AVOIDING TO TRADE SENSITIVITY FOR LINEARITY IN A REAL WORLD WFS

D. Greggio\textsuperscript{1,2,a}, D. Magrin\textsuperscript{1}, J. Farinato\textsuperscript{1}, R. Ragazzoni\textsuperscript{1}, M. Bergomi\textsuperscript{1}, M. Dima\textsuperscript{1}, L. Marafatto\textsuperscript{1,2}, and V. Viotto\textsuperscript{1}

\textsuperscript{1}INAF, Osservatorio Astronomico di Padova, Vicolo dell'Osservatorio 5, 35122, Padova, Italy
\textsuperscript{2}Università di Padova, Dipartimento di Astronomia, Vicolo dell'Osservatorio 3, 35122, Padova, Italy

Abstract. In the framework of the European ELT design, partially open-loop MCAO systems, coupled with virtual DMs, have been proposed to achieve AO correction using solely NGSs, to be selected in a Field of View as wide as allowed by the Telescope optical design. This concept is called Global MCAO.

The conceptual design of a very compact wave-front sensor, exploiting the just mentioned concept and characterized by a dynamic range limited by the stroke of the Deformable Mirror and by a limiting magnitude performance typical of a closed loop coherent wave-front sensor, have been presented in the past.

We present here an updated and more detailed study of the Very Linear WFS, which includes a synoptic study concerning its optical design, investigating also possible conceptual opto-mechanical realization of a probe capable to co-exist with the currently foreseen E-ELT LGS probes.

We also present a conceptual opto-mechanical design of a Global MCAO pathfinder, to be possibly installed on a 8-m class telescope, which might be a precursor of the E-ELT system, realized in a way to perform Low Layer correction for example at the VLT.

1. Introduction

The Global MCAO technique proposed for the European ELT promises to achieve adaptive optics correction with only natural guide stars (NGS) and a sky coverage of approximately 60% at the galactic pole (for further details about Global MCAO the reader can refer to [1-2-3-4-5]). In particular this new technique relies on the use of a wave-front sensor with very high linearity range and sensitivity (we will call it Very Linear WFS). The linearity requirement is needed to get accurate measurements of the wave-front shape in open loop (i.e. when the wave-front correction is applied after the wave-front sensor). On the other hand, the high sensitivity is required to use natural guide stars as faint as $M_V=17$ mag in order to achieve a good sky coverage. A conceptual opto-mechanical design of such a wave-front sensor was already presented in the past (see [6-7]) and it makes use of two different wave-front sensors at the same time:

1. a pyramid wave-front sensor, with high sensitivity but poor linear range

\textsuperscript{a} e-mail : d.greggio@hotmail.it
2. a YAW wave-front sensor, with high linear range but poor sensitivity [see 8]

The pyramid sensor is fed by the light of the reference star in the wavelength range 0.6 - 0.9 μm and works in closed loop with a local deformable mirror (DM). The YAW sensor measures the shape of the local DM and is fed by a monochromatic source (namely a He-Ne laser at λ = 0.6328 μm). The final open loop signal is obtained summing up the residuals of the correction measured by the pyramid and the signal from the YAW sensor.

This concept is shown in "Fig. 1", in which the light picked-up from the star through a folding mirror and the monochromatic light injected through a fiber are sent (through a collimator) to the DM, and the split through a dichroic is done after a re-focusing lens. The general idea, explained in "Fig. 1", is to collect the light from an annular area much bigger than the one we want to correct, and thus there should be a certain number of movable arms (based on the concept described in the figure) which can enter in the telescope FoV, select and fold the light coming from a reference (which we consider a star in the concept shown here, but it could be as well an artificial reference) and analyze the wave-front giving an open loop measurement of the aberrations.

Fig. 1. Conceptual scheme of the Very Linear WFS. Top: sequential diagram. Bottom: optical concept

Following this concept, several different optical design have been investigated and one among them was chosen to perform a tolerance analysis in order to check its feasibility. Finally we investigated also
the possibility to build a scaled version of the system for an 8m class telescope as a precursor of the E-ELT instrument.

2. The Very Linear WFS optical concepts

The main goal in the optical design of the VL-WFS is to achieve a nearly diffraction limited optical quality for both the pyramid and the YAW sensors in order to have only a small contribution to the final error budget from the optical components. Other requirements that have been considered for the optical design are the following:

- reduced system dimensions (occupied volume)
- small number of optical elements
- “AIV friendly” (reduced alignment tolerances)
- use of the same optics for both the “star light path” and the “laser light path” in order to minimize the non-common path aberrations

Geometrically speaking, the main issue is to join the laser light and the star light in order to have both of them illuminating the local DM and to separate them immediately before the wave-front sensors. This can be done in two ways:

1. Spatially separating the focal planes of the two beams by working off-axis
2. Using dichroic filters to separate the beams

Five different optical design have been considered (layouts are shown in "Fig. 3-7") and only one of them uses off-axis sources. All of them are characterized by a collimating lens followed by the local DM. The light passes through the collimator twice: before the reflection from the DM (incoming beam) and after the reflection from the DM (outgoing beam). In order to avoid the superposition of the focal planes of the two beams, it is necessary to move out from the auto-collimation point. This can be achieved moving the focal point along the optical axis or perpendicularly to it.

In "Fig.2" all the optical designs are compared with respect to the focal point of the collimator. The five optical design are denoted by letters A, B, C, D, E and the subscript "1" denotes the focal position of the incoming beam while subscript "2" denotes the focal position of the outgoing beam. Letter B represent the off-axis case, in which displacement along both x and y direction of the focal point allows separating between incoming and outgoing beam and between laser and star light. On the other hand, in designs A, C, D and E the axial displacement of the focal point is used to separate incoming and outgoing beams while dichroic filters are used to separate the light of the laser from the light of the star.

Fig. 2. Schematic representation of the five optical designs (letters A, B, C, D and E). The focal length of the collimating lens has been normalized. The subscript "1" denotes the focal position of the incoming beam while subscript "2" denotes the focal position of the outgoing beam.
Fig. 3. Design A. Top: Pyramid channel. Bottom: YAW channel

Fig. 4. Design B. Top: Pyramid channel. Bottom: YAW channel.

Fig. 5. Design C. Top: Pyramid channel. Bottom: YAW channel.
3. **Performance and Tolerance Analysis**

The main features of the optical designs are summarized in Table 1. The simplest design is B. It is characterized by a small number of optical elements and a good optical quality. On the other side, it makes use of off-axis optical elements that requires a longer alignment procedure and the light from the star and from the laser don't follow the same optical path. As an alternative solution we have chosen the design E for its simple configuration, low number of optical elements and good optical quality. Another advantage of design E is that its focal plane is less populated than design B, in which the input and output focal planes of both channels are next to each other.
The performance was evaluated in terms of SR on the focal plane of the two channels. The polychromatic PSF for both channels of design E is shown in "Fig. 8" and its peak value (corresponding to the SR) is equal to 0.99.

<table>
<thead>
<tr>
<th>N° optical elements</th>
<th>Optical common path</th>
<th>Off-Axis optics</th>
<th>SR @Pyramid</th>
<th>SR @YAW</th>
<th>Size [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Yes</td>
<td>No</td>
<td>99</td>
<td>98</td>
<td>1650</td>
</tr>
<tr>
<td>B</td>
<td>No</td>
<td>Yes</td>
<td>97</td>
<td>97</td>
<td>1690</td>
</tr>
<tr>
<td>C</td>
<td>Yes</td>
<td>No</td>
<td>94</td>
<td>99</td>
<td>1890</td>
</tr>
<tr>
<td>D</td>
<td>Yes</td>
<td>No</td>
<td>99</td>
<td>100</td>
<td>2000</td>
</tr>
<tr>
<td>E</td>
<td>Yes</td>
<td>Yes</td>
<td>99</td>
<td>99</td>
<td>1980</td>
</tr>
</tbody>
</table>

Fig. 8. Polychromatic PSF of design E. Left: pyramid channel. Right: YAW channel.

For the last optical design also a preliminary tolerance analysis was performed in order to check its feasibility. The most critical factor appeared to be the tilt of the Deformable Mirror (±20 arcsec) because of the long focal length used. This would probably require particular attention on the realization of the mechanical structure of the VL-WFS and on its alignment procedure. All the other tolerances (listed in Table 2) are within common tolerance values and are easily achievable. The final optical quality for the system has been calculated via Montecarlo simulations and we expect a Strehl Ratio equal to SR = 0.70 or better.

4. A precursor of the E-ELT: low layer AO correction

An interesting fact is that, considering fixed to 10’ the FoV where the stars shall be looked for, the same pupils overlap that we have on a 40m telescope at 10km height is obtainable with an 8m telescope at 2km altitude. Thus, we might think to an instrument designed for one UT at the VLT.
which could both be used to make science and to demonstrate the Global MCAO concept in the view of a possible future instrument to be implemented on the E-ELT.

Table 2. Manufacture and operational tolerances for design E.

<table>
<thead>
<tr>
<th></th>
<th>Manufacture Tolerances</th>
<th>Operational Tolerances</th>
</tr>
</thead>
<tbody>
<tr>
<td>Curvature radii</td>
<td>±0.2%</td>
<td>De-center X</td>
</tr>
<tr>
<td>Thickness</td>
<td>±0.1 mm</td>
<td>±0.05 mm</td>
</tr>
<tr>
<td>Abbe number</td>
<td>±1%</td>
<td>De-center Y</td>
</tr>
<tr>
<td>Refraction index</td>
<td>±0.001</td>
<td>Tilt X</td>
</tr>
<tr>
<td></td>
<td></td>
<td>±2 arcmin</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tilt Y</td>
</tr>
<tr>
<td></td>
<td></td>
<td>±2 arcmin</td>
</tr>
</tbody>
</table>

In fact, such an instrument could be designed to have 2 DMs, one conjugated to the ground and one conjugated to 2Km of height, correcting the atmosphere in the range between zero and about three kilometers, which would exploit in this way a kind of super ground layer correction or, alternatively, what we call Low Layer MCAO. Moreover, it would scale down to the 8m class telescope the concept of Global MCAO, introduced for the 40m class telescopes, without compromises.

We made a conceptual design of the VL-WFS for such an instrument. It is basically a scaled down version of the WFS arms introduced for the E-ELTs case, which is presented in section 2.

The final structure has the same characteristics of the arm designed for the E-ELT case, i.e. it is a light-weighted structure of about 15 Kg, very compact and with the obstruction minimized as much as possible, to facilitate the pointing also of references quite close to each other (the minimum distance between the references is of the order of 20”).

Scaling down the E-ELT arm, smaller CCDs and DMs can of course be used. The final dimensions of the arm is perfectly fitting in the UT Nasmith interface, as it can be seen in "Fig. 9”, where a possible setup with 6 arms have been considered.

![Fig. 9. An hypothetic VL-WFS setup for the UT Nasmith interface at the VLT (photo taken from the ESO website)](Courtesy of ESO (ESO web-site))
5. Conclusions

The proposed concepts of an instrument for E-ELT based on the VL-WFS arms show that it is possible to build a WFS characterized by high linearity and sensitivity at the same time. The WFS can be realized with currently existing hardware and technology and also the tolerances are within acceptable values. Additionally the proposed designs have the advantage that can share the available space with other sub-systems on the Nasmyth interface of the E-ELT, such as the LGS arms, and thus they might be used together or instead of them, with several possible configurations:

- Initially the telescope could start the operations using solely NGSs, adding only in a second time the LGS option; this would reduce quite a lot the money initially required for the telescope construction, being the laser construction and maintenance a significant fraction of the overall cost
- When the LGS option will be installed and working, the NGS arm might be used for the low order correction which is anyway requested to be done on 3 NGSs in the current design
- In case of any failure of the LGS facility (their reliability and maintenance is still today an open issue, at Keck the scientific productivity with the LGS is half of the one using NGS), there will be always a backup solution ready to take over

Finally, such an instrument can be completely scaled down to be installed and tested at the VLT, performing in this way the LL-MCAO correction and, depending on the kind of implementation and setup that this instrument might have, it might be both an instrument and a pathfinder for the E-ELT or just a demonstrator of the Global MCAO concept in the view of a future implementation on the E-ELT.

6. References


