Adaptive Optics Challenges for the ELTs

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ABSTRACT

In this short paper, we try to globaly describe Adaptive Optics (AO) in the context of the Extra Large Telescopes (ELTs). We give a very broad overview of where AO stands currently. We then discuss what would be the specifications of an AO system for an ELT. Finally, we review some of the engineering and theoretical challenges for ELT AO.

Keywords: Adaptive Optics, ELTs, Multi-conjugate Adaptive Optics

1. INTRODUCTION

Adaptive optics in astronomy is now a reality. Some 4-m class telescopes (ESO 3.6-m, CFHT) have been producing science grade AO compensated images for many years already. Earlier this year, the Keck AO system worked on the first night, and is now producing science. The Gemini telescope obtained AO near-diffraction limited images 100 days into its commissionning period (see figure 1). As the community gets educated in this new and rather complex technique, and learns how to use it, science results are flowing out. This is clearly demonstrated by the rate of science papers based on AO observations, which has been growing in an exponential way for the last years.[1] Although AO is a rather new techniques in astronomy, it is with no doubt getting mature.

We seem to have a good grasp over AO on up to 10-m class telescopes. What of AO on 30 to 100-m apertures ? This is not only a major step because of the (much!) larger aperture, but this is also a major challenge because of the change of status of AO; For ELTs to exist, and all science drivers agree, they have to have near-diffraction limited capabilities basically *100% of the time on 100% of the sky*. It would be pityful to have an ELT restricted to observe near 15th magnitude guide stars, and shut down when the seeing is not good enought for the AO to work. In turn, AO is getting promoted from a growing but still rather marginal technique to a full-time integrated telescope interface, as for instance a telescope autoguider. This is a radical change in status for AO, and will require solving a number of problem, like sky coverage (by the use of Laser Guide Stars), large compensated field of view (by Multi-Conjugated AO, see below), within others. It also means that the ELT AO systems will have to be somehow overspecified to cope with all seeing conditions, and possibly working at short wavelengths.

Of all the engineering domain needed to complete a project like an ELT, AO is probably the most challenged one. These challenges are of two kinds: Theoretical and technical. After working out the order of magnitude for the specification of the typical ELT AO in the next section, we discuss these engineering and theoretical challenges with a particular emphasis on the Multi-Conjugate Adaptive Optics (MCAO) concept.

2. ELT'S AO SPECIFICATION

We will assume that, as any other modern telescopes, the ELT will have to be located in a very good site. This however does not overwhelmingly weigh the dimensionning of the AO since, as was said above, the AO will have to work under all encountered conditions. As a baseline, we adopt $r_0(550\text{nm}) = 10\text{cm}$, which should cover most of the seeing cases. It is also obvious that such a facility as an ELT ought to be run under queue/optimum scheduling, so that, for instance work at longer wavelength can be done when the seeing is (really) bad. In all occurence, the AO system of an ELT can not be underspecified. The maximum use of the collecting power impose to work in a high Strehl ratio regime, down to the shortest wavelength possible (imposed by the science goals). This is of extreme

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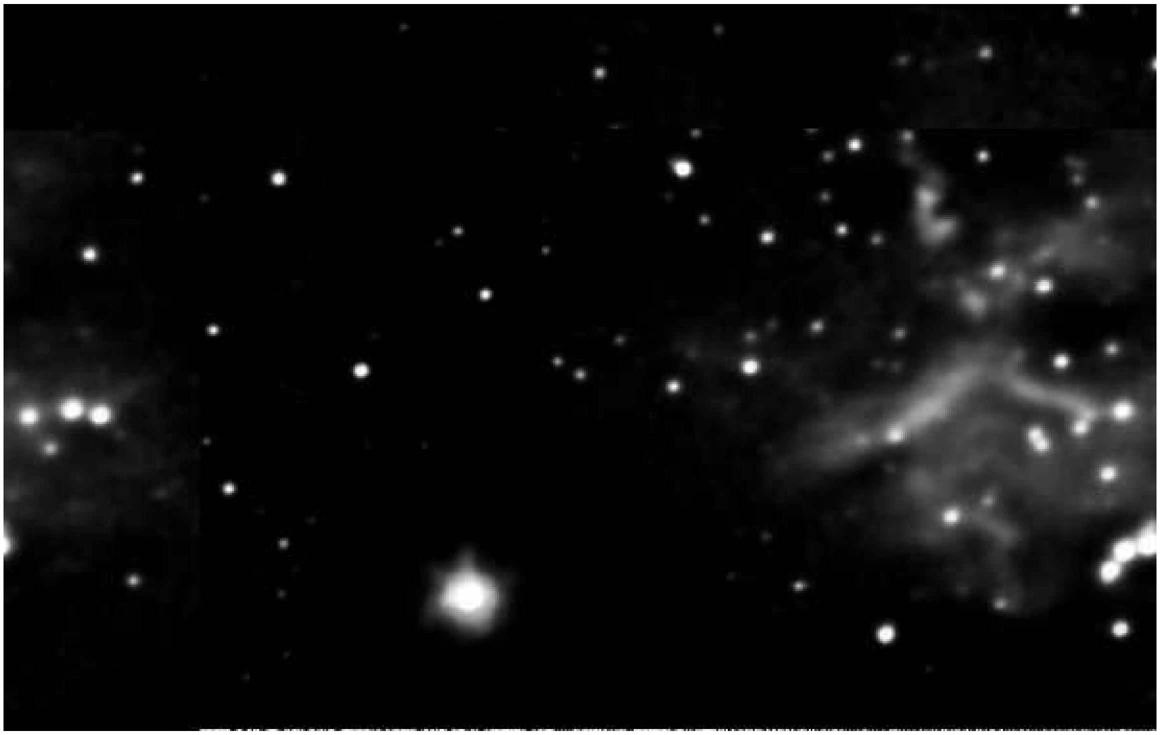


Figure 1. Image of the Star forming region G45.45+0.06 obtained with the University of Hawaii curvature AO system on GEMINI. The field of view is 12x19 arcsec. This color composite image is made from the deconvolved images in Bracket Gamma, K band and H band. Note that the deconvolution was used only to remove the halo around each point source, charateristics of partially compensated images. The resolution of the raw images, 120 milliarcsec, was not altered by the deconvolution process.

importance for spectroscopy for instance, and even more for applications where high contrast are required. For example, planet searching/imaging require Strehl ratio $> 90\%$.[2]

Table 1 gives performance estimates in term of Strehl ratio $\mathcal{S}$ for various actuator interspacings, under what can be considered as median seeing (as in most of the current good sites), and our criteria for "worse operation seeing" adopted above. The Full Width at Half Maximum (FWHM) of the compensated images is λ/D (and not $1.22\lambda/D$), which for a 50-m telescope translates into 2.2 milliarcsecond (mas) at 550nm, 5 mas at 1.25 μm, 7 mas at 1.65 μm and 9 mas at 2.2 μm.

Table 1: Performance Estimates

		r_0(550nm) = 10cm		r_0(550nm) = 20cm	
	Actuator pitch	$\mathcal{S}$(550 nm)	$\mathcal{S}$(1.65 μm)	$\mathcal{S}$(550 nm)	$\mathcal{S}$(1.65 μm)
Case 1	10cm	74%	97%	90%	99%
Case 2	25cm	25%	86%	64%	95%
Case 3	50cm	2%	61%	25%	86%
Case 4	100cm	Seeing limited	21%	2%	61%

For a 50-m telescope, these four cases correspond to the following AO system parameters (assuming a Shack-Hartmann wavefront sensor):

Table 2: System Requirements

	Number of actuators per mirror	Computer power [Gflops]	CCD Pixel rate per sensor [Mpixel/s]
Case 1	200000	$9\ 10^5$	800
Case 2	30000	$2\ 10^4$	125
Case 3	8000	1500	31
Case 4	2000	92	8
SOR	789	≈ 2	4×4.5

As a comparison, we have also listed the system parameters of the existing Starfire Optical Range (SOR) AO system, which is currently the highest order system in use. The numbers in table 2 for cases 1-4 are based on a MCAO systems using 3 DMs and 4 WFSs looking at 4 LGSs (see below), hence the large difference in computer power requirement between the SOR and e.g. Case 4. The computer power and CCD pixel rate do not assume any parallelism of the processing (except for the SOR that uses high parallelism for both computer and CCD read-out[3]). The figure for the computer power was derived assuming a classical scheme for the loop control, i.e. a matrix multiply with a control matrix of size (total number of actuators)×(total number of measurements) (3 DMs and 4 WFSs). There is certainly more subtle control algorithms that could reduce the number of operations, but they are not available yet, therefore our conservative estimate.

These numbers are obviously mind boggling. Even with massive paralellization, we have heard of no such thing as a 10^6 Giga Flops (*1 GFlops* $= 10^9$ *Floating Point Operation Per Seconds*), nor a 200000 actuator deformable mirror, without mentionning the 800 Mega pixel per seconds out of the Shack Hartmann sensor CCD.

These issues, together with the theoretical limitations, are addressed in the following sections.

The performance of the cases listed above obviously match different science programs. Regular imaging and spectroscopy from 500nm onward, high Strehl ratio coronography in the IR need systems as in case 1-2. Case 3-4 deliver an image quality compatible with regular imaging and spectroscopy in near IR, low to moderate Strehl imaging in the visible. Unless there are incredible advances in the silicon technologies and/or the theory of adaptive optics/turbulence compensation, there will have to be a trade between the science goals and the AO system feasibility.

3. THEORETICAL CHALLENGES

One of the last obvious theoretical show stoppers to full sky coverage with AO on a large telescope was the cone effect with Laser Guide Stars (LGSs). Because an LGS is at finite altitude (90km), the beam propagating backward to the telescope aperture does not follow the same path as the beam from a celestial object. This effect has been recognized early and quantified by several authors.[4,5] Its amplitude depends on the vertical profile of turbulence and on D/r_0 in the telescope aperture, which means that it becomes more critical toward shorter wavelengths or for larger telescope apertures (or for worse seeing). In a regular astronomical site and for an 8-m telescope, the Strehl attenuation due to the cone effect is typically 50% at about 1.25 microns, and reduces further (to almost zero) at visible wavelengths. This is of course redhibitory for ELTs. To solve this problem, several schemes were proposed, that use several LGS in order to probe the entire volume of turbulence crossed by the light coming from an object at infinity. The measurements from the various LGSs would then have to be processed/mixed to extract the relevant information. Independantly, Beckers[6] proposed to use several deformable mirrors to compensate for the off-axis degradation of the image quality in an AO system, due to the anisoplanatism of the phase corrugation (given that in all AO system up to date, there is only one deformable mirror, usually conjugated to the ground, to compensate for the phase distortions). No convincing control scheme were found to beat the cone effect until Ellerbroek,[7] Fusco et al[8] and us (this paper) proposed to associate turbulence tomography -using several LGS and wavefront sensors- and multiconjugate, and by considering the system as a whole, including both measurements and mirrors to minimize the phase error, without explicitely trying to reconstruct the 3 dimensionnal phase.

This scheme is called Multi-Conjugate Adaptive Optics (MCAO). It relies on the signal coming from a very limited number of guide stars (3-5, at first order independent of the telescope aperture and therefore also applicable to an ELT) to drive a limited number of deformable mirrors (2-3), conjugated at several altitude. The net benefit is a large increase of the compensated field of view, in the sense of a homogeneous image quality over several arcmin (2-3).

Let us now sketch how MCAO works and show an example of its performance.

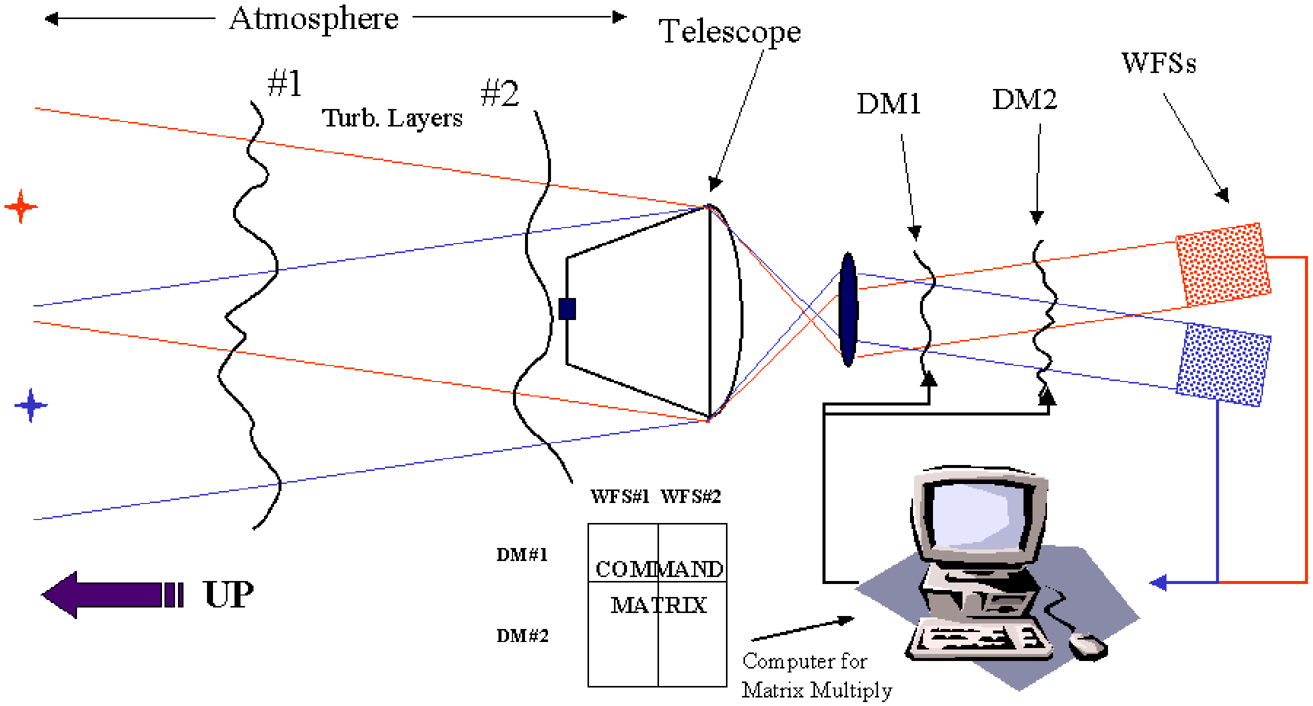


Figure 2. Sketch of the MCAO principle.

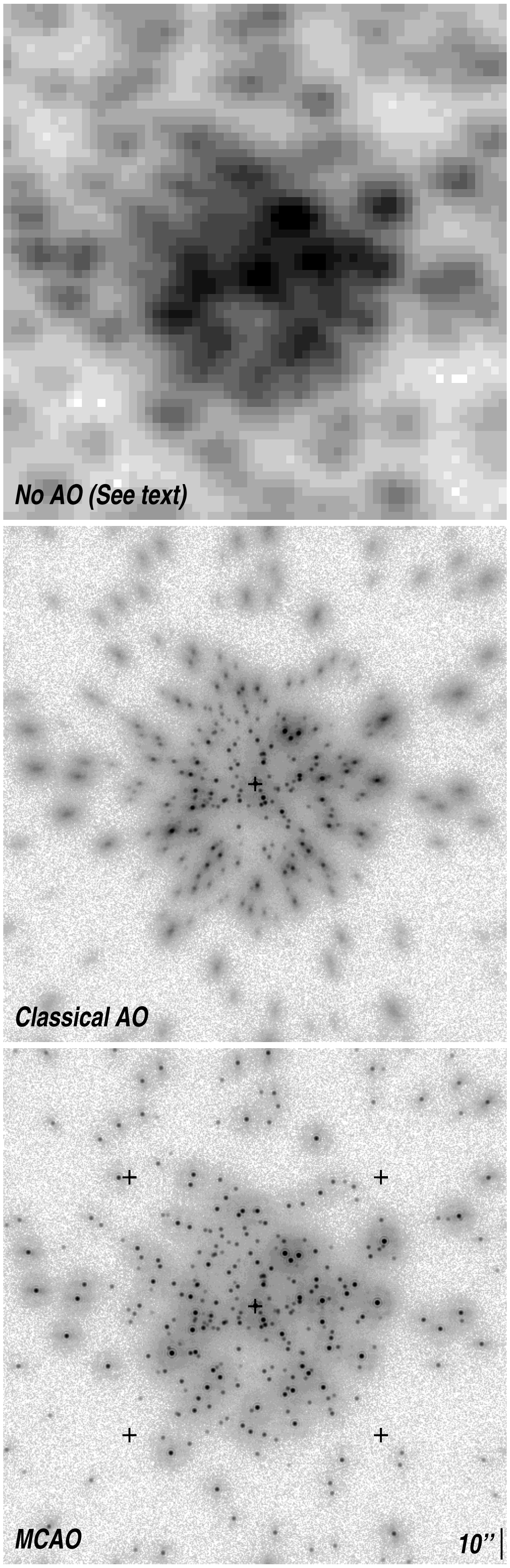
Figure 2 shows the layout of a MCAO system. Here, two wavefront sensors look at two guide stars (LGSs or NGSs) separated by a angle which is typically of the order of the required compensated field of view. The beams pass through slightly different volumes of turbulent atmosphere, however, both cross all layers. Several deformable mirrors (two in fig 2) are optically conjugated to different altitudes, which means that their *images* are in focus at these altitudes. In Fig 2, one of the mirror is conjugated to the ground layer (pupil of the telescope). If an optical aberration is present at ground level, the two sensors will deliver the same signal since the shear of the two beams is zero at this altitude. Because of the shear of the two guide star beams at the upper layer, the two sensor will measure different quantities if a phase distortion is present at this altitude (namely, the measured distortion will be shifted by the geometrical shear of the beam). As a classical AO instrument, this MCAO system can be “teached” how to react to a measured phase distortion by doing an “interaction matrix” between deformable mirrors and wavefront sensors. It will then figure how to split the phase correction between the two deformable mirrors, from the information collected by both sensors. As for classical AO system, several control algorithms can be used: Least square (this paper), minimal variance estimators (Ellerbroek 1994), Maximum a posteriori (MAP, Fusco et al 1999), etc... Early numerical simulations show that this method is quite stable, and that the performance behaves smoothly with, for instance, mismatch of the conjugation altitudes. Fusco et al (1999) found that three mirrors and five guide stars are sufficient to get the maximum efficiency from the MCAO system (same Strehl ratio over the wide field as the Strehl ratio obtained on axis with a classical AO system using the same actuator density).

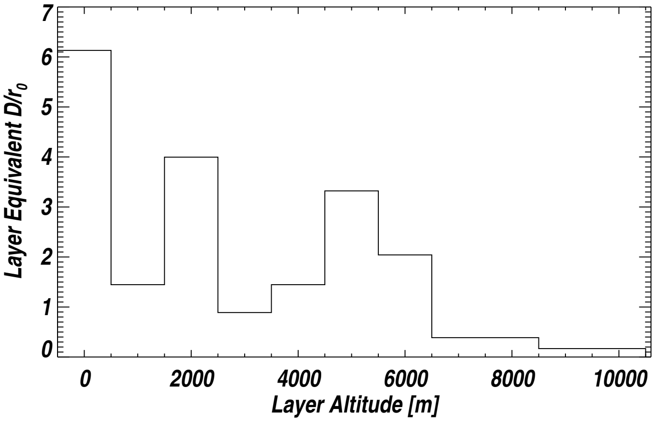
Figure 3 to 5 give an example of the performance of MCAO. Figure 3 displays the 11 layers turbulence profile adopted during this simulation, that is typical of astronomical sites (equivalent to 0.7 arcsec seeing). To demonstrate the gain brought by MCAO, we have simulated a stellar field containing a total of 320 stars, some field stars and a globular cluster, shown in figure 4. This field was processed by a Monte-Carlo numerical simulation including models of the deformable mirror, wavefront sensor, and the 11 layers turbulence profile. It includes temporal evolution of the turbulence. The telescope aperture is 8-m. The top field of figure 4 shows the 165” field with no AO compensation. To be able to see the image quality, each stars have been locally blown up by 15×, which makes the crowding appears worse than it really is. The middle plot is the same field, compensated by a single deformable mirror, single sensor AO system. The effect of angular anisoplanatism is evident. This is one of the current main limitation of producing

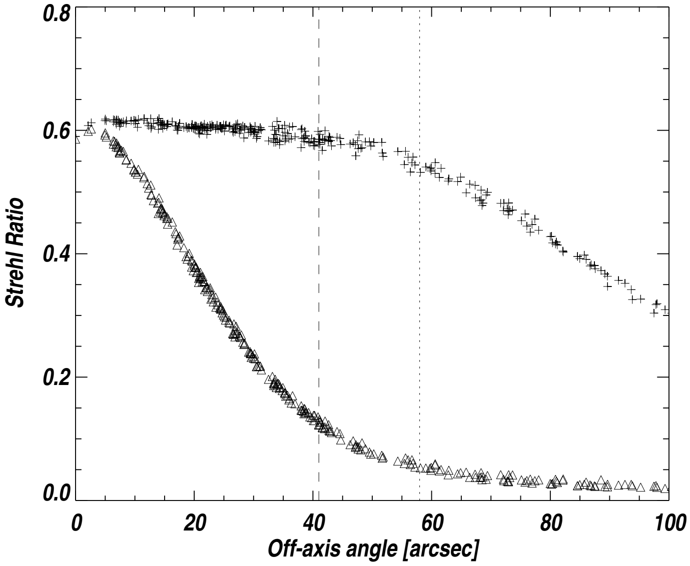
Figure 3 (below): 11 layers turbulence profile. D/r_0 is plotted per layer. D/r_0 integrated over the whole profile is 10.

Figure 4 (left): Simulated stellar field, containing 320 stars, and showed without AO, with a classical one-mirror pupil-conjugated AO and with a 2 DMs MCAO. Images at 2.1 μm on a 8-m telescope. The field of view is 165 arcsec on the side. Initial seeing is as shown on fig1, which translates into a seeing of 0.7 arcsec at 550nm on a 8-m telescope. Note that each star has been individually and locally blown up 15x to be able to better see the PSF variations. Because of this, the crowding looks worse than it actually is (especially on the No AO image). The guide stars are not shown on these images, but their positions is marked by crosses. See text for details on the configuration of the MCAO system.

Figure 5 (bottom): Strehl ratio versus field angle for a classical pupil-conjugated AO system (triangles) and a MCAO system (crosses), from the fig.2 star field. Note the flat Strehl ratio plateau, and the smooth decrease compared to the classical AO case.







science with AO compensated images. Because the PSF is not homogeneous over the FoV, the photometry is very delicate; Not only it is very difficult to have accurate calibration of the degradation of the PSF across the field, but also there is no deconvolution algorithm that can take such variations into account, and there are a limited number of PSF fitting packages that can (DAOPHOT can in a limited fashion). This is one reason to have an homogeneous PSF across the field, which is provided by MCAO as shown in the lower panel of figure 4. This MCAO uses 5 guide stars (located at the crosses) and two mirrors conjugated at 0 and 6km. Both deformable mirrors have an actuator pitch of 1-m. The images are computed at 2.1 microns. This dramatic improvement of image quality is quantified in figure 5, which shows the Strehl ratio of all the stars in this image for the MCAO and Classical AO cases. Notice the Strehl plateau within the FoV defined by the 4 outer guide stars, and the smooth decrease beyond that. The improvement in Strehl ratio ranges from one (no improvement at the center) to approximately 20 at the edge of the field, with a 10× improvement at the edge of the field defined by the outer guide stars.

To summarize:

- MCAO provides a solution to the cone effect, using a very limited number of Laser Guide Stars
- MCAO provides a homogeneous PSF quality over a large field of view (up to now 2-3 arcmin)
- The altitude conjugation of the deformable mirrors is not critical (performance degrade very smoothly with misconjugation)
- Additional Natural guide star(s) is (are) needed to measure tip-tilt, but this star(s) can be much further away than in regular LGS compensation (within the field of view of the MCAO system, i.e. several arcmin). This leads to 100% sky coverage for a single tip-tilt guide star on an 8-m telescope.

There is obviously many other areas where theoretical advances would benefit AO for ELTs, particularly, as underlined above, to aleviate some of the very heavy technological limitations. Faster/better estimators, streamlined control algorithms would be one. Prediction could also help.

4. ENGINEERING CHALLENGES

This section is purely qualitative, as (a) one deals with emerging technological developments, not proven to lead to usable devices and (b) the authors are mostly working in theory or practice of AO, and are in no way driving technological developments nor part of them.

As seen in section one, the requirements for an ELT AO are many order of magnitudes above what the currently used AO technology can achieved. Stepping up to those new levels require not a simple upgrade of the existing technology, but a whole new class of devices. As in table two, we subdivide in three major items: Deformable mirrors, computers and wavefront sensors/CCD/CCD controllers.

4.1. Deformable mirrors

Current deformable mirrors (DMs) are not expandable to several thousands of actuators. Piezoelectric (PZT or PMN) material has its limitations, and for several microns of expansion, one needs a minimum of material (the typical pitch of a PZT mirror is 4-7 mm), which prevents scaling up. Membrane/electrostatic/curvature mirrors suffer from the same problem, plus the fact that, the mirror being fixed only at its edges, the natural resonnance frequency of the mirror surface goes down as the number of actuators increases.

Interesting avenues for ELT AO DMs are liquid crystal devices and Micro Electro-Mechanical systems (MEMS). Liquid crystals would be the ideal device, as it works in transmission and would ease considerably the multi-conjugate opto-mechanical implementation. However, they have been in development for years and although progress have been made, they still suffer from a number of limitations which may not be solved in the next 10 years (chromatism, speed/binarity of the phase compensation, absorption bands). A number of laboratories (Lucent, AFRL) have started for some years to develop MEMS devices, with some results. These are based on silicon processing, and their potential large scale use for other applications make the success of their development more probable. Typical actuator pitches for the currently existing prototypes are of the order of 100 microns. One can therefore fit 2000 of them across an 8 inches wafer, which is more than enough for our applications. The current problems to solve are mostly related to the filling factor of the actuators (currently of the order of 70%). Stroke is small (a micron of less) both for current liquid crystals and MEMS, but this may not be a very critical issue, as turbulence is split between the several MCAO DMs.

It is expected that the Center for Adaptive Optics (CfAO) will play a leading role in the development and funding of these new technologies.

4.2. Computers

There is not much to say here, except that extrapolating the typical factor of 2 every two years in computing power does not provide an obvious solution to the problem at the 10 years horizon. Although radically new technology as optical computer may be a promising avenue, it is questionable that they will be commercially available in 10 years. A combination of optimized control algorithms, faster chips and massive parallelism is in our opinion the most probable outcome.

4.3. Wavefront sensors, CCD and CCD controllers

All sensor schemes could possibly be used for a high order MCAO system. The trade between Shack-Hartmann, curvature, shearing and pyramidic sensors will have to be made, one of the most important element being noise propagation at large number of actuators/subapertures. One could also think of a combination of several of these techniques. A Shack-Hartmann sensor, for the above defined Case 2 (subaperture size 25 cm), would have 200 subaperture across, which fits easily into existing CCDs. A possible scheme would be for instance 16 128^2 CCDs with 50×50 subapertures per CCDs, 2×2 pixels per subapertures, no guard pixels. For a 4 WFSs system, this would totalled to 64 128^2 CCD, and 64 controllers (existing controllers are adequate, as the one used by the SOR or the Keck systems, although more compact existing controllers could be used).

5. SUMMARY AND CONCLUSION

Although AO has become a mature techniques, producing astronomical science results, the steps to having AO on an ELT will be challenging. Because AO is an integral part of such telescopes, it has to be streamlined, robust, work in all conditions and provide 100% sky coverage. AO theory is now providing solutions for implementation of such systems, by the use of LGSs coupled with a close-loop Multi-conjugate system. However, technology is not yet ready to cope with the requirements imposed by the very large aperture, imposing extremely high order systems. Promising avenues include MEMS and liquid crystal correctors. Computing power is also an issue, and faster reconstructor algorithms would be urgently needed to unload hardware requirements.

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