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Article *in* Proceedings of the International Astronomical Union · November 2006
DOI: 10.1017/S1743921306000287

Scientific Requirements for Extremely Large Telescopes
Proceedings IAU Symposium No. 232, 2005
P. Whitelock, M. Dennefeld & B. Leibundgut, eds.

doi:10.1017/S1743921306000287

Adaptive optics for Extremely Large Telescopes

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Abstract. Adaptive Optics (AO) will be essential for accomplishing many, if not most, of the science objectives currently planned for Extremely Large Telescopes including GMT, OWL, and TMT. AO will be needed to support a range of instrumentation, including near infrared (IR) imagers and spectrometers, mid IR imagers and spectrometers, "planet finding" instrumentation and wide-field optical spectrographs. Multiple advanced AO systems, utilizing the full range of concepts currently under development, will need to be combined into an integrated architecture to meet a broad range of requirements for field-of-view, spatial resolution and spectral bandpass.

In this paper, we describe several of the possible options for these systems and outline the range of issues, trade studies and component development activities which must be addressed. Some of these challenges include very high-order, large-stroke wavefront correction, tip-tilt sensing with faint natural guide stars to maximize sky coverage, laser guide star wavefront sensing on a very large aperture and achieving extremely high contrast ratios for the detection of extra-solar planet and other faint companions of nearby bright stars.

Keywords. Adaptive optics, high angular resolution.

1. Introduction

The power of Adaptive Optics (AO) has been successfully demonstrated on all 8–10 m telescopes and the astronomical community is now convinced that AO is an essential element of all future Extremely Large Telescopes (ELTs) currently under study in both America and in Europe. Most of the Adaptive Optics systems now in operation are based upon the so-called Single Conjugate Adaptive Optics (SCAO) concept illustrated in Figure 1.

AO systems developed over the last 30 years have aimed at providing diffraction limited images for the telescopes, usually for relatively bright sources ($m_V < 13$–14) and over a Field of View (FoV) limited to the so-called anisoplanatic angle (typically $30''$ in the near

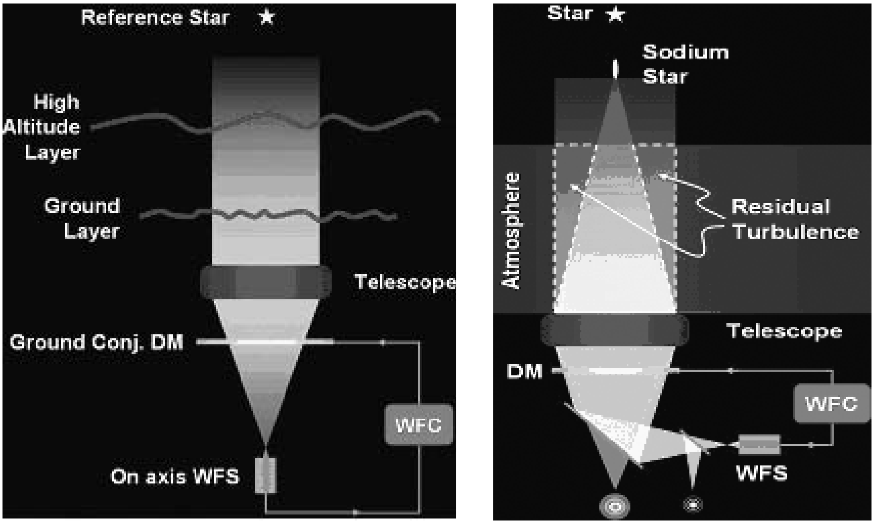

Figure 1. Left: Single Conjugate Adaptive Optics (SCAO) concept, Right: Laser SCAO with focus anisoplanatism

IR and 2″ in the visible). The required reference star brightness and the limited corrected FoV have dramatically constrained "sky coverage," defined as the part of the sky where the correction was possible, thereby restricting the application of AO to stellar astronomy. To increase the sky coverage, the concept of Laser Guide Star (LGS) was introduced by Foy & Labeyrie (1985), but the corrected FoV was still limited with the addition of a new limitation: focus anisoplanatism or the cone effect (Figure 1). Focus anisoplanatism, generally acceptable for 8–10 m telescopes, becomes a dramatic limitation for ELTs. The concept of tomography using several LGSs for wavefront sensing was proposed by Tallon & Foy (1990) and the concept of Multi-Conjugate Adaptive Optics (MCAO) using several Deformable Mirrors (DM) conjugated to different atmospheric altitudes was suggested to increase the corrected FoV by Beckers (1988), Ellerbroek (1994), Johnston & Welsh (1994) and Ragazzoni *et al.* (1999) (Figure 2).

MCAO with tomographic LGS wavefront sensing seems to be ideal, apart from the sky coverage limitation still imposed by the need for Natural Guide Star (NGS) measurements of atmospheric tip/tilt and tilt anisoplanatism. In reality, the complexity and cost of MCAO increases rapidly with performance requirements. The number of DMs depends upon the corrected FoV and on the desired residual RMS phase error as described by Tokovinin *et al.* (2000). The required number, type (Sodium or Rayleigh) and on-sky power of the LGS also depend on the residual phase error. As an example, the GEMINI MCAO system, optimized for a NIR corrected FoV of 2′, uses 3 DMs, 5 LGSs and 3 NGSs, as described further in Ellerbroek *et al.* (2003). Therefore MCAO is usually proposed for a relatively small corrected FoV (1–2′) when diffraction limited optical performance is required (studies of crowded fields and stellar populations, for example).

Although MCAO promises to provide attractive performance, some science cases (including extra-galactic observations and cosmology) require larger FoVs with "reasonable" partial AO correction. The metric used in this case is the Ensquared Energy (EE) in a pixel which may be as big as 50–100 mas. It had been known for some time that a strong turbulence layer usually exists close to the ground, called a ground or boundary layer. Example measurements may be found in Vernin & Muñoz-Tuñón (1994). By itself, this layer permits a large anisoplanatic angle. Models of the vertical distribution of

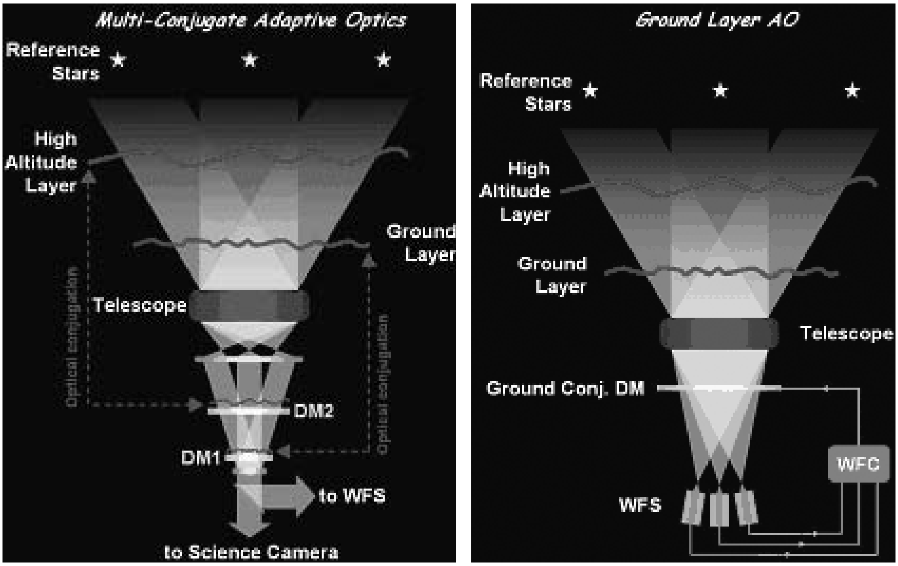

Figure 2. Left: Multi Conjugate Adaptive Optics (MCAO) concept, Right: Ground Layer Adaptive Optics (GLAO) concept

atmospheric turbulence structure constant, $C_n^2(h)$, at astronomical sites have been obtained by discretizing balloon soundings collected at Paranal and Cerro Pachon by Le Louarn *et al.* (2000) and Rigaut (2002), respectively, and a study of a portable turbulence profiler MASS has been conducted by Tokovinin & Kornilov (2002). The latter was motivated by MCAO design activities, which call for better statistical knowledge of the $C_n^2(h)$ profiles to determine the best conjugation altitude for the MCAO DMs and the altitude variability of the main turbulent layers.

¿From this tomographic analysis, the potential value of an AO system combining wavefronts from multiple lines of sight onto one DM conjugated near the ground was identified by Rigaut (2002). This concept is now called Ground Layer Adaptive Optics, or GLAO (Figure 2). It aims at improving the seeing over a field of view much larger than the isoplanatic angle, with uniform image quality over the entire corrected field.

MASS has now been tested on sky and has provided its first high altitude $C_n^2(h)$ profiles as described by Kornilov *et al.* (2003). MASS does not detect the turbulent boundary layer because it is a scintillation-based technique and consequently MASS measurements have been combined with DIMM measurements to determine the full atmospheric turbulence profile. Finally, because the altitude resolution of MASS is too poor to accurately determine the exact structure of the boundary layer over the first two kilometres for GLAO design studies, the SLOpe Detection and Ranging system (SLODAR) has been developed for this purpose Wilson *et al.* 2004. The combination of DIMM-MASS and SLODAR is ideal for long-term statistical study of the turbulence profile at a given site and more specifically for the determination of the performance of a GLAO system.

Preliminary measurements made at Paranal in 2003 with MASS-DIMM show that the boundary layer contributes at least 60% of the total turbulence. More recent measurements of the $C_n^2(h)$ profile made using both the SLODAR and DIMM-MASS have shown that 60% of the turbulence is located within the first 2 km and that 40% of the turbulence is concentrated at a height of about 200m (Figure 3). Several GLAO systems are now being designed for 8 m class telescopes on the basis of these measurements as described in Le Louarn & Hubin (2006) and Hubin *et al.* (2006).

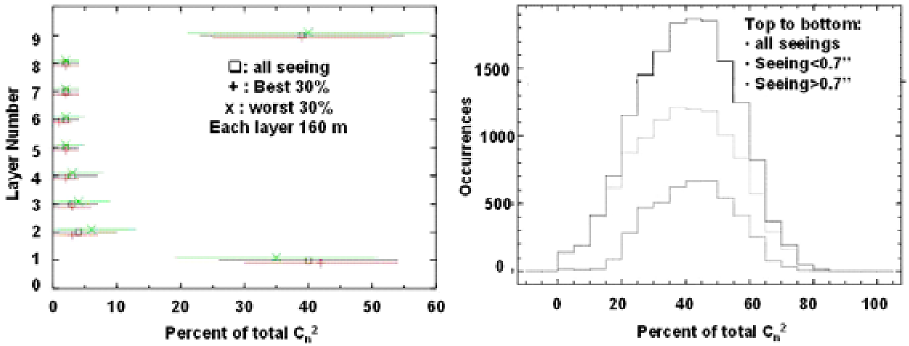

Figure 3. Right: Preliminary turbulence profile statistics; Left: Fraction of turbulence located at 200 m (Paranal)

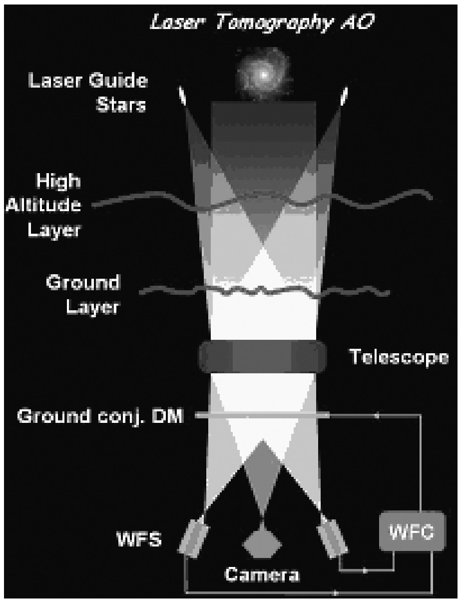

Figure 4. Laser Tomography Adaptive Optics (LTAO) concept

As discussed previously, GLAO is essentially a seeing reducer for a large FoV and the correction provided therefore remains relatively modest. To improve this correction, one can reduce the diameter of the LGS constellation to probe only the column of turbulence above the telescope and avoid the usual cone effect that would otherwise degrade the measurement of turbulence at a range of 8–10 km (Figure 4). The on-axis wavefront can then be reconstructed and applied to one deformable mirror conjugated to the ground or a low altitude, see for example Le Louarn & Hubin (2005). This concept, called Laser Tomography Adaptive Optics (LTAO), is able to provide a useful degree of atmospheric turbulence compensation at short wavelength with reasonable sky coverage, although a Natural Guide Star is still required to measure atmospheric tip/tilt. The LTAO simplification compared with MCAO is the requirement for only a single deformable mirror.

Another highlight science case for an ELT is the investigation of “The First Galaxies and the Ionization State of the early Universe.” This case aims to peer into the “Dark Ages of the Universe,” when the universe was re-ionized by the UV flux emitted by the

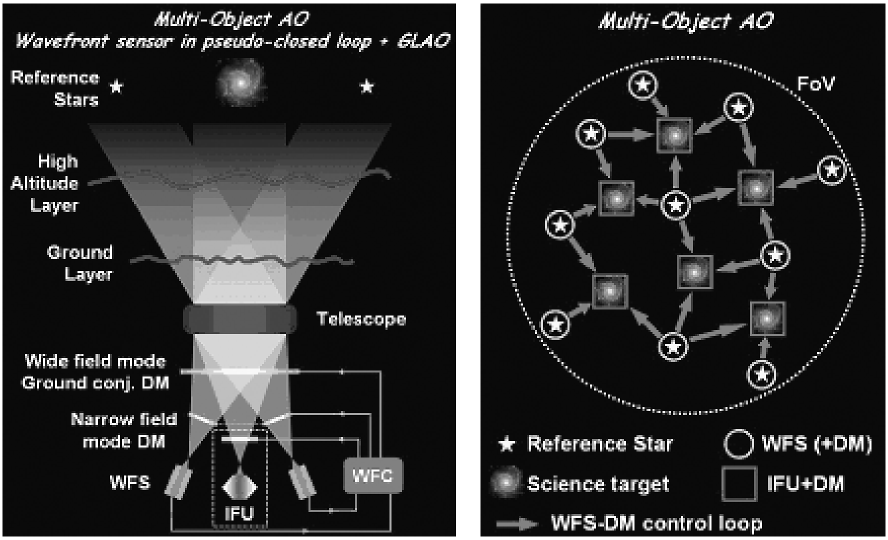

Figure 5. Left: Possible Multi-Object Adaptive Optics Concept combined with Ground Layer Adaptive Optics first stage correction, Right: Focal plane of a LTAO based instrument.

first sources of light. Recent observations of the high redshift universe suggest that stars and galaxies started to form and to assemble in the early redshift range of $z = 7$–15. Understanding this key epoch is of paramount importance and requires "multi-localized correction" over a large FoV (5–10′). As with GLAO, the metric is the Ensquared Energy in a pixel with a size of 50–100 mas.

The underlying adaptive optics concept – namely Multi-Object Adaptive Optics (MOAO) or Distributed Adaptive Optics (Figure 5) – is therefore to separately correct atmospheric turbulence in selected directions on the sky for individual science targets. This can be accomplished by paving the focal plane with WFS units aimed in the directions of the reference sources for local determination of the turbulent wavefront and with separate Micro Deformable Mirrors (MEMS) in each of the science channels. In this approach, the adaptive optics components operate essentially in open loop, as the wavefront sensors do not see the correction applied by the deformable mirror and do not operate around null. This concept requires wavefront sensors with a large linear dynamic range and deformable mirrors with high linearity and absolute accuracy as described in Hammer *et al.* (2002).

Alternative MOAO concepts are being considered to relax the requirements on WFS dynamic range and linearity by adding local deformable mirror for each wavefront sensor. Combining the MOAO and GLAO concepts seems a possible approach to reducing the stroke requirements for the local Micro Deformable Mirrors (Figure 5).

Direct detection and spectral characterization of exo-planets is one of the most exciting domains of present astronomy. Several "Planet Finder" systems are now under design for ground-based 8–10 m class telescopes, see for example Fusco *et al.* (2005) or Macintosh *et al.* (2004). These systems should allow astronomers to detect Jovian-like planet in a few years around stars of ages <1 Gyr. Extremely Large Telescopes are naturally well-suited for this exciting application, thanks to the gain in spatial resolution that could be provided by Extreme Adaptive Optics (XAO) systems coupled with high contrast imaging techniques such as coronagraphy and/or differential imaging.

The metric used for such systems is the contrast between the central star and the companion planet, typically 10^{-6}–10^{-7} for gas giant planets and down to 10^{-10} for rocky

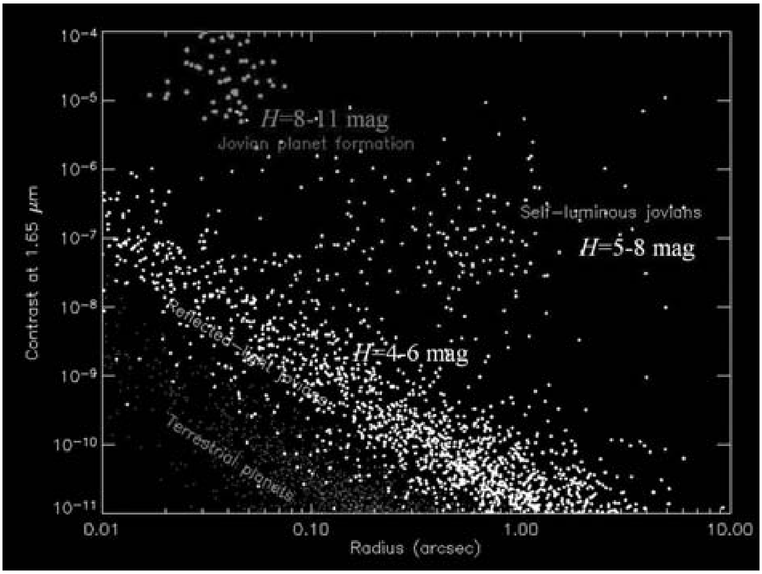

Figure 6. Left: Discovery Space for planets with sufficient contrast and separation from their parent stars.

planets. Figure 6 shows the "discovery space" for sample companion detection systems. A key element of such an instrument is the XAO system with a very high number of degrees of freedom and a high temporal update rate. The reference star is usually bright and on axis, with a few arcsec corrected FoV. XAO is essentially an extension of the SCAO concept, with a factor of about 10 more actuators and a factor of 3–6 higher temporal frequency. In addition, the wavefront sensor is optimized to minimize the halo in the vicinity of the bright star – for instance, by applying spatial filtering for a Shack Hartmann WFS or by using a Pyramid WFS as described in Verinaud *et al.* (2005).

2. Performance of natural guide star adaptive optics on ELTs

Several types of the above Adaptive Optics systems have been simulated using only Natural Guide Stars (NGS) for the case of a 100 m telescope. These systems were based upon wavefront sensors with 97×97 sub-apertures and a corresponding 98×98 large deformable mirror, both with square geometries. The (visible wavelength) wavefront sensors (WFS) are based upon zero read-out noise detectors, for instance the L3-based CCDs technology from E2V. The maximum frame rate considered is 500 Hz and turbulence profiles with $0.53''$ and $1.0''$ seeing have been simulated.

2.1. *Single Conjugate Adaptive Optics*

In this concept, the single WFS is used to measure the wavefront coming from a single on-axis natural guide star (NGS), and a single ground conjugated deformable mirror is used to correct the turbulence. Figure 7 plots the Strehl ratio versus the received photon flux from the AO reference star and Figure 8 provides the Strehl ratio loss in case the reference star is off-axis. We can see that without including an error budget for implementation errors, Strehl ratios of about 60% are achieved in K band for the case of $0.53''$ seeing and that half this performance is lost at an angle of about $20''$ off-axis from the guide star. The peak, on-axis Strehl ratio is determined by the number of DM actuators simulated (here 98×98 for technological reasons) and the update frequency of

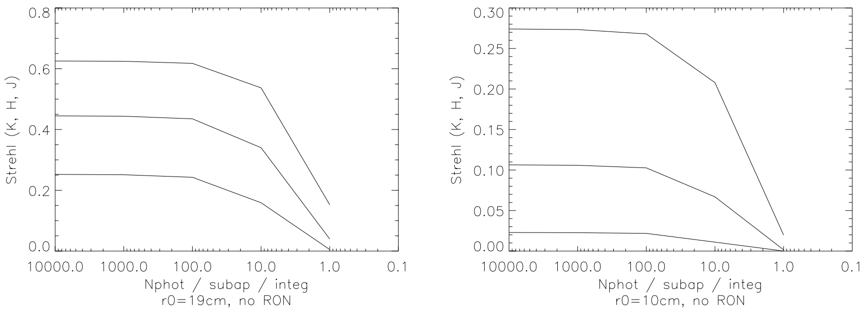

Figure 7. SCAO On-axis Strehl ratio (top to bottom: K, H, J) versus number of photons detected by the WFS. Left: $0.53''$ Right: $1''$ seeing.

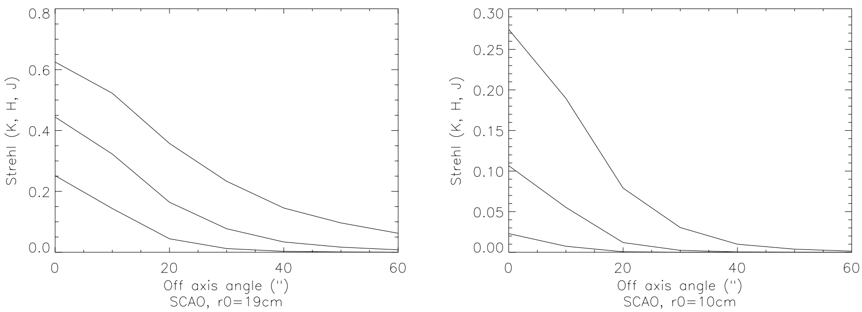

Figure 8. SCAO Strehl ratio loss due to anisoplanatism effect (top to bottom: K, H, J). Left: $0.53''$ Right: $1''$ seeing.

the correction. The limiting magnitude is set by the photon noise in the wavefront sensor centroiding process. Note that a 50 m telescope with the same number of actuators (and the same deformable mirror diameter for a given actuator spacing) will be able to reach Strehls of 80% in K band under median seeing conditions.

2.2. *Ground Layer Adaptive Optics*

The aim of GLAO is to provide a uniform seeing improvement over wide field of view, here $6'$ in diameter. Therefore, the proper metric is not Strehl ratio, but the ensquared energy collected in a pixel, here arbitrarily chosen to be 50 mas in width. In this approach, several NGSs are used as reference stars for wavefront sensing and their measurements are averaged to compute deformable mirror commands that provide uniform correction over the field. The deformable mirror is conjugated to the ground and is the same as that used for SCAO.

Figure 9 provides the Ensquared Energy gain versus the reference star flux. Figure 10 illustrates the typical shape of the corrected and uncorrected PSFs. We can see that significant gains (a factor of about 4) are obtained in K band for the case of $0.5''$ seeing. Even in the J-band a gain of a factor of 2 is achieved. Of course, the gains drop significantly for poorer seeing. In this case the main limitation is due to the $C_n^2(h)$ turbulence profile of the atmosphere and marginally due to the limited number of DM actuators.

2.3. *Multi Conjugate Adaptive Optics*

In this AO system, multiple NGSs are used to tomographically reconstruct the wavefront at several (here 2) altitudes, corresponding to the conjugation height of 2 deformable

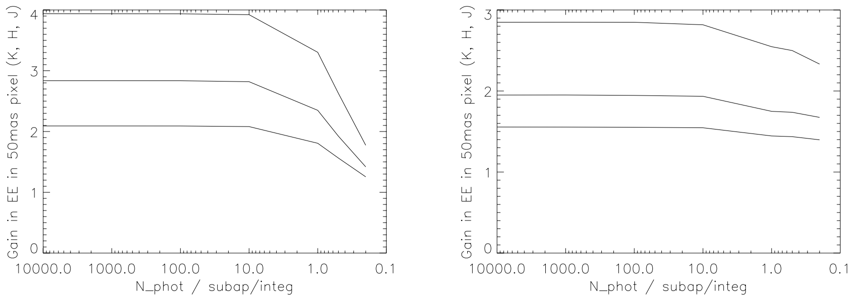

Figure 9. GLAO Ensquared Energy gain compared to seeing in 50mas pixel (top to bottom K, H, J bands). Left: $0.53''$, Right: $1''$ seeing. 6 NGSs are used in a $6'$ diameter asterism.

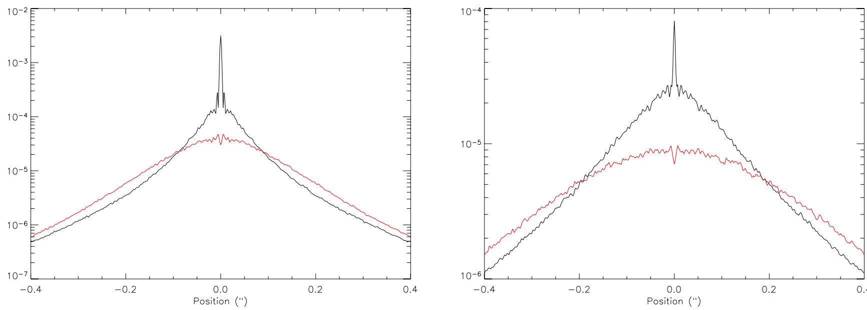

Figure 10. On-axis K band point spread function. The top curve is GLAO corrected, and the bottom curve is the seeing limited case. Wavefront sensing is performed with 6 NGSs in a $6'$ FoV. Left: $0.53''$, Right: $1''$ seeing. The signal level is 10ph/WFS/subap/NGS, corresponding to an asterism of 15 magnitude stars.

mirrors (here 0 and 8 km). Both deformable mirrors have 98×98 actuators although the high altitude DM is larger in size. The goal is to provide a uniform diffraction limited correction over a moderately large field of view (here $1'$ in diameter).

Figure 11 provides the Strehl ratio versus position in the FoV in the case of the good seeing model (0.53"), assuming that 6 uniformly distributed NGSs are available for wavefront sensing. Fifth and seventeenth magnitude guide stars have been simulated and we can see that fairly uniform Strehl ratios can be achieved. For the bright star case the performance is limited by the tomographic error, which is determined by the number of NGSs within a given FoV and the number of DMs. For the faint star case, the performance is limited by the brightness of the star constellation. Extrapolation to higher Strehl ratios, or to correction at shorter wavelengths, would require the implementation of laser guide stars.

2.4. *Multi Object Adaptive Optics*

In this concept, wavefront sensor "buttons" are used to sense the wavefront in the direction of guide stars present in the science field. IFU "buttons" are equipped with 100x100 actuators deformable mirrors, which are used to correct the turbulence in the direction of the astronomical objects. (Although not modelled in the linear performance simulations, we assumed that MOAO will benefit from a first stage of GLAO correction over $6'$ FoV to relax the requirements on the linearity and absolute accuracy of the "button"

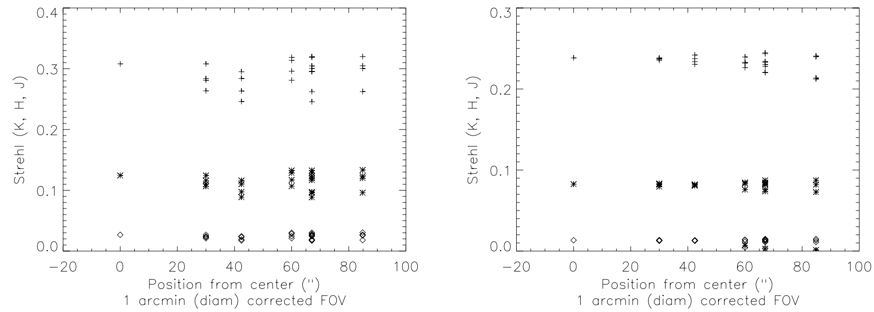

Figure 11. MCAO K, H, J band Strehls (top to bottom) versus FoV position for a constellation of 6 NGSs (3 in a $2'$ FoV and 3 in a $6'$ FoV) with 0.53" seeing. Left: 5th magnitude NGSs, Right:17th magnitude NGSs.

components). For MOAO performance estimation, we used actual astronomical fields with their available reference stars:

- Field 0: UKIDSS-XMM-LSS(center)
- Field 1: UDF (center)
- Field 2: COSMOS (center)
- Field 3: CFHTLS-d1 (center)
- Field 4: AC114 (center)
- Field 5: Abell 1689 (center)

Figure 12 provides the Ensquared Energy values and the gain compared to seeing in H-band. These results show that the performance of MOAO is superior to GLAO due to the optimization of the discontinuous correction in discrete directions, a limitation which is acceptable for observations of distributed galaxies. In return, MOAO is much more complex to implement than GLAO and relies on the presently undemonstrated concept of open loop AO.

It is important to note that even when the EE gain compared to seeing is "high," the absolute enclosed energy in a 50 mas pixel is relatively small, of the order of 10% at best. To overcome this limitation, Laser guide stars should be employed and a higher density of actuators may be required.

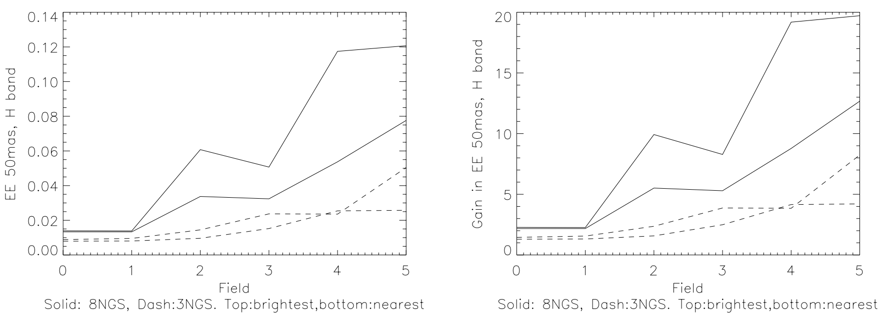

Figure 12. MOAO Ensquared Energy and Ensquared Energy gain relative to seeing for $1''$ seeing and several actual astronomical fields for the case of 50mas pixels and H band observations. Solid line: 8 NGSs, Dashed lines: 3 NGSs Top line: 8 (resp. 3) brightest NGSs, Bottom line: 8 (resp 3) nearest NGSs.

3. Adaptive Optics performance using laser guide stars

3.1. *Performance trends with aperture diameter*

Although the LGS cone effect may be largely eliminated through the use of multiple laser guide stars and tomographic wavefront reconstruction, the theoretical performance of LGS MCAO or LTAO still degrades slowly with increasing telescope aperture diameter. This defect occurs because 3-dimensional distributions of atmospheric turbulence exist which are undetectable to tip/tilt-removed LGS WFS measurements, but still introduce wavefront aberrations for sources at infinity. Examples of these "null modes" include pairs of quadratic aberrations in a 2-layer atmosphere, triplets of cubic aberrations in a 3-layer atmosphere, and so on. The magnitude of these modes grows with increasing aperture diameter for a Kolmogorov turbulence spectrum, but the effect is not catastrophic for typical atmospheric turbulence profiles at good astronomical sites.

The resulting trends in LGS MCAO performance with increasing aperture diameter are illustrated in Table 1 below for a representative set of system design parameters. This table summarizes J, H, and K band Strehl ratios at five points within a (square) $20''$ FoV for a LGS MCAO system with two DMs conjugated to ranges of 0 and 12 km, and 6 sodium LGS in an asterim consisting of a pentagon and one on-axis guidestar. The results were computed for a "typical" MASS/DIMM turbulence profile recorded at a Chilean site with $r_0 = 0.183$m and $\theta_0 = 2.02''$ at a wavelength of 0.5 μm. ELT aperture diameters of 20, 30, 50, and 100 meters were simulated, with a DM interactuator pitch (at the primary mirror) of 0.5 m in the first three cases and 1.0 m in the last (Increasing the actuator pitch for the 100 m ELT reflects both our assessment of technical feasibility and the limitations of our simulation codes). The diameter of the LGS asterism was also varied with the ELT aperture diameter to fully sample the DM at the 12 km conjugate.

Inspection of Table 1 reveals that LGS MCAO performance is relatively uniform across the $20''$ FoV for all 4 ELT aperture diameters, and that Strehl ratios reduce very slowly as the aperture diameter increases from 20 m to 50 m. Separate calculations using standard scaling laws for DM fitting error demonstrate that most of the reduction in performance for the case of a 100 m ELT is due to the increased interactuator pitch. A relatively simple LGS MCAO system consisting of 6 guide stars and 2 DMs is consequently of benefit to any ELT currently under discussion, assuming of course that the implementation challenges can be overcome.

D, m	20			30			50			100		
Ast. radius, arc sec	25			35			50			100		
Actuator pitch, m	0.5			0.5			0.5			1.0		
$(0'',0'')$	0.72	0.83	0.90	0.69	0.81	0.89	0.61	0.75	0.85	0.20	0.37	0.56
$(3.3'',0'')$	0.71	0.82	0.90	0.68	0.80	0.88	0.60	0.74	0.84	0.20	0.37	0.56
$(3.3'',3.3'')$	0.70	0.83	0.89	0.67	0.79	0.88	0.59	0.74	0.84	0.20	0.37	0.56
$(10'',0'')$	0.64	0.77	0.86	0.60	0.75	0.85	0.55	0.70	0.82	0.17	0.34	0.53
$(10'',10'')$	0.52	0.69	0.81	0.50	0.67	0.80	0.45	0.63	0.77	0.15	0.31	0.50

Table 1. LGS MCAO performance trends with ELT aperture diameter. See the text for the system and atmospheric turbulence parameters used for these simulations.

3.2. *LGS AO systems for the Thirty Meter Telescope (TMT)*

As described in Ellerbroek *et al.* (2005), current work on the Thirty Meter Telescope (TMT) project includes design studies for a total of 5 AO systems, 4 of them utilizing laser guidestars. The performance characteristics of three of the latter are outlined very briefly below; the description is very general because trade studies and design optimization is still ongoing as part of the TMT Conceptual Design Phase. Further performance results and design information will become available in the time frame of the instrument design study reviews scheduled for March of 2006.

3.2.1. *Narrow Field, InfraRed AO System (NFIRAOS)*

This is the first light TMT facility AO system, intended for use with up to three near IR scientific instruments. The first order AO design parameters are very similar to those studied in Table 1 above and consist of order 61×61 and 73×73 deformable mirrors conjugated to ranges of 0 and 12 km, 6 LGS wavefront sensors with 60×60 subapertures, and an 800 Hz update rate. Although described as a "narrow field" AO system, an MCAO capability is included to both (i) provide an upgrade path for future science instruments with FoVs on the order of $30''$ and (ii) improve sky coverage by compensating, or "sharpening," the images of IR tip/tilt natural guidestars over the majority of a 2 arcmin technical FoV.

Detailed performance modelling is ongoing as of this writing, but current error budgets predict an on-axis, higher-order wavefront error of 180 nm RMS, including both fundamental AO error sources and implementation effects. The on-axis performance of a future system upgrade is budgeted at 130–35 nm RMS, assuming that (i) the order 61×61 DM is replaced by a 121×121 mirror, (ii) an adaptive secondary mirror is available to provide the low-order, large amplitude correction no longer feasible with the new DM due to the smaller inter-actuator pitch and (iii) advanced laser systems are available to eliminate wavefront sensing errors associated with the nonzero thickness of the sodium layer (see below).

The tip/tilt error for 50 percent sky coverage at the galactic pole is estimated to be about 60–70 nm RMS wavefront error, including both turbulence-induced tip/tilt jitter and telescope wind shake effects. This value is based upon Monte Carlo simulations using the Spagna IR guide star model, assuming that tip/tilt measurements of up to 3 stars in the $2'$ diameter technical FoV are obtained using IR NGS wavefront sensors. Three tip/tilt measurements in different directions enable accurate estimation of the atmospheric tip/tilt in the direction of the science target, eliminating the effect of tilt anisoplanatism which would degrade performance if only a single off-axis tip/tilt guide star were used. The use of infra-red NGS wavefront sensors significantly improves these performance estimates on account of the diffraction-limited cores of guide star images in J band, which are still present but not significant at shorter wavelengths. But these simulation results require IR detectors with 5–10 electrons of read out noise at frame rates of approximately 500 Hz, which represents a significant performance improvement with respect to the best IR detectors which are available today (see below).

NFIRAOS is a post-focal AO system, with design characteristics based upon expectations for the potential performance of future piezostack DMs in terms of the number of actuators, physical inter-actuator spacing, and actuator stroke. These assumptions place constraints upon the number and order of the DMs utilized. Systems designed with requirements for either a larger corrected FoV or a smaller residual wavefront error would either be considerably larger or invoke the use of alternative DM technologies such as MEMS (see below).

3.2.2. *LGS MOAO for an InfraRed Multi-Object Spectrograph (IRMOS)*

The current design parameters for the TMT MOAO system include 8 laser guide stars and order 100×100 wavefront sensing and correction using some combination of micro DMs and low-order, large-stroke “woofer” deformable mirrors. Simulations indicate that the resulting DM fitting error and tomography wavefront reconstruction error yields enclosed energy values of about 50% within a 50 mas pixel for J, H, and K band observations of multiple small targets distributed within a 5 arcminute FoV. Performance is therefore dramatically superior to the NGS MOAO system described above, although implementation error sources such as non-common path aberrations and uncorrectable telescope aberrations have not yet been taken into account. Sky coverage is estimated to be quite high even for NGS tip/tilt sensing with seeing-limited guide stars in the visible, since the RMS tip/tilt jitter allowed with 50 mas pixels is relatively large.

3.2.3. *LGS GLAO for a Wide Field Optical Spectrograph (WFOS)*

The TMT *Wide* Field *Optical* Spectrograph is a challenging application for a GLAO system, since the thickness of the ground layer which can be successfully corrected using a single DM decreases with both increasing FoV and decreasing science wavelength. Simulations still indicate that GLAO measurably improves seeing at wavelength of $0.8\,\mu$m over a FoV of 77 square arcminutes, thereby enabling narrower slit widths, which reduce the required integration times by factors of 15 to 25 per cent for background-limited observations of point sources. This improvement is certainly non-trivial when the operations costs for a 30 meter class ELT are taken into account. These results are achieved with 5 sodium laser guide stars and order 30×30 compensation (assumed to be provided by an adaptive secondary mirror), although performance is a relatively weak function of either of these parameters.

3.3. *LGS AO implementation issues for ELTs*

As with smaller telescopes, LGS AO systems must cope with the issues of the cone effect, LGS tip/tilt uncertainty and the cost/complexity of developing reliable, facility class laser systems for an observatory environment. LGS AO architectures featuring multiple laser- and tip/tilt natural guidestars have been developed to address the first two of these issues and (as described in Drummond *et al.* 2004) recent progress towards developing higher power and more robust guide star laser systems is very encouraging. However, a number of additional implementation complexities have been identified for LGS AO on ELTs, including:

- The nonzero *depth of the sodium layer* becomes very significant for aperture diameters of 20–30 m or more, since the apparent elongation of the guide star as viewed at the edge of the aperture grows to at least 2.5 to 4.0 arcsec. LGS elongation increases the guide star signal level required for a given LGS WFS centroiding accuracy, and also increases WFS measurement errors due to the variability in the range and vertical distribution of the sodium layer. As described below, some of the approaches that have been proposed to counter these error sources include: (i) using a NGS WFS to measure and calibrate focus errors at an update rate of 10–1000 Hz, (ii) radial format WFS CCD arrays with pixel geometries aligned to the LGS elongation, (iii) noise-optimal centroiding algorithms updated in real time to match the changing shape of the LGS image, and/or (iv) guide star lasers producing short pulses that may be tracked as they transit the sodium layer. This last approach, sometimes referred to as “dynamic refocusing,” is probably a requirement for ELTs with aperture diameters much greater than 30 m and is highly desirable for any ELT.

• Laser launch systems must be implemented to project the multiple laser guide stars used for atmospheric tomography. The system concepts developed by Gemini Observatory and the University of Arizona for pathfinder 6–8 m class MCAO and LTAO systems, which project multiple guide stars using a single launch telescope located behind the secondary mirror, appear to be extensible to ELTs.

• LGS WFS designs become more challenging with increasing telescope aperture diameter. Even sampling the LGS signal can be difficult, since the location of the LGS focal plane varies considerably with elevation angle and the size of the defocused image of the LGS in the science focal plane is quite large (e.g., roughly 60–70″ for a 30 m class ELT). The possible design options include:

  ◦ For a post-focal AO system, the LGS WFS light may be sampled by a dichroic beamsplitter. In this case the LGS WFS design must include a "zoom lens" system to track the zenith-angle-dependent range to the sodium layer and null the optical aberrations induced by the telescope and post-focal AO optics, which can vary dramatically with the guide star range.

  ◦ For GLAO or LTAO system using an adaptive secondary, the LGS WFS light may be sampled using a pick-off mirror in the telescope focal plane. A fold mirror "trombone" may be used to compensate for the variable range to the sodium layer, but additional optics may still be required to correct the chromatic aberration which results from the finite range of the LGS. Additionally, the minimum angular separation between the guide star and the science target increases linearly with the telescope aperture diameter.

4. Key technologies: Status, requirements & development activities

4.1. *Key technology requirements for ELTs*

Figure 13 provides an overview of the key components expected to be required for a 50 m ELT and for the 30 m class TMT. These mirrors, detectors, lasers and signal processing systems are discussed further in the following paragraphs.

Expected implementation time →

	SCAO	GLAO	LTAO	MCAO	MOAO	ExAO
Adaptive Mirror	3m class with 30 mm pitch (6-8kact.); 100^2					
Piezo DMs	X	X	X	100^2	X	
MEMS	X	X	X	X	50-100^2	250^2
Vis. WFS detector IR WFS detector	High red QE; 1e RON 600^2; 0.6kfr/s High QE <5 e RON 128^2; 0.6kfr/s					2-3kfr/s 256^2; 2-3kfr/s
Guidestar lasers	X	~20-50W, pulsed				X
Processors	New concepts avoiding explicit matrix-vector multiplies					
LGS WFS	X	Dynamic refocusing + Elongated pixel CCD?				X

	First-light systems		Follow-on systems				
	MCAO	MIRAO	MCAO+	MIRAO+	GLAO	MOAO	ExAO
Piezo DMs	60^2	30^2	120^2	X	X	X	X
Adaptive M2	X	X	400-900 modes*				
MEMS	X	X	X	X	X	60^2+	120^2+
LGS WFS Det.	Radial format CCD arrays for 60^2 (120^2) subap.						X
IR NGS WFS Detectors	128^2-256^2 pixels, 400-500 fps, 5-10 noise electrons				X	X	1.5-3 kfps
Guidestar lasers	~50W, CW		~100W, pulsed	~50W, CW			X
Processors and algorithms	New concepts avoiding explicit matrix-vector multiplies						

*Piezo DM "woofer" a second option for MOAO or ExAO

Figure 13. Overview of required key technologies for a 50 m ELT (Left) and for the 30 m class TMT (Right)

4.2. *Adaptive mirrors*

4.2.1. *Large adaptive mirrors*

Using large deformable mirrors for an adaptive telescope provides several advantages: an AO system with low emissivity and high throughput, since no additional relay mirrors are required to insert the corrective element; the possibility to correct for a large FoV; and simpler implementation of the AO system up-front of the instrument.

Several observatories are operating or planning to implement large DMs on their current generation of large telescopes. A 642mm diameter, convex secondary mirror with

336 actuators has been developed and is being used by the MMT at Mt Hopkins, Arizona, as described by Brusa *et al.* (2004), and two 911mm diameter, concave secondary mirrors with 672 actuators are being fabricated for the LBT at Mt Graham, Arizona, at the time of this writing. A similar deformable secondary is being developed for a VLT Unit Telescope, with a diameter of 1120 mm and 1170 actuators for adaptive correction. Gemini is also investigating the possibility of implementing an adaptive secondary mirror on one of their telescope for a LGS GLAO system.

The usual concept for a large adaptive mirror (Figure 15) is based upon the deformation of a thin Zerodur shell controlled by an array of electromagnetic actuators. Each actuator consists of a fixed coil and a moving magnet glued on the back of the shell. The coil is mounted on an aluminium cold finger providing the structure of the actuator and the heat sink for the coil. The actuator cold fingers are mounted on a liquid cooled aluminium disk or cold plate. A back-plate inserted between the thin shell and the cold plate provides a stable optical reference for the thin shell. Capacitive sensors are co-located with each actuator to measure the distance between the back-plate and the thin shell, providing real-time feedback on the optical figure of the deformable mirror. The current to each actuator voice coil motor is controlled by a digital loop using the measurements provided by these capacitive sensors. A set of specialized DSPs control the shape of the thin shell in real time according to the commands received from the AO Real Time Computer.

Present Large DMs are therefore based on force actuators with a local control loop which guarantees the shape of the shell at any time. Extension of this technology to mirror diameters between 2.5 to 4 meters is now being investigated for ELTs in both the US and in Europe. The typical number of actuators expected for ELTs is between 400 and 7000 and segmented shells may be required.

4.2.2. *Piezo-stack deformable mirrors*

Piezo-stack DMs have been used on many, if not most, AO systems over the last 20 years. Recent development of this technology has been supported for a variety 8 m telescope AO projects and for TMT:

- Gemini-South MCAO project: two DMs from CILAS with 21^2 and 25^2 actuators, 5 mm pitch and 7 μm stroke.
- ESO Planet Finder project: a DM from CILAS with 41^2 actuators, 4.5 mm pitch, and 8 μm stroke
- TMT MCAO system: a feasibility study by CILAS of 61^2 and 73^2 actuator 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: $-35°$C has already been demonstrated with current actuator material. A 9^2 actuator DM prototype is in progress for TMT. A 50 m class European ELT would require a 100^2 actuator DM (especially for MCAO) with 5 mm pitch and approximately 10 μm stroke.

"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.

4.2.3. *Micro deformable mirrors*

R&D in Micro Deformable Mirrors, or MEMS, has been ongoing for approximately one decade, driven by potential applications in both atmospheric turbulence compensation and vision science and the desire to reduce AO system costs. Devices with 12×12 actuators are now available with good surface quality, 1 to $2\,\mu$m peak-to-valley stroke, high bandwidth, high repeatability, and 100% actuator yield. Progress with 32×32 actuator devices is encouraging and design work is proceeding for MEMS with 64×64 actuators and a peak-to-valley stroke of $4\,\mu$m. These parameters represent roughly the "entry-level" requirements for use of a MEMS device in either an AO system on a 30 m class ELT or a 8 m class ExAO system. An order 100×100 or 150×150 MEMS might be required for a ELT ExAO system and a stroke of about 8 to $10\,\mu$m would be necessary to eliminate the requirement to employ an additional low-order, large stroke "woofer" DM.

MEMS actuator sizes are typically on the order of 300 to $500\,\mu$m, so that even an order 100×100 MEMS would have a diameter of only 30 to 50 mm. This implies a magnification ratio of approximately 1000-1 for a ELT AO system, and MEMS are therefore considered primarily for narrow FoV AO systems such as ExAO or an MOAO "button." A new design with a somewhat larger actuator pitch could conceivably be an option for MCAO. Open-loop operation of MEMS (or any other DM technology) is a requirement for some MOAO system architectures. Lab tests have demonstrated that MEMS are highly repeatable, but the devices are not completely linear and more work will be necessary to accurately predict the open-loop response of a MEMS to a given set of actuator commands.

4.3. *Detector arrays*

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. Additional requirements arise for sodium LGS WFS detectors on ELTs as described below.

4.3.1. *Visible WFS detectors*

The recent development of nearly zero-noise detectors based upon an Electron Multiplication CCD (for instance from E2V) seems promising for AO applications requiring extremely low readout noise (RON). This technology uses register amplification to reduce the apparent RON below 1e at readout rates as high as 1.5 k frames/second. However, amplification or "excess" noise effectively reduces the quantum efficiency of the detector. The development of a 240^2 detector using 8 parallel readout registers has been funded in the frame of the VLT Planet Finder. 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 512^2 may be required.

As described above, LGS WFSs for ELTs are challenged by the significant degree of guide star elongation induced by the (approximately) 10 km thickness of the sodium layer. For a continuous wave (CW) laser this elongation reaches approximately $4''$ for a 15 m separation between the laser launch telescope and the WFS subaperture, or about $6''$ for a 25 m separation. Classical quadrant detectors cannot be used for wavefront sensing with this degree of elongation and the number of pixels required to adequately sample the guide star "streak" with a conventional CCD array may be prohibitive. The guide star signal level required for a given WFS centroid measurement error also increases in (at least) direct proportion to the amount of guide star elongation.

A MIT-Lincoln Laboratory project, funded by the NSF Adaptive Optics Development Program (AODP), is developing a "radial format" CCD array to minimize or eliminate the impact of these effects. This array's pixel geometry, illustrated in Figure 14, consists of rectangular strips of pixels which are aligned to the WFS subaperture geometry and oriented parallel to the local direction of the guide star elongation. For a CW laser system this geometry minimizes the number of pixels needed to adequately sample images of the LGS in each subaperture, thereby minimizing pixel read rates, readout noise and signal processing requirements. The array geometry also simplifies the computation and application of noise-optimal centroiding algorithms and current simulations predict that acceptable levels of WFS measurement accuracy will be achievable for a 30 m class ELT with currently demonstrated CW laser powers.

Additionally, if novel laser pulse formats currently under development are successfully demonstrated, charge tracking techniques may be used to “dynamically refocus” the radial format CCD array on short laser pulses as they transit the sodium layer. This would reduce laser power requirements further and eliminate additional error sources associated with sodium layer variability, as described further below.

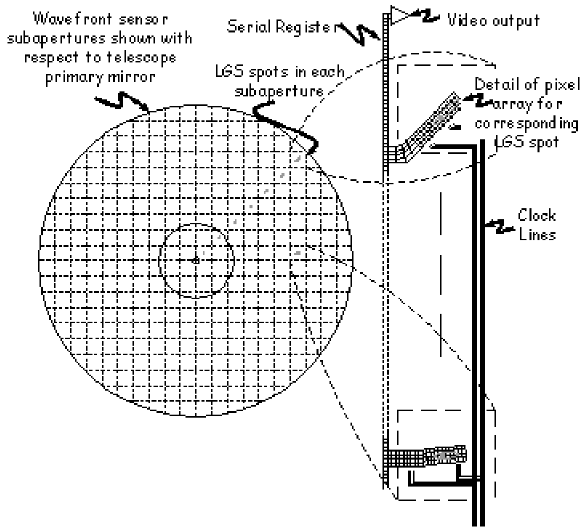

Figure 14. Radial format CCD array concept for use in ELT LGS wavefront sensors

4.3.2. *IR WFS detectors*

Fast, high speed, low-noise IR detectors would be highly useful for AO systems on both future ELTs and existing 8–10 m class telescopes. Tip/tilt sensing in the near infrared can in principal significantly improve the sky coverage of an LGS AO system, both because of the large number of “red” L and M class stars and the “sharpening” of IR images by the AO system. This second factor is particularly significant for an ELT. Sky coverage modelling of LGS AO systems for TMT indicate that very useful levels of sky coverage, verging on 50% at the galactic pole, could be achieved with IR WFS detector arrays with 128^2 to 256^2 pixels and 5–10 RON electrons at frame rates of 500–1000 Hz. Unfortunately, existing IR detector arrays are smaller and typically 2–10 times noisier at these frame rates (if they can be achieved at all). Recent progress with a variety of technical approaches including HgCdTe APD arrays and ASIC on-chip digitizers is highly encouraging, however, and R&D efforts in this area should benefit from the significant level of interest expressed by 8–10 m class observatories and other applications including interferometric arrays.

The performance *goals* for IR WFS detectors are more demanding, particularly for ExAO systems desiring to optimize their magnitude limits. An array with 3 RON electrons at a frame rate of 2.5 kHz (!) lies at the approximate upper bound of this range.

4.4. *Laser guide star facilities*

The performance of continuous wave (CW) sodium guide star lasers has improved dramatically in recent years, with the Starfire Optics Range demonstrating output powers of 50W in the lab and approximately 35W on the sky. A commercial supplier (Lockheed-Martin Coherent Technologies or LMCT) is now under contract to provide a system with similar capabilities for the Gemini South MCAO system. Such a laser system is predicted to provide sufficient power for 2–3 laser guide stars sensed with 0.25^2 m subapertures on a 30 m ELT, even accounting for the impact of increased guide star elongation. Further development of these laser systems to improve their reliability and maintainability is very important, however.

Although this progress with CW sodium lasers is encouraging, further development of pulsed lasers remains highly desirable for a variety of fundamental and practical reasons. The existing "macro-micro pulse" format with a duty cycle of 10–20% 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 μs in length and a 1–2% duty cycle would enable "dynamic refocusing" on the short 1–2 km laser pulse as it transits the sodium layer using the radial format LGS WFS CCD array described above. If practical, this concept will provide a number of important performance improvements on ELTS:

- elimination of sodium layer range uncertainty as a source of wavefront sensing error;
- elimination of sodium layer profile uncertainty as a source of wavefront sensing error;
- LGS power requirements would no longer depend (or only weakly depend) upon telescope diameter, increasing the feasibility of LGS AO for 50 m to 100 m class ELTs.

R&D towards lasers with this pulse format is ongoing, but remains 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.

Lastly, LGS facilities for ELTs would be significantly simplified if fiber optics could be used to relay the laser beam from the laser system to the laser launch telescope behind the secondary mirror (where it is located to minimize LGS elongation). The length of this propagation path is on the order of 45–75 m for a 30–50 m class ELT, and Stimulated Brilloin Scattering (SBS) becomes an issue if conventional fiber optics are employed at the required laser power levels. SBS broadens the laser spectral bandwidth significantly, thereby degrading the interaction of the laser light with the mesospheric sodium layer and dimming the guide star by orders of magnitude. However, recent tests with hollow core photonic crystal fibers (HC-PCF) suggest that fiber optics beam relays can probably be used with peak laser powers of 10–20W without inducing SBS. This level of performance will probably be acceptable for CW laser systems. Work to develop and demonstrate fiber optics usable with pulsed lasers with considerably higher peak powers is continuing.

4.5. *Wavefront reconstruction processors and algorithms*

All currently operational astronomical AO systems employ some variant of the standard vector-matrix multiply (VMM) control algorithm to determine DM actuator commands from WFS measurements. Assuming a constant DM actuator density and control loop update rate, the computational requirements for this approach scale with the fourth power of the aperture diameter D, or even as D^6 if the algorithm is updated in real time to adapt to changing conditions. In other words, the AO computation requirements for a 32 m ELT will be approximately 256 to 4096 times larger than for a current 8 m telescope if conventional algorithms are employed. This requirement lies somewhere between grossly inefficient and impossible, even assuming continued improvements in processor capabilities according to Moore's law.

A variety of new reconstruction algorithms have been developed in recent years to defeat the above D^4 and D^6 scaling laws. These methods are based upon spatial frequency domain models of the AO system and a variety of techniques borrowed from computational linear algebra as describe by Vogel (2004), including multigrid methods and preconditioned conjugate gradients. The computation requirements for these methods generally scale somewhere between D^2 and D^3, but they are frequently iterative and/or more difficult to parallelize than the conventional VMM algorithm. Simulations and analysis have demonstrated that there is no loss in theoretical performance for these newer techniques. Work by CfAO, ESO, and tOSC has recently started to develop real-time implementations of these algorithms. General-purpose CPUs are expected to be fully adequate for 8-meter class ExAO systems, while more sophisticated implementations based upon digital signal processors (DSPs) or field programmable gate arrays (FPGAs) are likely to be preferred for ELTs.

5. Demonstrators and field tests

Lab demonstrators and field tests are now being developed in the US and Europe to confirm the feasibility of new AO concepts for ELTs (GLAO, LTAO, MCAO, MOAO, ExAO) and to evaluate the actual and potential performance of these systems.

5.1. *Tomography tests*

5.1.1. *ESO Multi conjugate Adaptive optics Demonstrator: MAD*

ESO has built and is testing a Multi-Conjugate Adaptive Optics Demonstrator (MAD) to perform wide FoV AO correction both in the lab and on the sky as described in Marchetti *et al.* (2004). The aim of MAD is to:

• demonstrate on the sky the feasibility of the GLAO and MCAO techniques;

• perform an initial optimization of these techniques and explore other innovative approaches through extensive in-lab testing;

• evaluate the critical aspects of building and running such an instrument for an ELT or as a second generation VLT system.

MAD will be installed at the Nasmyth Visitor Focus of the VLT at Paranal in 2006 to perform on-sky observations.

MAD is a prototype GLAO and MCAO system providing AO correction in K on a $2'$ FoV using bright ($m_V < 14$) NGSs. MAD will be used to investigate two different wavefront sensing techniques: The Star-Oriented MCAO approach with 3 Shack-Hartmann WFSs, and the Layer-Oriented MCAO method with up to 8 Pyramid WFSs. MAD correction is performed with two DMs conjugated to ranges of 0 and 8.5 km. A multi-layer turbulence generator MAPS (Multi Atmospheric Phase screens and Stars) can be installed at the input focus of MAD for system testing and tuning in the laboratory.

Preliminary results have been obtained in the laboratory for the SCAO, GLAO and MCAO modes using the three Shack-Hartmann WFSs. Figure 15 illustrates that these concepts provide a meaningful degree of aberration compensation, but still need further optimization to achieve their predicted performance.

5.1.2. *Palomar Multi Guide Star Unit*

The Multiple Guide Star Unit (MGSU) system at Palomar consists of 3 order 16×16 and 1 order 3×3 visible Shack-Hartmann wavefront sensors. In conjunction with the Palomar facility Shack-Hartmann WFS, these sensors may be used to acquire open- or

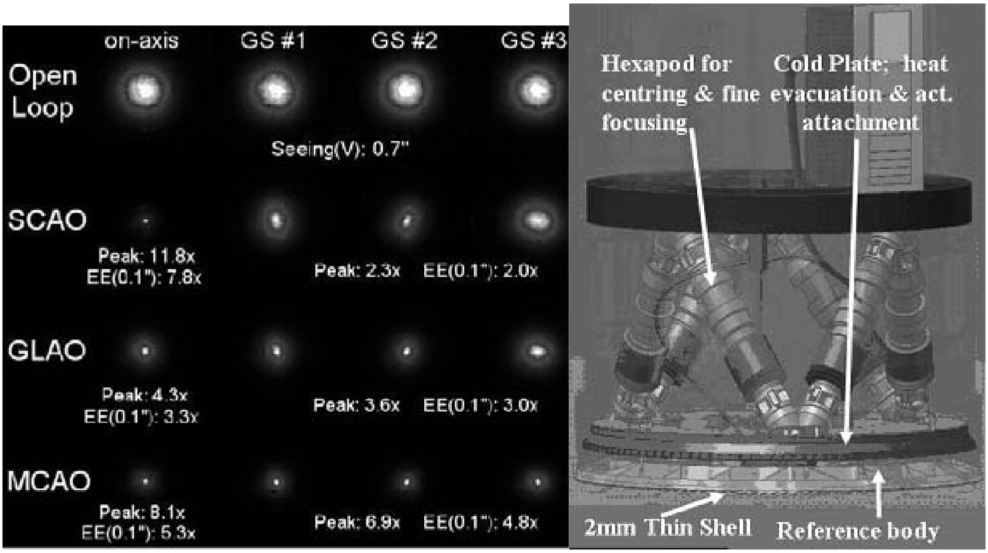

Figure 15. Left: Preliminary results obtained with MAD in SCAO, GLAO and MCAO modes on bright reference stars. Results are presented on axis and in three equally spaced directions at the edge of the 45″ radius field. Right: Large Deformable concept: a thin shell mirror controlled by force actuators attached to a cold plate with capacitive sensors providing position feedback relative to a reference body. An Hexapod attached to the cold plate provides rigid body alignment control (Courtesy: Micrograte and ADS, Italy).

closed-loop WFS measurements from 4 natural guide stars to study the potential performance of tomographic wavefront reconstruction for LTAO and MCAO. The data acquisition system supports synchronized data acquisition from all 4 order 16×16 sensors at 2000 Hz, as well as DM actuator commands during closed-loop operation. Palomar is also equipped with MASS and DIMM systems for simultaneous measurements of the atmospheric turbulence $C_n^2(h)$ profile. This combination of high spatial/temporal resolution, high signal-to-noise ratio on bright asterisms and independent atmospheric turbulence measurements is expected to provide quantitative confirmation (or correction) of current theoretical models for the performance of tomographic wavefront reconstruction.

The MGSU system was designed and fabricated under a grant from the National Science Foundation (NSF) and the final integration and calibration of the system is now proceeding under TMT sponsorship. Initial on-sky measurements were recently collected using 3 of the 4 wavefront sensors and are under study at the time of this writing.

5.1.3. *Laboratory for Adaptive Optics MCAO and MOAO*

The University of California at Santa Cruz (UCSC) Laboratory for Adaptive Optics (LAO) is now integrating a lab bench to simulate MCAO and MOAO control systems for a 30 m class ELT. The design features 9 simulated sources, multiple rotating phase screens to simulate Kolmogorov turbulence on a 30 m aperture, 3 spatial light modulator (SLM) wavefront correctors, 9 Shack-Hartmann wavefront sensors, and both image- and pupil plane scoring sensors to evaluate performance. Both MCAO and MOAO control approaches may be simulated by either including or bypassing the SLMs in the simulated LGS WFS optical path. The hardware has been integrated on the bench as of this writing and an SCAO system has been successfully simulated. Work is now progressing to characterize and calibrate the Shack-Hartmann wavefront sensors and the SLM-to-WFS influence matrices.

5.1.4. *ESO Multi Object Adaptive Optics*

The feasibility of the FALCON concept for MOAO based on Natural Guide Star as described in Hammer *et al.* (2002) has been the subject of a collaboration with the Observatoire de Paris (OdP) and ONERA since the beginning of 2002. Preliminary results of AO open loop control have been recently obtained on the BOA bench at ONERA. A more advanced demonstration of the MOAO concept is planned using the OdP SESAME bench in 2006. Combination of GLAO and MOAO in order to reduce the required stroke on the AO button micro-deformable mirrors will be further studied. For high ensquared energy requirements, MOAO will need Laser Guide Stars as recently highlighted in the frame of the OWL AO study. LGS GLAO-MOAO combined with Natural Guide Star for low order correction will be investigated in 2006.

5.2. *Extreme Adaptive Optics test beds*

5.2.1. *Laboratory of Adaptive Optics ExAO test bed*

Current work at LAO also includes a lab bench for testing Micro DMs and ExAO wavefront sensors. The system is currently configured with a 32×32 actuator MEMS obtained from Boston Micromachines, an interferometric wavefront sensor and a spatially filtered Shack-Hartmann Sensor. Current generation MEMS demonstrate approximately $1\,\mu$m of stroke, actuator yields of nearly 100% and can be flattened to 1–2 nm RMS within the spatial frequency passband of the MEMS actuators. Closed loop AO tests using a 20-actuator-diameter subpupil of the MEMS have demonstrated consistent, repeatable correction of 100 nm RMS wavefront errors to 2–3 nm RMS using the interferometric wavefront sensor, and 5–10 nm RMS using the Shack-Hartmann WFS. Continuing tests are planned to characterize the performance of future MEMS designs and devices.

5.2.2. *ESO High Order Test bench: HOT*

The High Order Test bench, or HOT (Figure 16), is currently under development by ESO in collaboration with several European Institutes. It will provide a means to investigate Extreme AO and high contrast imaging performance both for the VLT and for future ELTs. The aim of HOT is to:

- optimize WFSs concepts and control methods to reduce AO halo residuals close to the bright star, such as the spatially filtered Shack-Hartmann and Pyramid WFSs;
- investigate the woofer/tweeter control concept;
- investigate different coronagraph designs;
- study calibration issues;
- study the impact of implementation error sources on the final performance;
- study differential imaging techniques to improve contrast;
- study focal plane WFS concepts to directly reduce speckle in the focal plane; and
- evaluate new AO components for XAO, such as MEMS, zero RON CCDs and control systems.

The baseline concept for HOT consists of a high order turbulence generator, pyramid and Shack-Hartmann WFSs, a 60 actuator CILAS bimorph DM “woofer,” a 32^2 actuator Micro DM from Boston Micromachines “tweeter,” a coronagraph and an IR camera. Possibility to replace the bimorph deformable mirror by a 52 actuator electromagnetic deformable mirror from the Laboratoire d’Astrophysique de Grenoble is also planned. The provision to implement a differential wavelength imager, a focal plane WFS and a focal plane DM is foreseen.

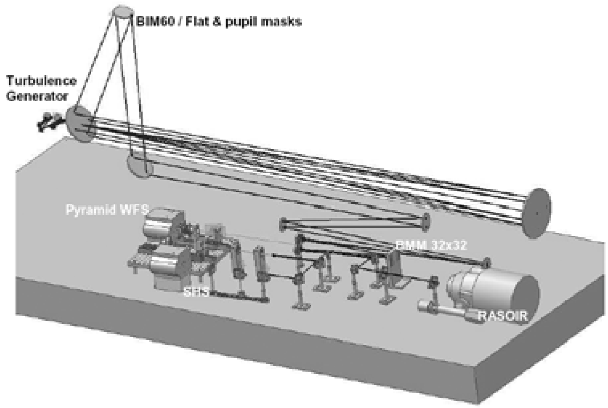

Figure 16. ESO High Order Test bench concept to demonstrate ExAO

5.2.3. *University of Victoria Woofer-tweeter control concept*

The University of Victoria (UVic) Adaptive Optics Laboratory is currently conducting an experimental validation of woofer-tweeter control algorithms. Woofer-tweeter architectures that involve the combination of a (possibly slower) low order, high stroke DM (woofer) and a (possibly faster), high order, low stroke DM (tweeter) have never been deployed before in an AO system. Yet this architecture is required in many planned ELT instruments to achieve the stroke required to correct the atmospheric turbulence on a large aperture. The UVic AO Lab uses a 140 actuator MEMs DM from Boston Micromachines as tweeter and a 52-actuator magnetic DM from Laboratoire d'Astrophysique de l'Observatoire de Grenoble as woofer. The final integration of the test bench, which will support several hundred Hertz frame rates, is being completed at the time of writing and several control algorithms have been designed and will be tested. Planned upgrades include a high order tweeter and enabling an MCAO mode for testing tomographic reconstruction algorithms.

6. 8–10 m class pathfinders

6.1. *VLT Adaptive Optics Facility*

The ESO Adaptive Optics Facility (AOF) as described in Arsenault *et al.* (2006) is one of the major second generation projects for the VLT. The key objectives are to:

- develop and operate an adaptive telescope with a 1.1 m, 1170 actuator Deformable Secondary Mirror (DSM) at diffraction limit;
- secure and improve large DM technology with 30 mm pitch and large glass thin shell manufacturing;
- master Adaptive Telescope calibrations and interlaced control loops;
- develop robust lasers, laser fibre transport, CCD and real time computers compatible with AO systems operated at up to 1 kHz;
- develop and operate a multi-LGS AO system to perform tomography;
- develop, operate and master two GLAO systems for use with a visible 3D spectrograph and an NIR imager;
- develop, operate and master an LTAO system in the visible; and
- develop extensive Deformable Secondary Mirror testing procedures in the laboratory as well as the GLAO systems.

The AOF will address many issues crucial for adaptive optics on future ELTs, including adaptive telescope development, operation/calibration, GLAO operation/performance, LTAO operation/performance, laser technology, and beam transport.

6.2. *Gemini Multi Conjugate Adaptive Optics*

The Gemini LGS MCAO system is designed to provide the primary, Facility-class AO function for the Gemini-South telescope Ellerbroek *et al.* (2003). Like the Gemini-North AO system Altair, the system is mounted on the Gemini Instrument Support Structure (ISS) and serves as an optical relay between the telescope and the other instrument ports. The system is designed to provide Strehl ratios of 0.6, 0.4, and 0.2 in K, H, and J bands over a 1 arcminute square FoV, with sky coverage expected to be on the order of 15–30% at the galactic pole. Some of the key features of the design developed to meet these requirements include:

- order 21×21, 25×25, and 15×15 piezostack DMs optically conjugate to ranges of 0, 4.5, and 9 km;
- five order 16×16 LGS WFS, with fore-optics designed to minimize non-common path aberration and pupil distortion at guide star ranges from 85 to 150 km;
- 2 tip/tilt and 1 tip/tilt/focus NGS WFS;
- a real-time control (RTC) system that computes approximately 1000 DM actuator commands from 2000 WFS gradient measurements at an 800 Hz frame rate with less than one frame of signal processing latency; and
- Beam Transport Optics (BTO) and Laser Launch Telescope (LLT) systems for projecting the 5 laser guide stars from behind the secondary mirror (to minimize LGS elongation) and maintain their alignment on the sky.

Work has now started on the 50 Watt laser system required to generate the 5 LGS, and work on all remaining components is well underway. The basic elements of the design concept, as well as the expected levels of performance, appear applicable to ELTs up to an aperture diameter of at least 30 m.

6.3. *Gemini Ground Layer Adaptive Optics*

The so-called "Aspen Process" for selecting second generation instrumentation for Gemini Observatory has included a feasibility study for GLAO. This system is intended to provide enhanced and uniform seeing over a 10 arcsec FoV at wavelengths of 0.7 to 2.2 μm. The basic elements of the design include a relatively low order adaptive secondary mirror controlling on the order of 80 Zernike modes, 4 relatively low-power sodium laser guide stars sensed by Shack-Hartmann wavefront sensors with 10×10 subapertures, and 3 natural guide star sensors used to measure the average atmospheric tip/tilt across the field and provide (relatively) slow focus measurements to calibrate for variations in the height of the sodium layer. The wavefront sensing subsystem replaces much of the current Gemini Acquisition and Guiding system within the ISS, enabling GLAO to be utilized by any Gemini instrument. On the basis of representative $C_n^2(h)$ measurements obtained at Cerro Pachon, the feasibility study concluded that "the best image quality conditions that at present occur only 20% of the time will occur 60–80% of the time when GLAO is in operation." Work has commenced on a Mauna Kea site monitoring campaign that will provide the turbulence statistics needed to confirm this prediction and optimize the design of the system for conditions at Gemini-North.

6.4. *Gemini Planet Imager*

The Gemini Planet Imager, or GPI, is also an element of the second generation "Aspen" instrumentation under development for Gemini. The system is designed to detect relatively young, warm gas giants orbiting nearby stars and to achieve contrast ratios of 10^{-6} to 10^{-7} in H band at a separation of $0.09''$ from a 4^{th} to 8^{th} magnitude star. The effort is about to begin its Preliminary Design phase. The basic element of the design include:

- order 44×44 wavefront correction, achieved using a 64×64 element Micro DM and a low-order, large stroke bimorph DM;
- a spatially filtered, visible Shack-Hartmann WFS with 44×44 subapertures and a 128×128 pixel CCD array;
- a maximum frame rate of 2500 Hz and a computationally efficient Fourier transform wavefront reconstruction algorithm;
- a Lyot coronagraph consisting of an apodized pupil and a focal plane occulting spot;
- an infrared, interferometric wavefront sensing system to calibrate non-common path and chromatic aberrations; and
- a lenslet-based, R=40 IFU with a pixel size of $0.014''$ and a spectral bandpass of 1.0 to 2.5 μm.

In addition to its own science case, this instrument will demonstrate many of the system concepts and component technologies now under discussion for future ExAO systems on ELTs.

6.5. *ESO VLT Planet Finder*

The ESO Planet Finder, described in Beuzit *et al.* (2006), is also a major second generation instrument for the VLT. The key scientific requirements include:

- to observe planets 14 (goal 16) magnitudes fainter than their host stars at small angular separations from $0.1''$ to $3''$;
- to explore the vicinity of stars down to 10^{th} magnitude for a total of 500 potential targets; and
- to characterize the detected objects using spectroscopy in Y to Ks with a spectral resolution of 30.

The VLT Planet Finder consists of ExAO system with 1370 actuators, a low noise WFS ($<1e^-$ RMS RON) at a frame rate of 1.2 kHz, a differential imager, a differential polarimeter (ZIMPOL) and an NIR Integral Field Spectrograph. As such it is an essential precursor of any ExAO, high contrast imaging system for an ELT.

7. Conclusions

ELTs will place high demands on Adaptive Optics, but the promise of high angular resolution can be achieved. Extrapolations of current SCAO, GLAO, and MCAO concepts for 8–10 m class telescopes will be feasible with evolutionary upgrades to existing component technologies. MOAO and ExAO are more challenging and will require qualitative advances. For all of these systems, an aggressive and focused roadmap to develop key technologies must be supported for visible (CCD) and IR detectors for wavefront sensing; large, piezo and micro DMs; control algorithms and processors; and continuous and pulsed lasers.

Important technology demonstrators are already in progress in both the US and in Europe, in particular for GLAO, MCAO, MOAO and ExAO. Full-scale GLAO, MCAO and ExAO pathfinders are being developed for 8–10 m telescopes.

Many opportunities still remain for significant innovation in this field, and progress towards the challenging objectives will definitely benefit from the continued large scale collaboration and strong involvement of the full AO community.

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Discussion

Longair: Could you comment about the success of the various AO systems in dealing with diffuse rather than point objects? Many cosmologists will be interested in, for example, surface brightness, distribution of galaxies at large redshifts.

Ellerbroek: The photometric and astrometric accuracy of an imager operating behind an MCAO system should be similar for both point- and diffuse sources, given that the AO-compensated PSF is relatively uniform over a 0.5–1 arcmin FoV and nearly constant over 1–2 arcsec. Predicting the performance of an IFU system with a pixel size considerably larger than $>1^{\circ}$ is difficult, since the response of the system to a bright point source superimposed on the diffuse source will depend strongly on the location of the source within a pixel. On going work on 8–10 m class AO+IFU systems is needed to understand the importance of this effect.

Longair: Would you like to comment on the scaling relations for adaptive optics which I presented this morning, namely, cost $\propto D^{(3-4)}$?

Ellerbroek: It is difficult to derive a general D^x scaling law for adaptive optics due to the variety of systems and components under consideration. For well established components such as CW lasers or piezostack mirrors, the cost curve may scale approximately as D^2 (mirrors) or even as D (lasers). For most AO modes (excepting EXAO with a pyramid sensor) wavefront reconstruction complexity scales with $D^2 \log D$ or possibly D^3, and should not be a cost driver. The key remaining components are IR WFS detector arrays, MEMS and adaptive secondary mirrors for these elements R&D costs may be as substantial as unit costs and it may be difficult to estimate a cost curve until technology is further advanced.

Hartung: For XAO: What is the point about (the reason for) combining Pyramid WFS with a Shack-Hartman WFS?

Hubin: The main objective of XAO is to promote a fast connection with minimal noise propagation from the WFS into the reconstruction process. For EPICS, using a pyramid WFS with 10^5 actuators DM controlled at 3 kHz (simple stage) would have been ideal. However, from the computing power view point the feasibility of this system would be off by a factor 100 assuming 'Moore's Law' over 10 years. This is the main reason for this double stage AO System: pyramid WFS with 10^4 at 3 kHz and Shack-Hartman with 10^5 actuators at 1 kHz for which fast reconstruction techniques exist (Fourier reconstruction for instance). For the pyramid sensor, only classical matrix-vector multiplication exists and is computationally demanding $\propto N_{vct}^2$.

Dennefeld: In MCAO, you foresee 'only' one ground layer and one high altitude layer. In some sites, the high altitude layers are more complex. Do you foresee systems with more than one high altitude layer correction? And with the one layer, is it planned to refocus (and how fast can it be done) if the altitude of this layer is changing with time?

Ellerbroek: MCAO systems with 3 or more DMs will increase the compensated FoV beyond the 0.5–1.0 arcmin which is provided by 2 DMs. However, it appears that 3 deformable mirrors at optical conjugates between 0 and 15 km cannot be packaged unless the optical design includes multiple optical relays, which would increase system cost, volume, mass, and emissivity.
MCAO performance is generally quite robust with respect to the distribution of the atmospheric turbulence profile, even if the conjugate ranges of the mirrors are fixed. See the presentation and paper by Olson and Ellerbroek for sample simulations.

Ardeberg: Introducing DM correction for additional turbulence layers will, at least in principle, affect both the Strehl ratio and the useful field of view. However, in practice we have to be content with a larger field only, or could we also hope for a larger Strehl ratio?

Ellerbroek: In general, increasing the number of DMs in an MCAO system will both (i) increase the diameter of the field corrected to a given Strehl ratio and (ii) increase the average Strehl ratio within a fixed FoV size. However, the **on-axis** performance of the system will not be significantly impacted, and this places a bound upon the Strehl ratio or the system unless other component parameters are improved (DM actuator pitch, control system bandwidth, implementation error budget, etc.).

Käufl: How tolerant are the various AO/XAO systems under discussion to objects that are not point-like, e.g. resolved stellar photospheres, comets, multiple stars, etc.?

There are more interesting science cases for high contrast imaging than exo-planets! They should not be designed out!

ELLERBROEK: Sources may generally be as large as λ_s/ds before the AO system even notices, where λ_s is the WFS wavelength and ds is the sub-aperture width. This angle may vary from 1.0 to 0.1 arcsec, depending upon the AO system in question. Larger objects (up to approximately λ/r_0) are acceptable assuming that (i) the WFS sub-aperture FoV is sized accordingly, (ii) the centroid gain or the WFS is estimated in real time to account for variations in the size of the source, and (iii) the source is relatively symmetric. Multiple stars may therefore be a difficult case.

KÄUFL: Are saturation problems to be expected with pulsed Na-laser operation?

ELLERBROEK: Saturation problems would probably occur with a narrow line sodium laser that would excite only a single 10 MHz velocity class or the ∼3 GHz (Doppler broadened) sodium line width. However, the saturation intensity may be increased by a factor of about 3 GHz/10 MHz=300 if the laser line width is broadened to 3 GHz. Since recent tests at the Starfire optical range with a 2OW, continuous wave, 10 MHz laser show no evidence of saturation, saturation is not expected to occur with a 20W, pulsed, 3 GHz laser with a duty cycle of 2–3%. This duty cycle will eliminate guide star elongation on a 30 m ELT and reduce it by a factor of 10–20 on a 100 m ELT.

IYE: What is the optimum conjugate height to increase the FoV? Does bringing the conjugate height to that corresponding to, say the dome seeing layer, help to increase the FoV?

HUBIN: We assume your question is related to the ground-layer AO mode. The answer is two fold: (a) it is highly desirable that dome seeing is as low as possible, for instance by controlling all heat sources in the dome, by monitoring the dome temperature during day time and by optimizing the in-flow at night-time, as done on most 8–10 m telescopes; (b) assuming this is done properly, the optimum altitude is probably a few 100 m above the telescope (DM conjugation as shown by the preliminary SLODAR measurements at Paranal.