the atmospheric aberrations without saturation of the DM. The expected residual phasing RMS of **50nm** wave-front is usually sufficient.

- A second level requirement is mostly related to XAO case. The partial correction of the wave-front aberration due to the segments misalignment by adaptive optics decreases the wave-front RMS and improves the image quality.

The improvement is effective if :

- The AO wave front sensing unit is sensitive to the segmentation errors (for instance a Pyramid sensor is theoretically better than a Schak-Hartmann).
- The AO correction unit (deformable mirror) is able to correct for them. The latter strictly depend on deformable actuators density and deformable mirror influence function shape.

Besides AO internal requirements, the capability of AO to correct for the segmentation errors depends on two main factors related to the wavefront:

- residual phasing wave-front RMS
- distribution of the RMS over the segmented mirror eigenmodes. The low order eigenmodes can be better corrected by adaptive optics than the high order modes

For extreme contrast (~10^{-9} at 0.1-0.2 arcsec for instance) the *static part* of the residual wave-front after AO correction should be **close to the nanometric level.**

Some parts of the static errors can be corrected by AO (the one in the common optical path), and other parts cannot (the non common path between coronagraph and WFS for instance.). For the latter, a calibration source and pre-correction is needed either using off-sets on the main XAO DM or with an additional active mirror. The co-phasing errors (which are common path) are particular since they occur on the primary and thus no calibration source can be used to calibrate the possible residuals uncorrected by AO.

Precisely, it is not yet completely clear how well the AO system will be able to correct for the co-phasing errors. We however know that:

- The post-focal DM can in principle correct for all the spatial frequencies creating speckles in the corrected area. The remaining dirac-like discontinuities only create speckles far from the center.
- A Pyramid sensor with low modulation can, in principle, identify the speckles due to co-phasing errors in the so-called corrected area (separations less than λ/d where d is the XAO sub-aperture size) and thus a correction phase can be computed. This is because a Pyramid sensor probes directly the focal plane.
- A Shack-Hartmann sensor can only identify a part of the speckles due to co-phasing errors: it tries to correct for the tilt and the discontinuities, but not for the piston errors.

Detailed End-to-End simulations and experiments are needed to address fully this issue.

Hence the requirements on co-phasing error residuals for XAO will depend on the WFS used, and will be of the order of:

- **10-20 nm** (TBC) if an efficient phase sensitive sensor can be used (a Pyramid for instance)
- less than **1-5 nm (TBC)** for very high contrast, if a Shack-Hartmann is used.

7 Appendix G: Existing and planned demonstrators and path finders

7.1 MAD

The Multi-Conjugate Adaptive Optics Demonstrator (MAD) is a prototype GLAO and MCAO system. The aims of MAD include (1) demonstration in the laboratory and on sky the feasibility of different GLAO and MCAO (reconstruction) techniques, (2) initial optimization of theses techniques and explore other innovative approaches through extensive in-lab testing and (3) evaluation of the critical aspects of building and running such an instrument for an ELT or 2nd generation VLT system.

MAD is designed to perform wide Field of View (FoV) adaptive optics correction in K band (2.2 µm) over 2' on the sky by using relatively bright (mV < 14) Natural Guide Stars (NGS). The MCAO correction is implemented by using two Deformable Mirrors (DM); one optically conjugated at the telescope pupil (ground layer turbulence correction) and the second one conjugated at 8.5 km above the telescope aperture for the correction of the field anisoplanatism. Two different wavefront sensors (WFS) are permanently installed on the MAD bench for investigating two different reconstruction techniques: The Star-Oriented MCAO reconstruction will use 3 Multi Shack-Hartmann WFS, while up to 8 Pyramid WFS are available for the Layer Oriented MCAO method. MAD is provided with a 1 arcmin FoV IR camera scanning the 2 arcmin FoV of MAD to evaluate the correction performance in K band. For testing and tuning the MAD system in the laboratory, an atmospheric turbulence simulator (Multi-Atmospheric Phase screens and Stars, MAPS) is installed at the system entrance for mimicking a layered time-evolving atmosphere with Paranal characteristics.

MAD is currently running closed loop GLAO and MCAO in the lab, see also Figure 7-1, and on-sky measurements at the Nasmyth Visitor Focus of the VLT will take place in 2006.

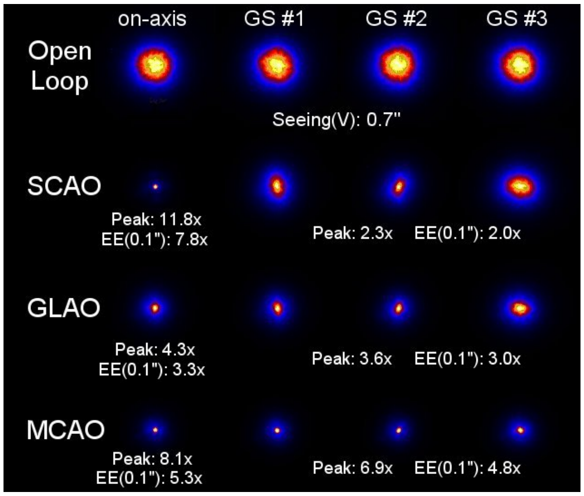


Figure 7-1. Preliminary results obtained with MAD in SCAO, GLAO and MCAO modes on bright reference stars. Results are presented on axis and in three equally spaced directions at the edge of the 45'' radius field.

7.2 ESO’s High-Order Testbench for Adaptive Optics (HOT)

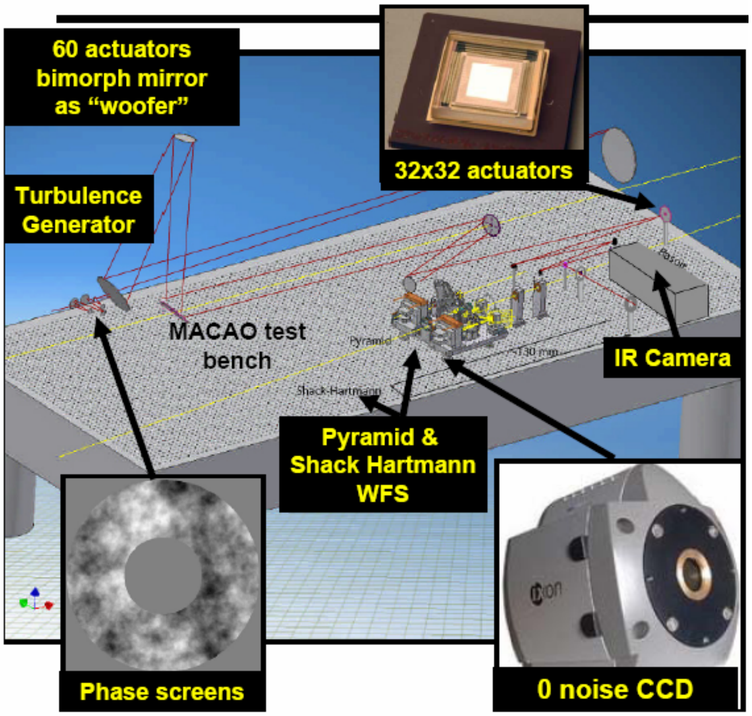


Figure 7-2. Overview of the HOT test bench and the main components, like DM and phase screens.

HOT will implement an XAO system on the MACAO test bench, which includes star and turbulence generator, mimicking realistic conditions at a telescope. The 32x32 actuator MEMS DM, PWS and SHS using the essentially read-noise free L3 CCD60, and the ESO SPARTA real-time-computer (RTC) provide an ideal test bed to study XAO under realistic conditions. Among the large variety of tests, the following topics will be studied:

- System calibration, interaction matrix
- Noise propagation
- Linearity, linear range and cross-talk
- Misregistration. Effects of mismatch between DM and WFS
- Aliasing error. Effects of high spatial frequency turbulence on WFS measurement.
- PSF characteristics & residual aberrations
- Chromatic effects
- Extended object for wavefront sensing.
- Performance (Strehl, sensitivity, robustness)
- Special PWS issues (modulation, diffractive regime, impact of pupil shape)
- Special SHS issues (spatial filtering)
- Woofer/Tweeter concept (2 DMs – 1 WFS, relevant for deformable secondary mirror control with active optics and for OWL)

HOT will be installed at ESO/Garching. ESO will deliver the DM, the optical setup, and the SHS RTC, the University of Durham builds the SHS and Arcetri builds the PWS including its dedicated RTC.

The HOT test bench may be extended to even more complex experiments involving not only XAO and coronagraphy, but also key elements of the instruments themselves:

- Focal WFS: a focal plane sensor as close as possible to the final science detector (or even using it) will permit to improve the ultimate contrast achievable
- Differential imaging: R&D and test of super-polished optics
- IFS: tests of different kind of IFS and related issues (cross talk)
- Polarimetry: perforamance and stability of polarisation modulator.
- New concepts… (FTS for instance…)

7.3 SESAME test bench

SESAME is a multipurpose optical bench at Observatoire de Paris (France), including: sources, atmospheric turbulence, VLT telescope interface and adaptive optics system simulation tools, with several output channels where users can also install their dedicated experiments. It is a very open system and was designed to be a MCAO test facility. SESAME also provides the users with a user room, facilities (network, etc), and a technical support (documentation, staff). SESAME consists of:

- a variety of reference sources for wavefront sensing, with various extensions or position in the field, working in the visible and near IR
- a turbulence generator (using reflective and transmittive synchronized, rotating phase screens)
- calibration sources
- a deformable mirror in the pupil plane, bimorph-type, 31 actuators from CILAS, integrated in a gimbal mount for tip tilt correction and 96-channel analog i/o board, for controlling the DMs
- 4 wavefront sensors in parallel, Shack-Hartmann type, synchronized
- an open control computer based on PC with a user and open software interface for high-level languages (Matlab, IDL, Mathematica, Yorick, etc).

SESAME simulates an 8 meter telescope, with a seeing adjustable from 0.5 to 1.5 arcseconds in the visible. Within a Field of View of ±2 arcminutes in diameter, the turbulence is simulated in a 3D fashion, spread into 3 to 5 layers with variable heights from 0 to 30 km. One or more laser guide stars with a conjugate height between 90 and 300 km can be simulated together with natural guide stars. The temporal evolution of the turbulence—generated by rotating phase screens—is synchronized with the wave-front sensors, in order to control the correlation time τ_o. After the pupil DM, the optical path is divided into 4 channels, several can be equipped with Shack-Hartmann sensors, and the others are open to any experiment. These channels can observe any point of the field. The imaging channel can work in the 0.5 - 1.65 μm domain. These channels have a VLT-like optical interface (f/15, pupil at 16.00 m), see Figure 7-3.

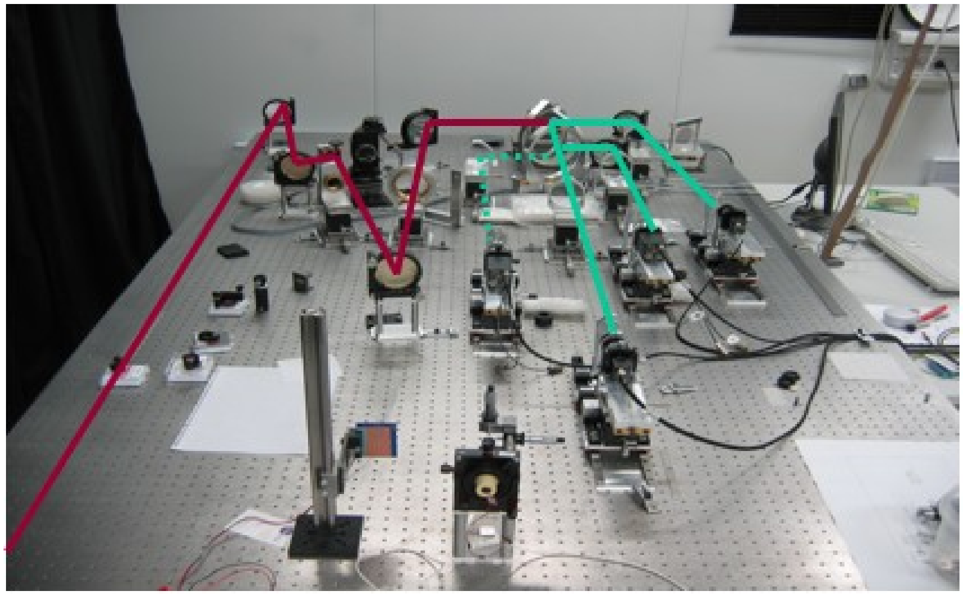


Figure 7-3. Overview of the SESAME test bench. Indicated in red is the upstream optical path down to the pupil DM, in green the downstream path in the 4 parallel channels.

SESAME can be used either with turbulence to simulate the uncompensated atmosphere and the AO corrected atmosphere, or without turbulence, with the DM as a calibrated aberration generator both static as well as dynamic.

SESAME has been in operation at LESIA (Observatoire de Paris) for 6 months now, for the demonstration of the critical items concerning MCAO and MOAO systems. The laboratory demonstrations and validations with SESAME currently in progress, include the wavefront sensor concept, open loop wavefront measurements and operation, WFS linearity, control algorithms, impact of DM performance issues, like open loop operation, reliability, reproducibility, stability and linearity, and calibration issues. SESAME allows for the testing of the MOAO components either in closed loop or in open loop. The core MOAO operation can be tested by using several WFSs in the FoV and controlling dedicated DMs. Furthermore, the GLAO corrected turbulence can be simulated by using the pupil DM itself or directly by removing the ground layer phase screen. Multi WFS operation can be easily tested.

7.4 The ONERA AO Bench BOA

The ONERA AO bench is a fully operational AO bench now used for experimental validation of new AO concepts or devices. BOA has also be tested on sky.

BOA is optimized for visible wavelengths and made of a turbulence generator—which can be either rotating phase screens or a warm-cold air turbulence cell—, a telescope simulator, the AO system and a Princeton visible imaging camera. The BOA system is composed of a 10x10 piezo-stacked array DM (made by CILAS company), which will be updated in the next month with a higher order DM; a fast Tip-Tilt mirror (bandwidth > 2 kHz); a 128x128 Dalsa camera (sampling frequency = 270 Hz) for WFS (which will be replaced by a 128x128 L3CCD @ 500 Hz in the next months); a versatile RTC (developed by Shaktiware) including classical and sophisticated control laws (from simple integrator to optimal Kalman scheme). The imaging arm can be equipped with a 4-quadrant phase mask coronagraph developed by Observatoire de Paris (LESIA-GEPI).

BOA has recently provided a large number of new laboratory results for the development of future AO systems (SPHERE, future MOAO / MCAO systems):

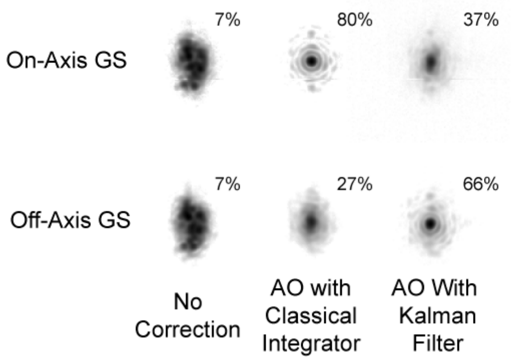


Figure 7-4. Spot of the on axis GS and off axis GS—equivalent to 2 arcmins on a 8 m telescope—at 633 nm. In each case, the WFS is measured on axis but the correction is optimised: on axis for a classical integrator and off axis for the Kalman filter.

- Experimental validation of various control algorithms based on Kalman filtering, like off axis correction, which is a first step towards optimal MCAO/MOAO control laws [Petit et al, CR Physique 6, Jan. 2006] (see Figure 7-4) and filtering of vibrations, which is essential for XAO applications and ELT). First experimental results confirm that more than 90 % of the vibration can be filtered out with a well optimized control law, even for temporal frequencies larger than the AO system bandwidth.

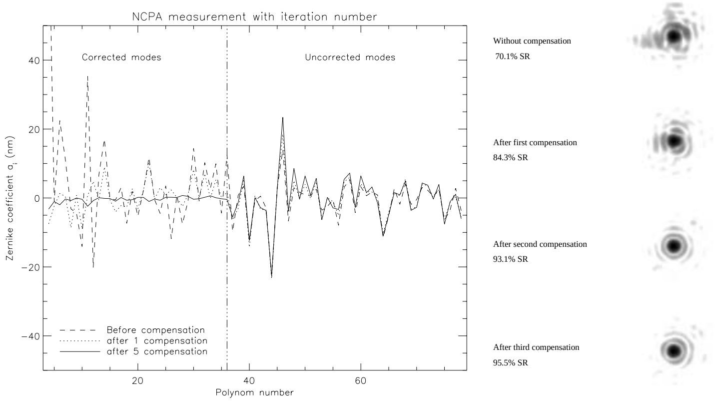


Figure 7-5. Use of a phase diversity algorithm on BOA for non common path aberration pre-compensation. Measured aberration before and after the pre-compensation procedure. An internal SR of 95 % @ 633 nm has been measured on the focal plane image.

- System calibrations like non commonpath aberration measurement and pre-compensation. The measurement algorithm—phase diversity—, as well as the pre-compensation procedures have been optimized to achieve extremely high SR on the bench (larger than 95 % @ 633 nm, equivalent to 20 nm rms error), see Figure 7-5 [Sauvage et al, SPIE, 5903, 2006 (San Diego)]. The second system calibration investigated is AO loop calibration procedure, especially optimization of the interaction matrix measurement.

- New WFS concepts / devices like focal plane filtering for aliasing reduction for Shack Hartmann sensor [Fusco et al, Opt. Lett. June 2006] and new algorithms for centroid estimation (WCOG, Correlation) [Nicolle et al, Opt. Lett. December 2004].
- Test of Coronagraph concepts like the testing of new image post-processing techniques of AO-assisted coronagraphic and differential imaging (see Figure 7-6).

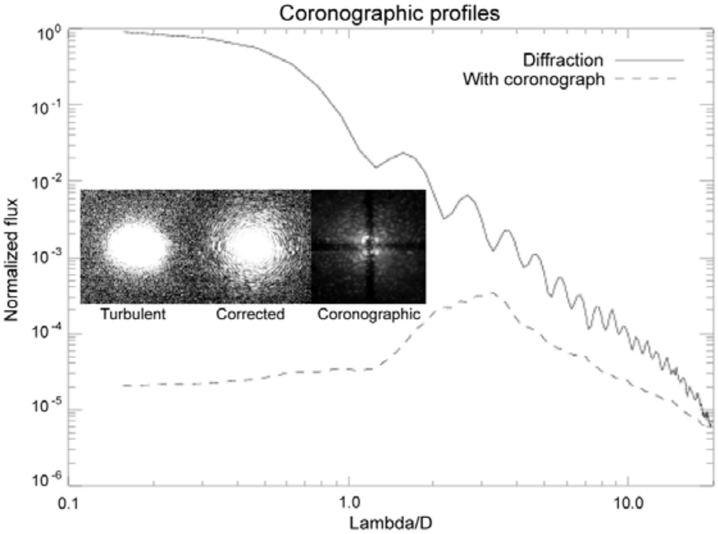


Figure 7-6. Comparison of classical and coronagraphic image (with turbulence). The AO correction is around 85 %.

7.5 The ONERA MCAO Bench HOMER

HOMER (Hartmann-Oriented MCAO Experimental Resource) is a new MCAO bench which is funded by the French Ministry of Defence and will be developed in the next two years at ONERA. The bench is currently under design and its main characteristics will be:

- A turbulence generator, multiple sources (point-like sources or extended object), and at least two rotating phase screens
- Two deformable mirrors (LAOG technology): 8x8 actuators in the pupil and 12x12 actuators in altitude (with an adjustable altitude)
- A large FoV WFS (8x8 sub-apertures) is foreseen with multiple sub-FoV in each sub-aperture.

This bench will be dedicated to the study of GLAO and MCAO performance, calibration and control, WFS concepts (SO, numerical LO, Multiple FoV) and WFS measurement issues (large FoV, large spot motion, extended sources).

The bench integration is planned for a first light in September 2007.

7.6 VLT Adaptive Optics Facility (AOF)

The VLT Adaptive Optics Facility project aims at upgrading one of the existing 8m Unit Telescopes to full Adaptive Optics operation. The project consists of a multiple elements upgrade: replacement of the existing M2 unit by a high-order Adaptive Secondary, installation of a 4 laser guide stars Facility completed by an adapted instrument park. The 4LGSF will allow large FoV correction and enhanced sky coverage, while the use of CW

Fibre lasers will allow for demonstration of this technique which may also be proposed for ELT systems in pulsed format. A common Real-Time Controller platform, SPARTA is being developed which will serve the AOF AO modules, with its suite of built in routines and standardized interface controllers. Two AO-assisted instruments, each fitted with its own AO module are mounted on the opposite Nasmyth platforms: GALACSI is the AO module for MUSE, a visible light integral field spectrograph with a 1'x1' Field of View and GRAAL the AO module for HAWK-I, a large field imager with a 7.5'x7.5' FoV. Both instruments will be using GLAO to provide a moderate correction over the large field of view and LTAO for high strehl on-axis for MUSE Narrow field mode. An integrated test facility, ASSIST will allow functional testing of both the AO systems and the Deformable Secondary Mirror.

Apart from delivering a fully integrated Adaptive Optics Facility, each of the elements is a precursor for the E-ELT, by demonstrating the viability of the individual components and the optimized operation of the integrated facility. The VLT AOF has been approved and entered its Preliminary Design Phase at the beginning of 2006.

7.7 SPHERE

The ESO Planet Finder 'SPHERE' is a 2nd generation instrument for the VLT dedicated to the direct detection of extrasolar giant planets. SPHERE is the most demanding AO-assisted instrument currently under construction due to its high requirements in terms of achieved contrast. SPHERE aims at being able to characterize planets with a contrast up to 10-7 between the host star and the companion planet.

Several techniques are applied to enhance the detectability of extrasolar planets: The eXtreme AO system of extremely high order will provide the required image quality, with typical Strehl Ratios of 90% in the near-infrared. The contrast will be further enhanced by coronagraphy, suppressing most of the light of the host star. Differential imaging, both spectral as well as in polarization, will be used to further enhance the contrast between host stars and planets, especially in the case of giant planets with presence of methane or by observing the star reflected emission, strongly polarized by the atmosphere of the planet.

With the requirements on the AO system being considerably higher than for any other application, both in terms of required hardware (deformable mirror with a large number of actuators, low-noise fast-readout wavefront sensor detector, etc.) as well as in terms of real-time control, the SPHERE is an excellent pre-cursor for AO systems for ELTs. The AO system for the SPHERE will be of comparable complexity as the first light AO systems for a 30-60 meter ELT, while it will also be a precursor for near-unity Strehl Ratio regime and a demonstrator for the XAO concept. SPHERE enters its Preliminary Design Phase in early 2006, with first light expected by mid-2010.

7.8 WHT Past, Current and Planned demonstrators

The 4.2m William Herschel Telescope, one of the Isaac Newton Group of Telescopes (ING), has two Nasmyth platforms: GRACE, a controlled environment containing the NAOMI adaptive optics facility and associated instruments, and GHRIL, a general experimental laboratory containing a large optical bench and separate electronics room. GHRIL has been the location of a number of experiments concerned with laser guide stars (all using a 5W pulsed Rayleigh laser):

- Experiments on shared-optics launch effects relevant to parallel-beam laser concepts. These include measurements of scattering and fluorescence effects and are described in [Clark et al., SPIE 4839, 516-523, 2003].
- The PIGS prototype on-sky tests. This was a collaboration between MPIA, Arcetri, Durham and ING.
- An experimental GLAO test using a low-altitude laser beacon. The equipment for this is described in [Morris et al., SPIE 5490, 891-904, 2004].

The latter system is being developed into a test bench for three novel ELT-directed laser guide star concepts: the Durham SPLASH and P4 concepts, and the ESO shearing interferometer concept. This new test bench is called the Rayleigh Technical Demonstrator (RTD) and the joint experiments are known as CALDO [Bonaccini et al, SPIE 5490: 1315-1326, 2004]. The equipment which will be available includes a 97-actuator Xinetics mirror, FPGA-based control system, shuttered CCD, APD array, and L3 CCDs.

The GRACE platform has also been used for ELT-directed experiments. In this case the NAOMI segmented mirror was used by the Arcetri group [Esposito et al, Opt Lett, 2005] to test pyramid-WFS-based segment co-phasing on-sky. A new version of this instrument for permanent installation in GRACE has now been funded by the UK (PPARC).

A proposal is being developed in the context of FP7 to enhance the GHRIL platform facilities for further use as a test bench for ELT technologies including, but not limited to, “classical” and novel laser guide star concepts, such as those described in section 4.

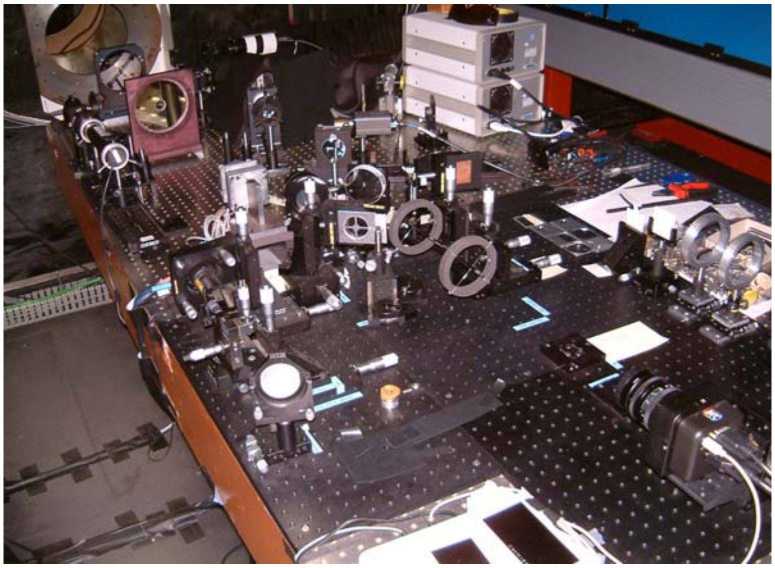


Figure 7-7. PIGS experimental setup in WHT/GHRIL, courtesy Stefan Kellner, MPIA