RETRIEVING HIGH LAYER ATMOSPHERIC TURBULENCE STATISTICS ON E-ELT SCALES

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In the framework of the Extremely Large Telescope design study, the Work Package (WP) 12000 is studying the Site Characterization for an European Extremely Large Telescope. In particular, INAF is in the WP 12300 group for the Large scale atmospheric properties study. Previous studies done in many astronomical sites have been optimized on spatial scales comparable with 3m-4m to 10m class telescopes. The strong interest of the Astronomical Community in giant telescopes imposes a different site characterization opportune for 30-40m class telescopes. One of the central point in the Adaptive Optics for Extremely Large Telescopes is given from the achievable sky coverage. Generally speaking, sky coverage is dominated by the high altitude layers correction. In other words ground layer adaptive optics has a sky coverage much larger than other kind of corrections. That means that ways to improve the sky coverage in the sensing of high altitude layers can be very effective in terms of overall performances. Moreover, there are good reasons to translate high coherence time of flowing layers, in a generalized Taylor assumption, into larger sky coverages. This paper presents the optical design of TOE, The Onduline Experiment, a WaveFront Sensor for sensing a Very Large Field of View on-board the VLT and possibly other telescopes as GranTeCan in Canary islands. Such a WFS is to be intended as a tool to probe the atmospheric parameters in the free atmosphere (i.e. far from the ground layer) on a linear scale of the same order of magnitude of the diameter of the ELTs currently in the design phase.

Keywords: Site Characterization: Wavefront sensing; Adaptive Optics; Extremely Large Telescope.

1. Introduction

In this paper we outline the opto-mechanical design of TOE, acronym for The Onduline Experiment, a WaveFront Sensor (WFS) for sensing optical turbulence on Very Large Field of View (FoV) on-board the VLT and possibly other 8m-class telescopes. Such a WFS is to be intended, in the framework of the WorkPackage 12300 in the ELT-Design Study, as a tool to probe the atmospheric parameters in the free atmosphere (i.e. far from the ground layer) on a spatial scale of the same order of the diameter of the ELTs[1,2]. In the following such a baseline length is assumed to be D=42m. The experiment is designed to probe the atmospheric turbulence at altitudes within 5 and 15 km from ground. A new concept wavefront sensor will measure the first derivative of the phase delay on linear scale of about 40m thanks to a large FoV optical system. Such a system is intended to measure the signal generated by a large number of reference stars on field of 7arcmin Field of View (for example on a bright open cluster) on a single observation. Frame rates larger than 10Hz offer the possibility to build first derivative temporal series on ELT diameter scale using a single VLT telescope. Such a frequency has to be larger than the typical crossing frequency of r_0 patch size on a 40 m scale. The instantaneous first derivative map will be used a posteriori to compute an average power spectrum (PS): the goal is to verify if the average PS slope follows Kolmogorov $k^{-11/3}$ power law (k is the frequency) and to identify possible deviation from this law, especially on very low spatial frequencies (corresponding to the ELT ones): this may have a large impact on the ELT adaptive optics (AO) design defining a reference value for the maximum atmospheric stroke expected. But most interesting results will come from the temporal series analysis, which are intended to test Taylor hypothesis: measuring coherence time of wavefront aberration structures, of different size, crossing the sensor Field of View it is possible to build a coherence time versus spatial frequency function. This function will be used to define the improvement on the limiting magnitude for adaptive optics reference stars generated by the possibility to average for different frames the optical aberration, which is crossing over the telescope aperture.

2. Wavefront Sensor Concept

The basic idea is to place on the focal plane an optical window with a transmissivity that varies sinusoidally along one axis between 0% (Intensity $= I = I_0\,(1-\sin\phi)\,/2$, with $\phi = \pi/2$) and 100%($\phi = 3/2\pi$, ϕ being the phase value) and a detector on a subsequent re-imaged pupil plane, in order to reconstruct the global and local tilt of the WF in only one direction. Let's consider the light from a single star, in absence of atmosphere: the effect on the image of the pupil (which is uniformly illuminated, because the light from the star is collimated) of the presence of the sinusoidal pattern is shown in Fig. 1. If the light of the star focuses where the transmissivity of the pattern is minimum (0%), the pupil will be dark, but moving the pattern along the axis orthogonal to the sinusoidal modulation the luminosity of the pupil varies uniformly as a function of the point of the sinusoid where the image of the star lies. The sinusoidal pattern intensity modulation allows us to detect a signal which is proportional to the movement of the object on the focal plane (tilt). Let's now introduce a atmospheric originated tilt

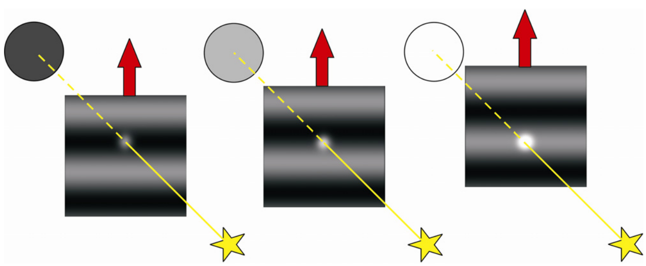

Fig. 1. Focal plane image is refracted by the sinusoidal pattern. Moving it along arrow direction, the light incidence point will change and the pupil illumination, represented by the circles, will change accordingly. In absence of aberration, one can measure the position of the barycenter of the star on the focal plane as a function of the intensity of the re-imaged pupil.

on the WF. The effect is proportional to the movement of the star image on the focal plane. So, if the sinusoidal pattern is fixed, the result is the same we've just described for a moving pattern in absence of atmosphere. For a given tilt, if the image of the star forms where the spatial derivative of the transmissivity of the pattern is maximum (where the phase of the sine is $\pm\pi$ and the transmissivity is then 50%), then the detected signal for tilt will be maximum too. In order to obtain the tilt in both axis, one can divide the light from the star in two parts (e.g. using a beam splitter) and analyze them by the introduction of two orthogonal sinusoidal patterns. As the detector is placed in the pupil plane, it is possible to divide it many sub-apertures where, for the purpose of the WF sensing, we are interested solely in tip-tilt. Each sub-pupil behaves exactly like the pupil in the previous example, so a time-variable tilt of the WF in the sub-pupil will produce the same modulation in intensity predicted for the entire pupil. So, in order to detect the WF high-orders due to the atmosphere, one can analyze the pupil illumination after the sinusoidal pattern. The signal one can obtain from each sub-pupil will be proportional to the first derivative of the WF, which is the local tilt, on that sub-aperture. In other terms, the WFS gives a map of the local tip-tilt in each sub-aperture. If the star is on the point of maximum variation of the transparency with the tip-tilt movement, or close to it, the gain will be maximized to detect the local tip-tilt. So, in the case of a single reference star, one will try to place the sinusoidal pattern in order to have the star in the central position between the minimum and the maximum of transmissivity, to maximize the output signal. An intuitive way to describe the response can be expressed using vectors: on a two dimensional plane the signal intensity is given by the sum of two vectors both with modules equal to the residual intensity after the transmissivity pattern, but one fixed along the y axis, the second with xy-projections respectively proportional to $\cos\phi$ and $\sin\phi$. The step of the sinusoidal pattern should be enough large to avoid wrapping around of this information and not so large that the signal becomes too weak. As a rule of thumb the rms of the tip-tilt fluctuation should be of the same order of one radian phase: the step of the pattern will be, at least, of the order of 2π times the expected seeing. What happens if a large number of stars is now in place? Each of these stars will contribute to the formation of the pupil image and each of it will be modulated by local tip-tilt in the same fashion. Because of the sinusoidal transparency of the pattern, the amount of light from a star that reaches the detector is the sum of two above described vectors. While the half of the light of the whole set of stars will permanently reach the detector the other half is piled up, generally speaking, in a random-walk summation way. The sensitivity of the WFS is equivalent to the average of the star in the FoV (however with a depth of focus given by the field of view where all the stars are collected, provided a large enough number of collected stars is involved). The signals originated by different reference stars are optically superimposed in a Layer Oriented fashion[3], in fact if the CCD is exactly conjugated to the pupil plane then all the stars pupils overlap making the WFS sensitive to ground layer turbulence, while slightly defocusing the CCD the pupil images corresponding to different stars move, replicating the pupils super-imposition geometry such as it is actually realized at different altitude conjugating the sensor at the desired plane.

3. Laboratory Experiment

We realized an optical setup to test the wavefront sensing ability of such as WFS. The first part of the optical setup foresees a system with a plate holding some optical fibers to simulate the stars over a 2' FoV. The divergent beam coming from the fibers is then made parallel by a lens, to simulate the light coming from infinity. After the lens, a stop is simulating the telescope entrance pupil and, just before it, turbulent screens can be positioned (using a custom made holder) simulating the atmospheric layers ranging from a few hundred meters to about 15Km. A lens positioned after the stop is making the beam converging into a focal plane, where the sinusoidal pattern plate can be inserted on a linear stage. A commercial objective is finally re-imaging the telescope entrance pupil on a CCD camera, see Fig. 2. Using one single fiber, in order to obtain the largest signal

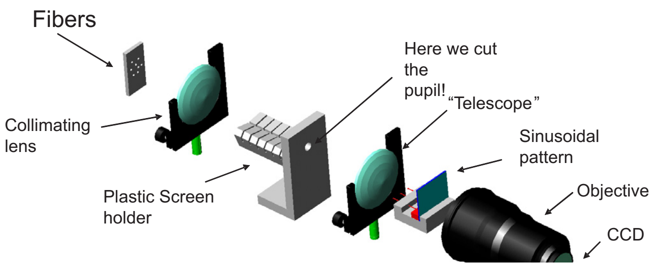

Fig. 2. The laboratory experiment arrangement.

and the most linear response we placed the sinusoidal pattern in order to project the star focal image on the sine flexure point ($\phi = \pi/2$), where the transmission spatial derivative is maximized. The task of the experiment is to show that we can measure a turbulent wavefront (created by positioning one turbulent screen in the dedicated holder). To accomplish such a task, we repeated several measurements of the same turbulent screen shifting it along an axis orthogonal to the optical one, moving it of known step, simulating somehow an evolution of the atmosphere. At the end through cross correlation we were able to identify the actual step applied and with very high correlation value (of the order of 80%).

4. Simulations

Numerical simulations analysis had two different aims: to verify the wavefront sensing concept and to check the ability of the system, such as it has been configured, to sense atmospheric layers spectral behavior. Atmospheric turbulence has been simulated by a phase screen generated using $k^{-11/3}$ power spectrum, the telescope and cameras have been simulated in a purely diffractive mode such as Fourier transformation of the phase screen masked by the obstructed pupil. For each reference the complex array corresponding to focal plane image has been multiplied by an array representing the sinusoidal transmissive pattern (transmissivity from 0 to 1) and Fourier transformed back in order to obtain intensity modulation on pupil image. Finally the different reference pupil images are added together. A strong relation between sensitivity and the position of the reference stars focal plane image with respect to sine phase of the pattern came out from simulation, see Fig. 3. According to Layer Oriented scheme the super-imposition of the pupils depends on stars field positions and conjugation altitude: first derivative measurements of the conjugated layer are correctly super-imposed on the CCD, but with different amplification (positive or negative depending on the corresponding transmissivity spatial derivative) and weighted for the reference stars intensity. This kind of simulation take into account the diffraction effect "grating-like" due to the transmissivity pattern: such as effect being evident on small sine wavelength (again see Fig. 3) leading to a minimum $\approx$ 10" value. The need for ground layer subtraction from the high layer signal came out from a detailed numerical analysis of the system using a real multi reference approach with real stars positions and magnitudes (NGC2215, on a FoV of 7'). In fact since ground is the strongest layer it will introduce on the wavefront measurement large phase errors which are super-imposed to the high layer corresponding signal. This test repeated for 500 atmosphere realizations evidenced the capability to measure correctly the injected turbulence power spectrum with average correlation between simulated measurements and simulated phase screens of the order of 70%.

5. System Overview

The instrument has been designed to be mounted at Nasmyth adapter rotator of VLT. Anyway, it preserves an intrinsic versatility to interface it with other 8-meter class telescopes: from the mechanical point of view, changing the connecting flange; from the optical point of view, it depends of course from the F/number of the considered focal plane; if the F/number is simi-

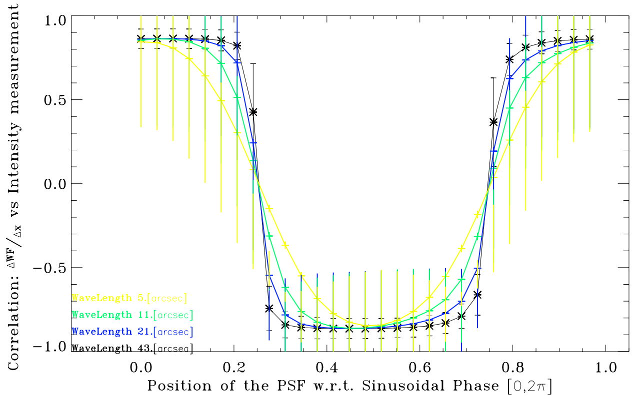

Fig. 3. This plot presents the correlation value between first derivative of the original phase screen and simulated signal as function of the position on the sinusoidal pattern, ϕ. The function has been computed for 4 different sinusoidal wavelengths (5", 11", 21" and 43"). We used 1" seeing phase screen, one reference star, averaging over 20 atmospheric layer realizations. This plot shows the relation signal and transmissivity spatial derivative: in fact $\phi = 0$ and $\phi = \pi$ the signal and the first derivative of the WF are respectively very well correlated (+1) and anti-correlated (-1) according to the sign of the derivative.

lar to the F/15 VLT one, the retrofit is almost straight forward, otherwise additional optical components shall be considered. We decided to split the FoV in four parts at the Nasmyth focal plane level, using a system based on smaller optics. Thus, there are four commercial photographic objectives just after the VLT Nasmyth Focal plane, dividing a 7'FoV into four 3' subfields. The instrument is sensitive to the WF derivative along one axis only, placing four parallel sinusoidal pattern plates exactly on the Nasmyth focal plane and just before the four objectives. These patterns can be moved using linear stages along the direction orthogonal to the lines of the grating, in order to maximize the instrument sensitivity. Each objective produces a pupil image on a CCD camera (in total four), which can be moved along a direction parallel to the optical axis of the instrument by motorized linear stages, to conjugate the sensor to altitudes ranging from ground to about 20Km. Three objectives will be conjugated to the same high altitude layer, while the fourth will be conjugated to the ground, sensing the contribution of the ground layer to be removed off-line. In order to sense turbulence on the 40 meter scale on a layer at 4.5km TOE should be optically conjugated at 9 km, pointing the VLT at 60 degrees from the Zenith.

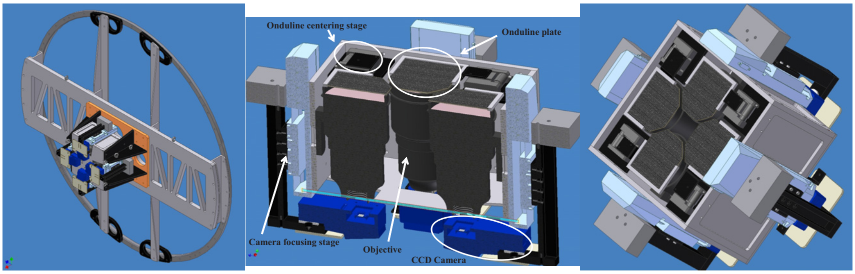

Fig. 4. A mechanical overview, from the left: the sensor mounted on the adapter rotator flange, an overall cross-section view of the instrument and a front view.

6. Conclusions

We presented the TOE experiment design, which aims to measure the free atmosphere turbulence characteristics on a 40 meter scale by the means of a new concept WFS. Laboratory tests verified the WF sensing concept and numerical simulations of the multi reference approach assessed the instrument capability to derive turbulence power spectrum. Although the sensor has been designed in order to be mounted on VLT Nasmyth adapter rotator, can be easily modified to be mounted on other telescopes of similar characteristics. TOE experiment will pose the limits for possible limiting magnitude gain of adaptive optics system aboard ELTs by measuring the coherence time of the frozen turbulence (Taylor) hypothesis.

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