TOE: The Onduline Experiment - A new kind of WaveFront Sensor to characterize astronomical sites for Extremely Large Telescopes

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ABSTRACT

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 3-4 meter to 10 meter class telescopes. The strong interest of the Astronomical Community in giant telescopes imposes a different site characterization opportune for 30-40 meter 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 meliorate 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 poster 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 Gran TeCan 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 under consideration in this period.

Keywords: Wavefront sensor, atmospheric characterization, adaptive optics, extremely large telescopes

1. INTRODUCTION

This conceptual design study is part of a more extended project aiming to study the Site Characterization for an European Extremely Large Telescope. In particular, INAF is involved in the group for the Large scale atmospheric properties study.

The goal of the project is to derive the atmospheric turbulence statistics on a 30 – 40 m scale by an experiment using one or two UTs of Very Large Telescope, installed on the Paranal site.

One of the key point in the Adaptive Optics for Extremely Large Telescopes is the achievable sky coverage. This is dominated by the photon flux available from a number of natural reference stars, then it is related to the star magnitude distribution function and to the adaptive system limiting magnitude. Depending upon the kind of Adaptive Optics system adopted, this can vary: generally speaking, sky coverage for multi-reference adaptive optics is dominated by the limiting magnitude for the high altitude layers correction.

In a typical example, one can considers the fluxes coming from a number of reference stars scattered in a FoV of a few arcminutes, being perturbed by an high altitude layer. We can define as figure for sky coverage improvement the coherence time of a frozen layer, under the Taylor hypothesis, such as the time in which this layer can be defined constant in a commoving reference system. Infinity coherence time translates into perfect Taylor hypothesis matching.

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while being smaller than the usual atmosphere coherence time means that there is no way to achieve the Taylor hypothesis at all. The value of this figure can translate into an huge gain in terms of sky coverage. While usual works on prediction of the wavefront are based upon a sort of long term prediction of the wavefront evolution, we are speaking here of a short term prediction (of the order of one atmospheric coherence time) using, however, as a basis for the calculation a number of measurements, made through a previous time of the order of the Taylor coherence time mentioned above. The ratio between the two, with the proper setup of the AO system, can translate directly into a gain in terms of available flux equal to the number of measurements usable to compute the next correction step.

Further to the direct measurement of the stroke of the turbulence a direct, firm measurements of the behaviour of turbulence screens at the E-ELT (Extremely Large) scales, confined to the only high altitude layer, can translate into a direct evidence of the possibility to enhance sky coverage by a big factor.

2. TASK OF THE EXPERIMENT

In this document the outline of the optical design of a Wave Front Sensor (WFS hereafter) for sensing a Very Large Field of View (FoV hereafter) on-board the VLT and possibly other 8m-class telescopes is shown. 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). Possible ELT sites may share these atmospheric characteristics on a spatial scale of the same order of the diameter of the ELTs to date designed. In the following such a baseline length is assumed to be \( L = 42 \) m.

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 40 m thanks to a large Field of View optical system. Such a system is targeted to measure the signal generated by a large number of reference stars on field of 7 arcmin FoV (for example on a bright open cluster) on a single image. Frame rates larger than 10 Hz offer the possibility to build first derivative temporal sequences 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 meter 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 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 limiting magnitude improvement related to short-timescales predictive algorithms.

How much the effectiveness of such an algorithm can shift the limiting magnitude depends, largely, upon the unknown behaviour of the atmosphere subject of this study. In principle, however, a decorrelation of the “frozen” layer on a spatial scale of 10 m, or over a time of the order of half a second would allow to increase the limiting brightness required to close an AO loop by about five magnitudes. In the computation we assumed \( r_0 = 40 \) cm, a wind speed at the layer altitude of the order of 20 m/s, further to not having significant turbulence crossing the main ones, at least where the wavefront sensor system is able to conjugate its measurements. Lasting, it is known that the actual magnitude improvement depends on the wavefront sensor camera RON, offering very high sky coverage also to pure natural guide star adaptive optics systems.

3. WAVEFRONT SENSOR CONCEPT

A brief description of a novel concept for wavefront sensing based on a sinusoidal pattern placed on the focal plane of a pupil reimager is given here. The basic idea is to place an optical window with a transmission that varies sinusoidally along one axis between 0% and 100% on the focal plane and a detector on a subsequent pupil plane, on the way to reconstruct the global and local tilt of the WF in only one direction.
Introducing a global tilt on the WF, the effect is a movement of the image of the star on the focal plane, which is proportional to the first derivative of the WF itself. So, if the sinusoidal pattern is fixed, the result is the same we have just described for a moving pattern in absence of atmosphere. For a given tilt, if the image of the star forms where the derivative of the transmission of the pattern is maximum (that is to say where the phase of the sinusoid is $\pi/4$ and the transmission is 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 (or, in layer-oriented fashion, conjugated at any specific range) one can focus on the light collected from a single sub-aperture where, for the purpose of the WF sensing, we are interested solely in tip-tilt. 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. The sampling of the pupil is decided, like in any pupil plane WFS, at the level of the detector, giving allowance for some massive or moderate rebinning to adjust the sampling to the desired one. Numerical rebinning is also possible, as usual, at the expense of a larger overall RON. Such a local, specific of a single sub-aperture, tip-tilt will translate into a modulation of light onto the detector placed on the pupil plane. Such a modulation will show up half of the light of the star in the considered sub-aperture, plus the projection along one fixed axes of a vector whose length is again equal to half of the light of the star, rotated by an amount corresponding to the phase of the sinusoidal pattern where the star light is falling over. If in one position the star is just on the point of maximum variation of the transparency with the tip-tilt movement, or close to it, the gain will be surely enough 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 find the star in the central position between the minimum and the maximum of transmission, to maximize the output signal. 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. In practice as a rule of thumb the rms of the tip-tilt fluctuation should be of the same order of one radian phase. In other words the step of the pattern will be of the order of $2\pi$ times the seeing in the conditions of the measure.

If a large number of stars is now considered 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, one can consider that the amount of light from a star that reaches the detector is the sum of two vectors, the first fixed and the other free of rotate, with the same phase of the pattern in the position where the image of the star lies. 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. In this way the sensitivity of the WFS is equivalent to the one looking the average star in the FoV. Although this has the merit of working well with any kind of starfield, there are ways to improve its sensitivity just distorting the pattern in order to match the choosen starfield. This can be done with different degree of accuracy, leadings to pattern that can loosely match the starfield and others requiring careful matching. However in our realization we decided to skip such an option, making the whole sensor somehow less sensitive but with greater flexibility. In practice, the lowered sensitivity would allow us to use it efficiently only on selected areas of the sky particularly rich of bright stars. As will be clear in the following, the Ground Layer can be directly measured online during the observations. Still the way such an information has to be replicated per each of the used star in order to cancel out from the high layer measurements is linked to the above mentioned issues.

### 3.1 Lab experiment

The set-up of the lab experiment (see Fig. 1) is done in a way to mimic the system sky-telescope-wavefront sensor. All the optical elements are off-the-shelf with the purpose to minimize costs and delivery time. 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 15 km. 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 (75 mm focal length, F/1.4) is finally re-imaging the telescope entrance pupil on a CCD camera. The sinusoidal pattern plate is a commercial one.
In Fig. 2 we show how the light coming from three different (one on-axis and two off-axis) sources propagates along the optical path of the lab experiment.

The final setup of the laboratory experiment is shown in Fig. 3, where each component is explained in the following:

1. Laser, used for alignment purposes;
2. Folding mirror for the laser beam;
3. Optical fibers system (tunable in intensity), which can be removed in case the alignment laser beam is needed; the fibers can be moved in two axes in the FoV;
4. Collimating lens, L1;
5. Turbulent screens holder and telescope pupil stop;
6. Focusing lens, L2;
7. Sinusoidal Pattern Plate;
8. Pupil re-imaging objective and CCD camera.

Fig. 3. The overall layout of the final lab setup, from the fibers simulating the stars to the detector.

The sinusoidal plate has been selected with a wavelength of 2 mm, which turned out to be reasonable to position as much references as we can in the linear part of the sensor, with the aim to maximize the WFS sensitivity. Only one plate is used, meaning that the WFS is sensitive only to the tilt in one axis. The turbulent screens are the same that we have used for a previous experiment. 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, as explained before). To accomplish such a task, we repeated several measurements of the same turbulent screen for different positions of the sinusoidal pattern plate, moving it along the only direction possible, a translation parallel to the base plane, simulating somehow an evolution in the atmosphere.

In conclusion, we obtain a very good correlation between the same turbulent screen measured in two different position, of the order of 80%, and this is giving a clear evidence of the capability of the wavefront sensor to reconstruct the aberrations of a turbulent layer.

Moreover, single star and multi-reference simulations have been performed with two different goals: first to verify the wavefront sensing concept by numerical simulation and second to verify the ability of the system, such as it has been configured, to sense atmospheric layers spectral behaviour, all performed with IDL software.
4. SYSTEM OVERVIEW

The instrument is based on the Layer Oriented (LO) principle allowing to scan different turbulence layers conjugating with different altitudes. Although every pupil plane WFS is indicated to be used with LO technique, in addition we have devised a new one based on a sinusoidal plate as just described in Section 3. Such a sensor presents moreover the advantage to use all the field stars to make wavefront sensing without the constrain to place an optical element in correspondence to each reference.

Using LO technique, when the instrument is conjugated to a certain altitude, what one can see is not just the pointed layer but also the contribution of layers located at different ranges. In particular, one can expect the dominant source of noise being the ground layer especially when the instrument is conjugated to low altitude (about 4 – 10 km), so it is necessary to find a way to subtract it.

The instrument has been developed with the aim to be mounted at VLT. Anyway, it preserves an intrinsic versatility that permit to interface it with other 8-meter class telescopes.

Developing the WFS concept, the requirements in term of covered FoV of the pupil reimager becomes the dominant point in the choice of the adopted optomechanical solution.

Once appointed the sinusoidal pattern way, a study of some possible optomechanical solution started investigating a few possible concepts in order to re-image the whole FoV on a single detector. Some solutions based on commercial Baker-Schmidt Cameras coupled with large detectors or with commercial photo objectives were rejected because, although the most in principle elegant solution, a number of practical issues due to the extreme fast optics and of the size of the detector arise. So we decided to split the FoV in four parts at the Nasmith focal plane level, using in this way a kind of array of systems based on smaller optics. Thus, there are four commercially available photographic objectives posed just after the VLT Nasmith Focal plane, which are sampling the FoV into four sub-portions. Another decision is that the instrument is able to check the atmospheric tilt only along one direction, simplifying in this way the instrument design. This is why there are four sinusoidal pattern plates positioned exactly on the Nasmith focal plane and just before the four objectives; they are parallel to each other and with the possibility to be moved using linear stages in a 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, and each camera (in total four) can be moved (through the means of linear stages) along a direction parallel to the optical axis of the instrument in order to focus each camera (or, better, to conjugate it) to a certain altitude, ranging from ground to about 20 km. Three objective will be always conjugated to the same altitude, to focus the layers present at that height, while the fourth will always be conjugated to the ground, with the task to sense (and remove afterwards) the contribution of the ground layer.

At the range chosen to have the layer sampling, pupil overlap depends upon the stars collected by the instruments. These are grouped into a few patches of 3 arcmin in diameter. Roughly speaking the overlap of the 8m pupils at the selected range is such that two pupils on the edge about smack each other. A larger FoV for each single objective would not translates into a better overlapping of the pupils (although would be more linear and elegant solution if technically feasible).

The experimental aim of the instrument determines the choice of a partial pupil coverage on the focal plane with a consequential low resolution, and it is also visible in the choice of commercial components as objectives, cameras and linear motorized stages.

Combining the various choices described so far, it results that each of the single objectives in the instrument has a FoV of 3'; to sense a turbulent layer on a 40 meter scale it is necessary conjugating at 9 km pointing the 8 meter telescope 60 degree from zenith.

As written above, ground layer sensing is needed to subtract its contribution from the measurement of the high layers. This might be accomplished using a beam splitter on each of the channels, but this requires a large back focal distance and additional optomechanics and detectors; this is why, in order to keep an easy design, we have chosen to sense the ground with an independent field of view camera.
5. OPTOMECHANICAL DESIGN

The optomechanical design should allow to cover a field of view of 3 arcmin to sense turbulence on a 40 meter scale. The optical design study for such an instrument started from a Backer-Schmidt Camera model, it passed through a combination of two commercial photo objectives and found its better solution in an array of 4 commercial photo objective, Nikon 200 mm F/2, placed on the telescope focal plane. Because of the commercial use of this F/2 objective, its optical designs aren’t public, we simulated it using the technical details provided by Nikon. Another data given by Nikon that has a great importance in the optical design, is the distance between the physical end of the objective body and the nominal focal position that is 46 mm. Each objective can cover a field of view of 3’. In the optical design study we correlate the altitude of the atmospheric layer conjugated with the objective to the distance between the entrance lens of the objective and the CCD position.

We want to sense layer at an altitude of 9 km, knowing the instrument FoV, to reach a 40 m sky footprint the telescope have to be pointed at about 60° from zenith. Of course, moving the telescope from zenith just along one axis, the footprint shape is oval and after all considerations concerning the meta-pupil dimension and the intra-focal position of the chip driving the choice of the CCD, the camera APOGEE ASCENT 11000 has been selected. Plotting the data concerning the atmospheric layer altitude and the correspondent distance between the telescope focal plane and the CCD position, we can estimate that 1 mm of CCD misplacement along optical axis corresponds to 400 m in the sky, thus meaning that, to conjugate to a maximum altitude of about 20 km, a travel of 50 mm is required for the linear stages used to adjust the focus position of the detectors. In particular, 3 objectives are deputed to High Layers WF sensing, while the latter one will be conjugated to ground WF to allow ground layer turbulence removal from High WFS data. Conjugation is realized by 4 linear stages, which move the CCD to the desired position along optical axis. We assume that each sub-aperture has a diameter of 20 cm and considering acceptable a pupil movement in a range of 1/10 of sub-aperture, we have 0.03 mm tolerance.

The WFS mechanical design is derived from the optical design and concerns a geometric lay-out that allows the 4 Nikon objectives to be as close as possible one to each other; a rigid aluminium frame on which the 4 Nikon objectives are appropriately screwed; translational horizontal movements (left–right) of the “onduline” patterns above the objective entrance lens; translational vertical movements (optical axis) of each CCD cameras; a high-stiffening interface structure in order to limit optical components displacements.

In Fig. 4 the whole instrument can be seen, with rectangular aluminium plates carrying the 4 motorized “onduline” frames and the 4 motorized CCD cameras, with all linear stages supplied by Phisik Instrumente: M-110 series (travel range 5 mm) for the “onduline” and M-505 series (travel range 50 mm) for CCD cameras.

![Fig. 4. The main WFS assembly, a rhomboidal lay-out of the Nikon objectives, the linear stages carrying the “onduline” frames and the CCD assemblies.](http://proceedings.spiedigitallibrary.org/ on 07/15/2015 Terms of Use: http://spiedl.org/terms)
In order to better understand, a cross-sectional view is shown in Fig. 5:

Fig. 5. Instrument cross-section view.

Looking at the instrument following the light path, first there are the four sinusoidal plates, each one contained in an appropriate holder mounted on a linear motorized stage that allow moving them together in the direction perpendicular to the lines of the grating. Such stages are fixed to an aluminium box that contains the four commercial objectives. The box shape and material are chosen to be the lighter and the stiffer possible. Below each objective there is a CCD camera that collects the pupil image. Each camera is mounted on a motorized stage that allow it to come close or move away from the objective in order to change the altitude layer to conjugate with. Stages are again fixed to the aluminium box. The whole instrument is in turn mounted on a steel flange designed to match the Nasmith derotator interface of the VLT, see Fig. 6.

Fig. 6. The complete mechanical assembly and the FEA analysis.
Moreover, Finite Element Analysis has been performed with gravity vector lying on x-y plane (Fig. 6). The FEA has shown that max displacement is about 100 microns and interest the CCD cameras in twist-bending solicitation. In average, the elastic deflection is encompassed in a very small range (within 70 microns), the only ameliorable point being the lateral supporting of the cameras in order to avoid twist-bending deflections.

6. ELECTRONIC DESIGN

6.1 Motion Control

Each of the 8 axes will be controlled by the suitable controller supplied by Physik Instrumente. The eight controllers will be divided in two groups: one devoted to z-positioning and one to the positioning of the “onduline”. Therefore each group will consist of four controllers, arranged in a “daisy chain” configuration. Each group will be accessed through one RS-232 serial interface, connected to the Instrument Work Station (IWS). Each individual device in a group will be accessed through its ID in the daisy chain, which is configured in the front panel of the Motor Controller.

The instrumentation software is in charge of controlling the devices and performing the observations foreseen for this experiment. Given that the number of devices to be controlled is small, that a very limited number of observing procedures are currently foreseen (actually, just one) and that there is no requirement to conform to the software standards in place for VLT instrumentation, the architecture of the instrumentation software is extremely simplified. The hardware architecture for the CCD cameras is illustrated in Fig. 7.

![Fig. 7. Architecture of control hardware.](image)

The software environment on the IWS will be based on the VLT Software (VLTSW). Thus the operating system will be Scientific Linux. The most recent release of the VLTSW available at the time of development will be installed in the IWS. Besides the VLTSW, ITT Interactive Data Language (IDL) will also be installed in the IWS.

6.2 Data flow

The expected data flow during observation can be computed as follows: the CCD will be read windowed at 2672×2672 pixels, with a binning of 4×4, therefore a single frame will be 668×668 pixels in size. We expect to acquire frames at 10 Hz rate, which means 668×668×10 = 4.5 Mpix/s, at 2 bytes per pixels (16 bits digitization) the data rate per CCD will be about 9 MB/s. Data from each CCD will go through an USB channel to the IWS. The USB 2.0 (theoretical) maximum bandwidth is about 60 MB/s, thus we conclude that the USB channel is not a bottleneck.

Data from all the CCDs will be stored (in parallel) on disk, given that the SCSI bandwidth is 320 MB/s and that we will employ a RAID 10 storage array, we conclude that the disk subsystem will be capable of dealing with the incoming data flow. A typical observation will last a few minutes (~ 3 minutes), the total data volume acquired (with the specified binning and frame rate) is about 6.5 GB. In the hardware configuration currently foreseen, observations can be stored in the IWS disk.
6.3 Interfaces

The interface with the VLT environment are essentially four:

1. Optical: the entrance focal plane of the instrument shall match the Nasmith focal plane.
2. Mechanical: a dedicated flange will connect the instrument to the rotator bearing of the Nasmith Interface.
3. Electrical: essentially, the only requirements are a line with the power supply and a network connection.
4. Cooling: an incoming and outgoing line with glycol water might be required for the cabinet cooling.

7. CONCLUSION

We described an instrument that, using off-the-shelf components and a new kind of WFS, will be able to measure large scale turbulence looking forward to future ELT adaptive optics project. If realized it will give fundamental information about Taylor hypothesis and turbulence power spectrum at large scales.

Here optomechanics concepts and WFS characteristics had been presented demonstrating the feasibility of the sensor, supported also through laboratory experiment.

REFERENCES