FP6 ELT Design Study WP 9400: Novel AO Concepts for ELT

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Abstract: Within the Framework Program 6 (FP6) of the European Union a design study for an European Extremely Large Telescope (ELT) was started in 2005. As part of this study the work package 9400 is tackling the task to investigate new wavefront sensor concepts for such a telescope. The rational behind is that an ELT will strongly depend on Adaptive Optics (AO) to employ its full diffraction limited capability, but current Natural Guide Star sensing techniques suffer large sky coverage limitations. A Laser Guide Star (LGS) can reduce such limitations but suffers with increasing telescope diameter more and more from technical issues like the spot elongation, differential de-focus, etc. The work package is investigating the problems of AO at ELT and new sensing techniques to overcome the technical difficulties. We summerize how current Natural Guide Star AO systems perform, discuss key components of AO in respect to ELT and than move on to LGS and their problems at ELTs. Finally there is an overview of the concept studies carried out within the work package 9400.

Keywords: ELT, AO, MCAO, LGS, Novel AO concepts, PIGS, SPLASH, Virtual Wavefront Sensor, Variable Wavefront sensor, FP6

1. INTRODUCTION

Most of the current 4m to 10m class ground based telescopes are equipped with Adaptive Optics (AO) compensating the atmospheric turbulence to reach the diffraction limit. The idea for such a system was already proposed in the mid 50th [1], found its way into astronomy in the 90th and is now on the stage of maturity.

The major parameters to characterize the performance of an AO system are Strehl, limiting magnitude of the guide star and isoplanatic patch. Simplified, the Strehl tells how much light ends in the inner core of the Point Spread Function (PSF). The Limiting Magnitude of the Guide Star gives the faintest star the AO system still works on. The isoplanatic patch defines the area in which the system provides correction, what strongly depends on the atmosphere. Table 1 shows what current systems approximately achieve. An AO system of a 8m telescope has the usual performance of about 0.6 in Strehl, a limiting magnitude of about 17 and an isoplanatic patch up to $1'$. To reach peak performance a bright guide star is needed (about 9th magnitude) and reasonable seeing conditions ($0.7''$ in V). These constrains limit the sky coverage!

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Table 1. Performance of current AO systems.

Name of AO System (Telescope)	Reference	peak/avrg. Strehl in K	Isoplanatic patch diam.	Limiting Peak/ Absolute M_V
Keck-I	[5]	0.5/-	$60''$ $(24'')^*$	8/14
Subaru AO	[3]	0.3/-	$80''$	12/18
NAOS (VLT)	[2][4]	0.6/-		10/17
MACAO (VLT)	[6]	0.65/-		9/17
ALTAIR (Gemini-N)	[7][4]	0.6/0.2	$50''$	11/16
PALAO (Palomar)	[8]	0.7/-		8/14.5
PUEO (CFHT)	[9]	0.8/0.6		13.5/17
ALFA (Calar Alto)	[10]	0.7/0.5		8/14
AdOpt (TNG)	[11]	0.6/-		8/15

2. KEY COMPONENTS

The key components of an AO system are deformable mirrors, the detectors and computing power to run the real-time control. All these components have to become larger or faster to reach the needs of an ELT but there might be solutions that even with current technology the technical needs can be satisfied.

2.1. Deformable Mirror (DM)

The number of actuators and the size of stroke are main parameters of a deformable mirror. The amount of actuators have to increase a factor 100 from existing DM to reach the needs of an ELT which is diffraction limited in the visible. With high density DM it might not be possible to achieve the stroke needed ($> 2\mu m$). The demands on the number of actuators can be solved with segmenting deformable mirrors, i.e. filling the aperture with 100 of current DM, while cascading several DM can provide the stroke needed. One DM with less actuators but high stroke and another with large number of actuators but low stroke.

2.2. Detectors

Linear to the number of sub-apertures, the number of detector pixels have to increase. There are currently no monolithic detectors available, neither IR nor visible, providing the amount of pixels. But there is no strong need to have one monolithic detector. The sensor optic could be designed to support a multi detector configuration.

2.3. Computing

If the number of actuators increases a factor of 100 the additional need of computing power increases with the square root of it. This means 10000 times more computing power than current systems. A commercially available workstation with 4 CPU is in these days able to handle a 1000 actuator loop [12]. Using Moors Law such machine would scale to the needs of an ELT in about 13.2 Years. Heavy parallel processing could handle the needs already today.

*Up to this diameter the performance degrades only marginally.

3. SKY COVERAGE

AO depends on a guide star bright enough to sense the wavefront aberration. The more spatial frequencies one want to correct the brighter the star has to be. In the Galactic Plane it is easer to find a proper guide star while at the Galactic Poles this is more difficult, as there are less stars. Conventional single star AO has a usual sky coverage of 4% and below but can raise for certain targets and low Strehl demands to about 22% [13]. One way to get a larger sky coverage is to use several fainter stars and co-add them. Simulations for LINC-NIRVANA an instrument using such AO technique shows a sky coverage of 98% in the Galactic Plane, down to 17% at the Poles. Such estimates are based on statistics. Therefore it is not sure if the favored target can be observed with AO or not. Laser Guide Stars give a further opportunity to observe targets even with no Guide Star close to the target. Sky coverage between 50 to 100% can be reached. The full 100% is not possible as there is still need of a star for tip tilt correction which can be fainter and further away from the target as Guide Stars usually are. However LGS suffer some crucial technical problems which scale with the telescope diameter and can not be solved easily for an 30m or even 100m telescope.

4. LGS AT ELT: THE PROBLEMS?!

LGS suffers from problems related to the finite distance of the LGS and its vertical extension.

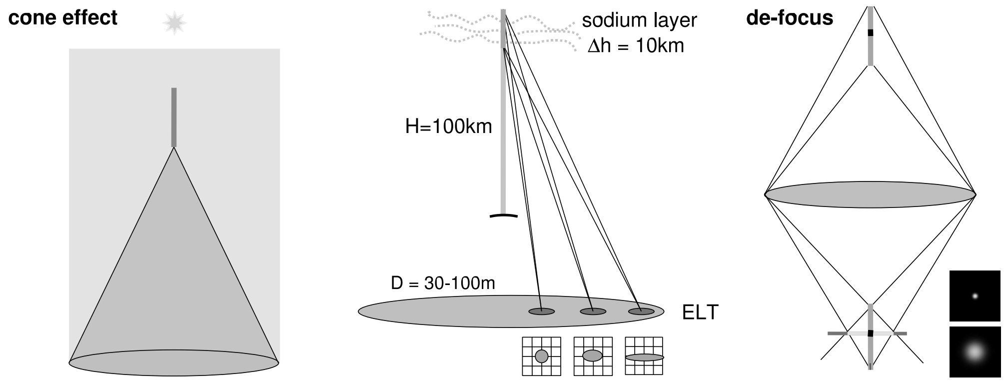

Figure 1. The finite distance and extended length in vertical direction of the the laser guide star leads to several problems within the sensor. **Left, Cone effect:** The LGS does not probe the full atmosphere like a NGS. **Middle, Perspective Elongation:** Off axis projection of the LGS leads to elongated spots in the sensor plane. **Right: De-focus** The finite distance of the LGS and it's vertical extension makes it difficult to define one image plane without de-focus and internal abberations.

4.1. Cone effect

The light of a LGS does only probe a cone of the atmosphere not the full volume like a NGS. This leads to increased anisoplanatism. Multi LGS in a MCAO fashion can remove the cone effect. But such solution results in additional constrains on the field, geometry and number of LGS. Investigations on the parameter space results in up to several LGS and field size over which the LGS have to be projected goes up to more than 200″ [14].

4.2. Perspective elongation

The Perspective Elongation results from the projection of the vertical extended LGS on the image plane. The effect increases the further away from the launch axis the sub-aperture is located. The sensitivity in the elongation direction gets reduced and the sub-aperture has to be extended in the elongation direction to avoid aliasing with neighbor sub-aperture.

4.3. De-focus

The finite distance and the vertical extension introduces three further kind of problems which can be named as extended focal depth, dynamic focal plane and differential abberations.

4.3.1. Extended focal depth

The vertical extension of the LGS makes it impossible to get one focused image of the LGS in the focal plane. This problem is normally targeted with range gating or temporal gating, respectively. Only a small part of the vertical extended LGS is used (i.e. in Fig. 1 right the portion shown in black). The laser is pulsed and synchronized with the detector. But the larger the telescopes gets the smaller the gating time has to become [15]. The laser pulse can not get infinitely small. There is a technical limit. To increase the photon return dynamic refocusing can be used [16]. This technique follows the laser pulse during its vertical travel while permanently collecting the photons. Therefore not only the light of a small fraction of the vertical extended LGS is used but a large fraction of its length.

4.3.2. Dynamic focal plane

Due to telescope movements the distance to the LGS permanently changes. The larger the zenith distance the further away is the sodium layer in the atmosphere. The sensor must be able to compensate for such distance change and needs to track it.

4.3.3. Differential abberations

The LGS is at a finite distance. The telescope optics itself is designed and optimized for targets in infinity. Therefore it will introduce internal abberations to such a finite focal plane. With changing the sodium layer distance such abberations will change.

5. THE NEW CONCEPTS STUDIED

The work package Novel Concepts for AO within the ELT design study studies four different concepts which goal on solving several of the problems mentioned in the previous chapter.

5.1. PIGS - Pseudo Infinite Guide Star Sensor

PIGS is a concept using two sensing devices (Fig 2). A mask with annular slits in the infinity focus sensing in radial direction and a reflecting rod in the LGS focus sensing the azimuthal direction. The rod uses the light of the LGS over its full vertical length and therefore has no light loss due to temporal gating. As a real 3-D device the rod has also no problem with the Perspective elongation and extended focus depth. The dynamic focus plane can be covered with a longer rod. Only the differential abberations have to be treated in addition. The cone effect can be solved with an MACO setup of such sensor.

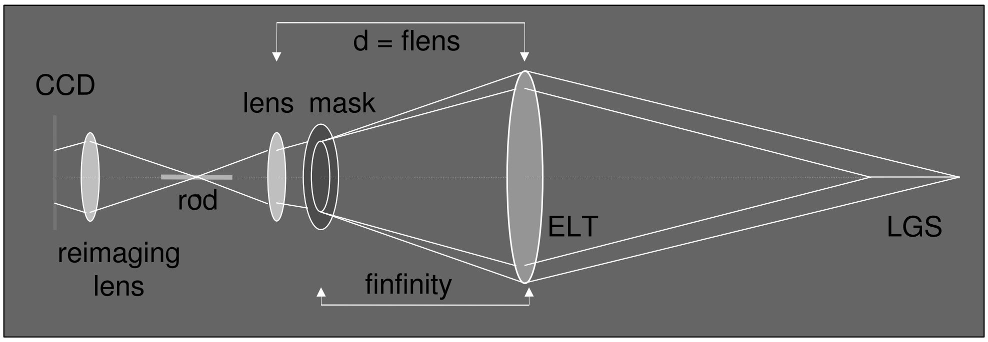

Figure 2. Setup of the PIGS concept with two sensing devices. A mask with annular slits in the infinity focus and a reflective rod in the LGS focus.

5.2. SPLASH - Sky Projected Laser Array Shack Hartmann

SPLASH projects a Shack Hartman pattern already on sky instead of dividing the light in the sensor. Therfore it solves the cone effect. As it is a parallel projection over the full telescope aperture there is no perspective elongation effect. The extended focal depth has to be treated with temporal or range gating, while the dynamic focal plane can be solved through re-focusing over time. Telescope abberations have to be treated in addition.

5.3. Virtual Wavefront Sensor

The virtual WFS concept was invented for the Euro50, a 50m telescope project of the Observatory Lundt. The concept implements a reference source within the AO system which is measured in parallel to track the telescope abberations. In the virtual WFS the measurements of the reference source is compared with the LGS sensor measurements and the telescope aberration can be extracted. This concept is taking only care of the differential abberations.

5.4. Variable Wavefront Sensor

The variable wavefront sensor exists of several ideas which are connected to a system that can react to dynamic changes during observation. One main part an acoustic cell filled with water which is used as lens-let array of an SH sensor. Applying a sound wave and changing their properties the power of the lens-let array can be changed and adapted to the layer altitude, LGS altitude, etc. The cone effect is solved to multi lasers. The spot elongation is handled with fourier analyzes instead of simple centroiding. Therefore multiple and extended sources, like LGS, can be used. In certain setups a kind of dynamic refocusing and focal plane tracking can be implemented with such concept. Telescope abberations have to be handled separately in addition.

6. CONCLUSION

ELT will depend on Adaptive optics to reach its full capability.One of the crucial drawbacks of AO is the dependence on guide stars. The sky coverage for single NGS AO is quite limited. MCAO will increase the sky coverage but ELT will depend on LGS to solve this problem to satisfaction. Key components of an AO system do not appear as show stopper for AO on ELT. There are ways to solve the problem of larger and faster. But scaling conventional LGS to an ELT will also scale the size of the known technical difficulties of the LGS approach like cone

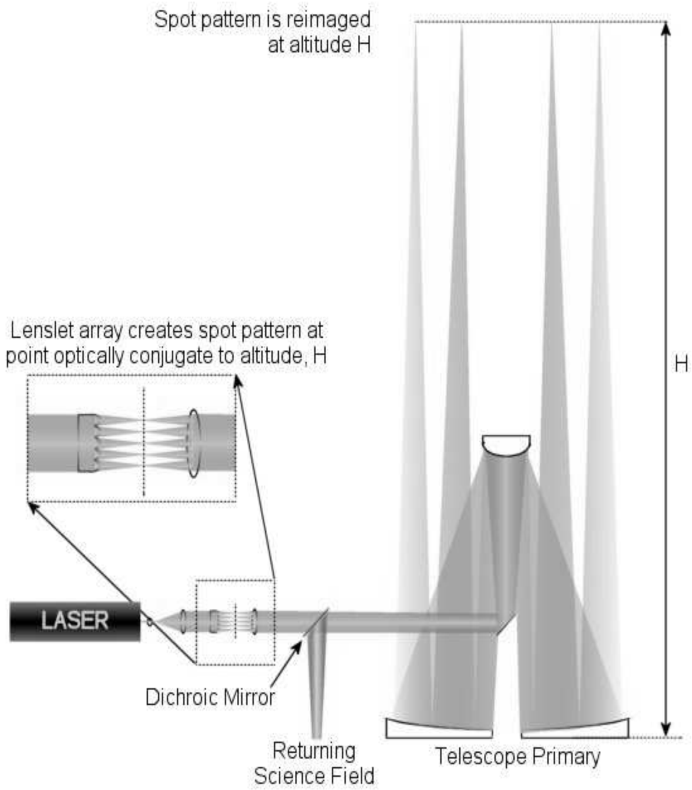

Figure 3. Setup of the SPLASH concept. A Shack Hartmann pattern is projected through the main telescope on sky. The relative location of each spot is measured in the image.

effect, perspective elongation and abberations. Four new concepts to the already known ones, like MCAO, dynamic refocusing, temporal gating, etc, are under investigation, PIGS, SPLASH, virtual wavefront sensor and variable wavefront sensor. We try to understand if they can solve the problems in a simpler and more effective way. Our current conclusion is that in general the cone effect can be solved through MCAO. The perspective elongation effect is targeted by PIGS, SPLASH and the fourier analyses of the Variable WFS. Abberations due to extended focal depth are solved by temporal gating with or without dynamical refocusing and PIGS. Focal plane changes are fixed by refocusing or intrinsic (PIGS). The virtual wavefront sensor is targeting the problem of differential abberations. All these concept are or will be tested in the next years within the work package Novel AO Concept for ELT. Than it will be more obvious which are feasible solutions for LGS AO at an ELT.

7. ACKNOWLEDGMENTS

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