Pyramid based locally closed loop wavefront sensor: an optomechanical study.

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Abstract. Pyramid wavefront sensors have shown their ability to achieve ultimate performances in terms of usage of starlight photons. Several of these advantages, however, do relay on the fact that the starlight is focused onto the pyramid pin after being properly corrected. While conventional adaptive optics systems (including multi conjugated ones) automatically imply such a feature this is not true for Multi Objects or non conventional Multi Conjugated AO systems, or more in general for the ones where the compensated area is somehow different from the area searched for references. We have developed the concept of locally closed loop systems in a compact way along with various approaches to metrologically measure the wavefront with enough absolute accuracy, in contrast with the accuracy to vanish the residual in the conventional use of wavefront sensors. We show an optomechanical study conceived for the E-ELT and a choice of existing components in order to achieve the goal of detailed wavefront sensing with high dynamic range on the faintest references where a pyramid sensor can achieve significant results.

1. Introduction

The Adaptive Optics (AO) plays a fundamental role in the Extremely Large Telescopes (ELTs) era [1, 2, 3] and, moreover, the justifications to build such a mastodontic telescopes, taking into account the huge amount of money and manpower needed, will be extremely weak without the possibility to fully exploit their theoretical spatial resolution. As main consequence, special effort has been spent in the last years in the development and optimization of lasers for artificial stars generation in order to achieve the full sky coverage. Unfortunately, lasers are affected by fundamental problems such as the un-sensitivity to the very low order aberrations, which obliges to use anyway Natural Guide Stars (NGS), or the cone effect, which makes necessary to use much more references to cover the same Field of View (FoV). As a consequence, new ideas going in the direction of using in a more efficient way the natural light coming from the stars could make the difference and this is the case of the Extremely Linear WaveFront Sensor (EL-WFS). This study has been inspired by a quite new concept of Multi Conjugated AO (MCAO) with Natural Guide Stars for Extremely Large Telescopes (ELTs). The main idea is summarized in the following while a more detailed

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explanation can be found in [4]. Despite this, given the more and more wide awareness in the community on the necessity to assist the MCAO Laser Guide Stars (LGS) system with natural guide stars [5-8], an high sensitivity and very linear NGS sensor may find its justification as general purpose. We will show an opto-mechanical design extremely compact and feasible with existing technology and components or that will be for sure available at the time of ELT construction.

2. New concept MCAO NGS based

The idea beyond this new concept is to use a much bigger FoV to look for the WFS reference stars. In this way, the probability of finding suitable reference stars will become very high, increasing consequently the Sky Coverage reachable by the system.
For a 8 m class telescopes the footprints of a few stars at a range of several km, i.e. 8-9 km, still well overlap at a FoV of 2 arcmin. Increasing the size of the telescope entrance pupil (35-40 m) will increase also the overlaps of the footprints, allowing the exploitation of a larger angle of sight. The high altitude turbulence can be disentangled from the one at the ground by using the light from the different guide stars which crosses the atmospheric layers at different locations. For an E-ELT telescope aperture this figure ramps up to 10 arcmin, that is also the FoV for which the telescope is corrected.
Unfortunately, increasing the angle of the NGS line of sight implies a decreasing of the depth of focus of atmospheric turbulence estimation, that is the capability to correct thicker slices of atmosphere. In order to correct the same or a larger thickness, maintaining the same spatial degree of turbulence compensation, it is necessary to introduce a number of DM conjugated at high altitude roughly equal to the increase of the FOV, i.e. 5 DM, that is very impracticable and inefficient. This problem can be overcome by introducing the Extremely Linear WFS (EL-WFS) able to measure the wavefront instead of the deviation from zero. This allows to numerically close the loop with respect to a time evolving reference. Using the signal from EL-WFSs it is possible to numerically reconstruct the pattern of actuations for each DM (which number and altitude location is decided by the user) regardless they are physically existing or not, and then it is possible to re-compute the best configuration to give to the one-two real DMs, to compensate for any direction inside the 10 arcmin FoV and for any FoV size (the smaller the batter). This technique allows the correction of the scientific FoV, looking for NGSs over 10 arcmin FoV increasing dramatically the Sky Coverage. A preliminary estimation of the Sky Coverage have been computed in [9].

3. Extremely linear WFS concept

The EL-WFS should present at the same time two characteristics, an high sensitivity and an extreme linearity, that are not easily available in the usual WFS. The Shack-Hartmann, the Curvature or the Pyramid based sensors, since they have been conceived to perform in close loop and their linearity range is normally not high enough to provide open loop measurements. One could think to optimize the characteristic of any of the mentioned WFS to increase the linearity range (few lenses in the S-H case, small defocus in the Curvature case, modulation in the Pyramid case) but, in any case, being the WFS linearity inversely proportional to the

sensitivity, the sensor will of course decrease its capability to see the small details of the wavefront. On the other hand, YAW sensor [10] presents a very wide range of linearity, defined at the moment of the construction, but at the same time a poor sensitivity.
Thus, one could think to a combination of WFS, one very sensitive and working in close loop with a DM internal to the sensing system, and another one with a very high dynamic range looking at the shape of the DM i.e. the pupil shape.
In our configuration, a Pyramid [11] is closing the loop on a DM in order to exploit its high sensitivity while a YAW sensor continuously monitors the same DM shape illuminated as the light incoming from the telescope though an optical fiber as the light incoming from the telescope. The YAW pupil shape measurement, corrected by the residuals given by the Pyramid, will be the outcome result.
One can think to implement the two channels in an overlapping configuration over a common mechanical arm having a pick-up mirror able to capture the reference star light and feed the EL-WFS. In this way, every arm can be positioned on a natural reference giving the open loop measurement of its wavefront, that will be used to reconstruct the WF distortion at different altitudes, as explained in the previous section, and to send the signal to the real DMs.

4. EL-WFS Optical design

As explained in section 3, the very linear NGS sensor takes advantages of a first channel implementing a high sensitive WFS, the Pyramid, in closed loop with a DM and a second channel mounting a extremely linear WFS, the YAW, able to monitor on-the-fly the DM shape, i.e. the pupil. The design driver of the here proposed optical configuration is to work with all the optical elements on axis for both the channels, facilitating the alignment process and the maintenance of the alignment itself. This version of the NGS sensor has been conceived for the E-ELT and, in particular, to be installed at the Nasmyth focal station. For the E-ELT configuration, it has been assumed a primary mirror diameter of 39300 mm with a central hole having diameter 11100 mm and an effective focal length (EFL) of 686964 mm giving an output F number of 17.48. The NGS sensor optical design has been optimized in the wavelength range 600-900 nm.

4.1. Channel 1: pyramid in closed loop

In Figure 1 the optical design of channel 1 is shown. The F/17.48 beam incoming from the telescope is capture by a pick-up mirror at the E-ELT Nasmyth location and redirected to feed the NGS channel 1. In proximity of the entrance FP, a small window (thickness 3 mm, diameter 4.2 mm) is placed with a tilt of 2.5 degrees with respect to the optical axis. This window has been dimensioned to let pass through an unvignetted Field of view of 1 arcsec. The window is necessary in channel 2 optical path allowing to work on axis as explained in the following. For channel 1 the window introduces a negligible amount of astigmatism (the angle is small) that, anyway, can be calibrated. The beam is then quasi-collimated by a triplet (diameter ≅ 88 mm, EFL = 1443 mm) that illuminates the Deformable Mirror (DM). The DM has an active area having diameter 72 mm. A suitable DM could be an ADAPTICA product having a diameter of 76 mm with 28×28 actuators. The bundle of rays is then reflected back to the triplet (double pass) and focalizes at the first FP. Because the triplet is not exactly collimating the incoming rays, in the second passage the beam is focalized at a different location with respect to the entrance focal plane. In particular, the triplet EFL has been set to allow the installation of an annular mirror (diameter 26 mm) at the same location of the N-BK7 window with the same tilt of 2.5 degrees and, thanks to the exploitation of the central hole, without vignetting of the beam and interferences between the beam passing through the window and the beam reflected by the annular mirror (see Figure 2). The beam at the first FP is F/26.55. The beam is then rescaled to F/17.48 by means of a doublet working as focal reducer and forms the second FP where the pyramid is placed. Between the doublet and the pyramid, it is located at 45 degrees a dichroic filter able to reflect the He-Ne 632.8 nm and to transmit all the other wavelengths. The dichroic filter separates the beam between channel 1 (full bandwidth but HeNe) and channel 2 (only HeNe). The optical quality due to the NGS sensor optics is very high, in fact at the pyramid vertex (second FP) the theoretical Strehl Ratio of the polychromatic PSF is 98.75 (see figure 3). The pyramid has made in N-BK7, has a vertex angle equal to 4.6 degrees and an height of about 6 mm. A second doublet collimates the four beams forming the four pupils on the detector. The pupil size has been determined in order to sample 196 sub-apertures over the diameter corresponding to 200 mm on the primary mirror. Assuming 24 micron as pixel size (as E2V CCD 220, 240×240 pixels), the detector format required to cover the four pupils area (including redundancy) is about 416×416 pixels. This format is compatible with the new generation E2V CMOS sensor, actually under development and expected to be available in 2013, that is expected to have 720×720 pixels [12]. Never the less, the four pupils can be divided, for example using four mirrors in pyramid configuration after the final doublet, in order to feed a dedicated E2V CCD 220 for each pupil.

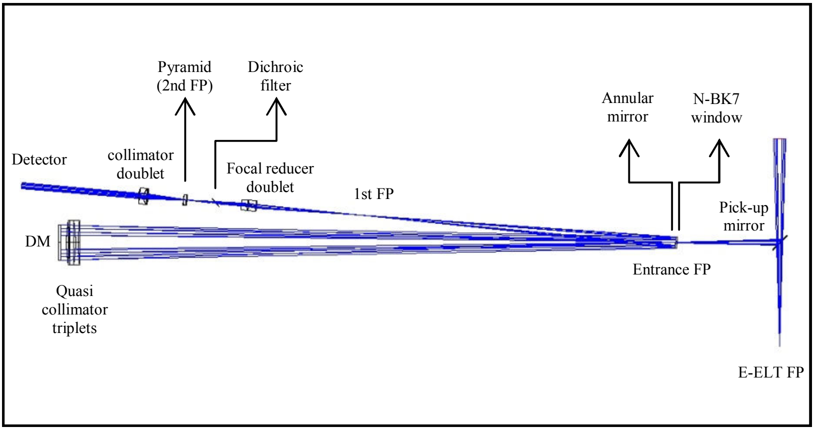

Fig. 1. Optical layout of channel 1.

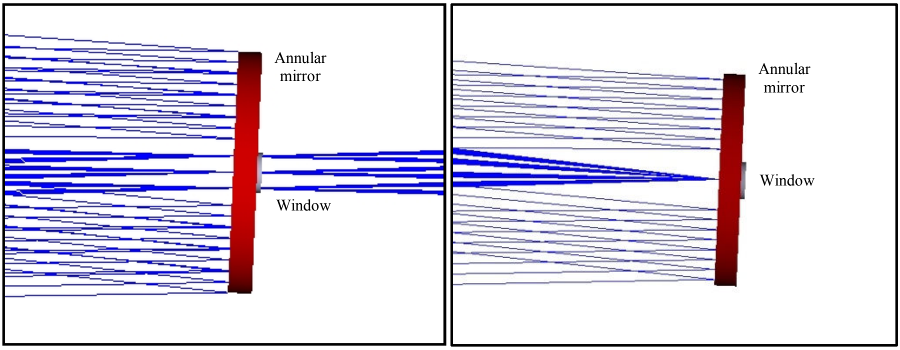

Fig. 2. Layout of the N-BK7 window and the annular window. In the channel 1 case (left image), the beam incoming from the telescope (from right to left) pass through the N-BK7 window and has no interference with the beam coming back from the DM (from left to right). In the channel 2 case (right image), the beam incoming from the monochromatic source is reflected by the N-BK7 window towards the DM and has no interference with the beam coming back.

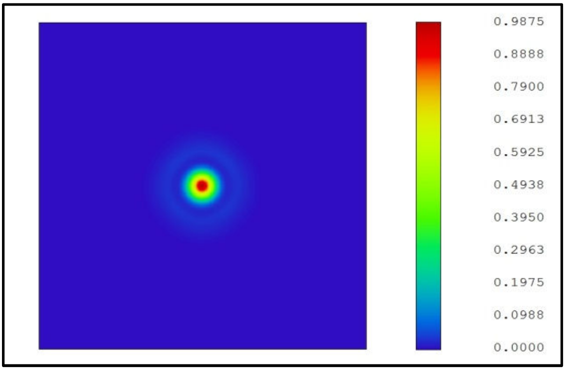

Fig. 3. Polychromatic PSF at the pyramid vertex. The theoretical Strehl Ratio is 98.75.

4.2. Channel 2: YAW monitoring the DM shape

In Figure 4 the optical design of channel 2 is shown. The aim of the channel 2 is to continuously monitor the shape of the DM. The adopted source is a monochromatic optical fiber fed with HeNe laser. A doublet (diameter 52 mm), together with a proper mask (stop) mimicking the primary aperture and central hole, transforms the generated beam in a F/17.48 beam. An annular mirror, placed at the first FP, deviates the bundle of rays towards the entrance FP, without any vignetting of the first channel beam because of the mirror hole. The beam reaches the N-BK7 windows and the non-transmitted part (4%) reforms the FP equal to the on axis entrance FP generated by the telescope. The low efficiency of the transmitted part can be counterbalanced by increasing the power of the monochromatic source up to a satisfactory illumination level. The beam, then, repeats the same optical path of the channel 1 case up to the dichroic filter, this means it is quasi-collimated by the triplet, is reflected by the DM, is re-focalized at the first FP and rescaled at the second FP to F/17.48 trough the focal reducer doublet, bringing the information of the DM shape and of the common path optics. The dichroic filter reflects the channel 2 beam (HeNe) at 45 degrees with respect to the first channel beam. A flat mirror folds the following optical path to reduce the encumbrance. At the second FP a YAW sensor is placed (here represented with a pyramid for simulation reason) and, after this, a doublet, acting as collimator, reforms the four pupils with the same scale as for the channel 1. The optical quality at the YAW entrance (second FP) has an theoretical Strehl Ratio of the monochromatic PSF equal to 97.42 (see figure 5).

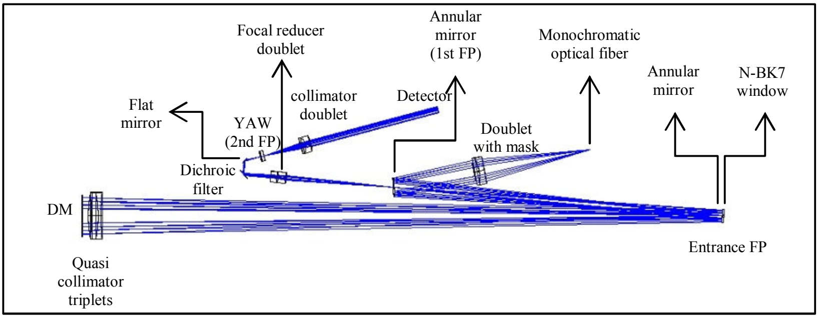

Fig. 4. Optical layout of channel 2.

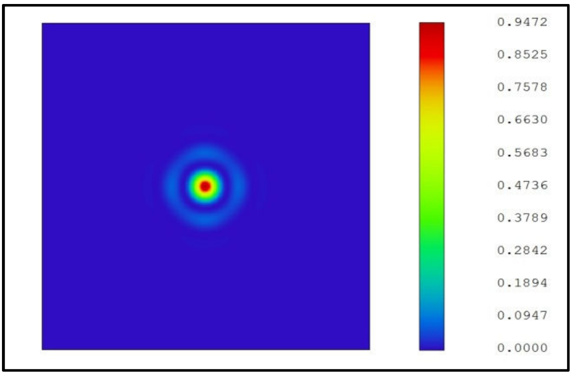

Fig. 5. Monochromatic PSF at the YAW entrance FP. The expected Strehl Ratio is 94.72.

5. Mechanical design

Following what we said in Section 3, the basic idea is to have a number of movable arms which can be inserted and moved before the focal plane in order to pick-up the light of a few natural stars. The constraints followed in the mechanical design concept, shown in Figure 6 and outlined in this section, are the following:

• minimization of the obstruction in the focal plane, since it is highly probable that several arms will be used in the same area to pick-up the light of other references for telescope auto-guiding, active optics and other adaptive optics issues, like the laser ones
• light-weighted structure, since it has to be positioned in a part of the FoV
• compact structure, to minimize the occupied volume
• CCD and DM orientation positioning, for cabling issues

The result is a structure very robust but compact and light-weighted, which can be easily positioned throughout the FoV or in part of it, and share the space with other arms with different tasks.

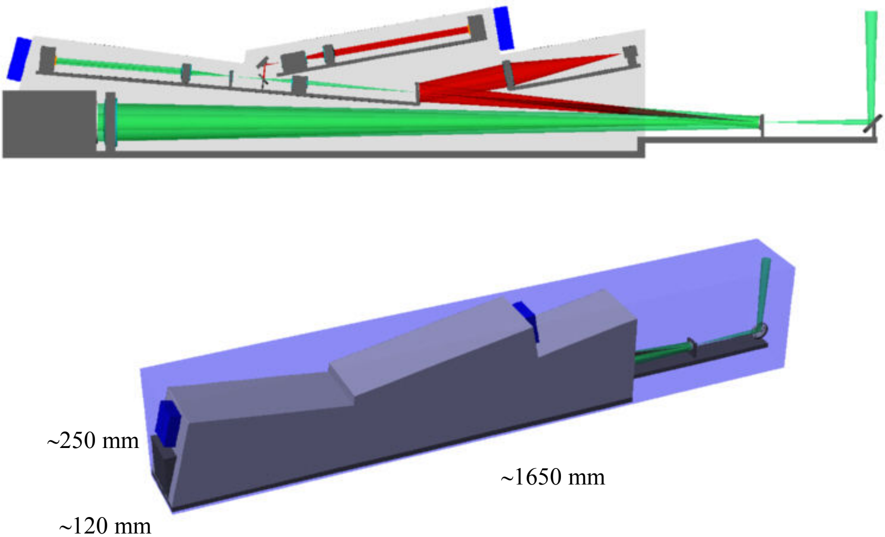

Fig. 6. Scheme of the mechanical structure of the EL-WFS.

6. References

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