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Field Tests of elongated Sodium LGS wave-front sensing for the E-ELT

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Abstract. Wavefront sensing using extremely elongated Sodium Laser Guide Stars (LGS) is a key concern for the design of a number of first generation ELT AO modules. One of the main challenges is the mitigation of the effects induced by extreme elongation on the wavefront measurements. Before the final design studies of the E-ELT instruments, a Na LGS wavefront (WF) sensing on-sky field experiment at this scale is strategic and mandatory to provide spatial and temporal wavefront measurements on a true LGS, subject to the atmospheric and mesospheric variability. The fine comparative analysis of such data with synchronously acquired WF measurements on a NGS will be unique to test a number of algorithms, configurations for spot sampling and truncation and WF reconstruction schemes including multi-LGS configurations. We propose to use CANARY, the Multi-Object AO demonstrator installed at the WHT (4.2m) . CANARY is now equipped with a Rayleigh LGS and also provides several natural guide star WFS. It shall be adapted to the Na LGS to provide the same pupil sampling than the NGS WFS for direct comparison. A compact, transportable laser system, such as the WLGSU developed at ESO, positioned at a varying distance from the WHT will be used to provide off-axis launching (up to 40m), simulating the whole range of LGS spot elongations obtained on the E-ELT. In addition, this experiment will include varying rate Sodium profiling and open and close-loop operations including offloads from profiling. In this paper, we present the objectives and the design of the proposed experiment and detail our strategy in terms of experimental setup and data reduction. A global error budget for the whole experiment is derived and spin-offs for the adequate dimensioning of E-ELT LGS-AO modules WFS are demonstrated.

1 Introduction

Wavefront (WF) sensing using Sodium Laser Guide Stars (LGS) is a key concern for the design of a number of first generation Extremely Large Telescope (ELT) Adaptive Optics (AO) systems, as for the two first instruments (Harmony and Micado) of the European ELT (E-ELT). One of the main challenges is the mitigation of the effects induced by extreme Na LGS elongation on the WF measurements. Before the final design studies of the E-ELT instruments, a Na LGS WF sensing on-sky experiment at this scale is mandatory to validate the potential performance and provide relevant spatial and temporal WF measurements on a true LGS, subject to the atmospheric turbulence and mesospheric Na variability. The elongation-induced measurement error can be analyzed in terms of detection noise error, anisoplanatism error and measurement non-linearity error. Up to now, this problem has been investigated through numerical simulations and laboratory experiments mainly for Shack-Hartmann (SH) WF sensor. [1] have numerically shown that detection noise error can be mitigated by MMSE WF reconstruction approaches.

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Anisoplanatism effect can be mitigated by using the adapted turbulence covariance matrix in a weighted least square reconstruction [2]. Numerical simulation results have been reproduced by laboratory experiments [3] but are still questionable due to the used simplified models compared to the atmosphere. Non linearity error has been demonstrated by analytic and numerical studies [4] and low bandwidth NGS WF sensor has been experimentally demonstrated to mitigate such an error [5]. But once again these studies are limited by the used atmospheric models (Na profile, turbulence, temporal evolution).

2 Why setting up an on-sky experiment

We propose to set-up an on-sky experiment at the scale of an ELT [6] taking advantage of both the ESO transportable Na laser and launch telescope [7] and the CANARY AO experiment installed at the WHT in the Canaries Islands [8].

The first goal is to record on-sky, for the first time, fully relevant data of Na LGS elongated SH patterns including all the variability and complexity of the Na layer coupled to the atmospheric turbulence in a configuration similar to the E-ELT. The produced large volume of data will be reduced off-line to be able to test all possible centroid algorithms and different SH spot parameters as field truncation and pixel sampling. It will allow the identification and quantification of all the error terms and then the building of a WF error budget for the E-ELT. Some on line processing of the elongated spots will also provide first performance evaluation and allow us for some feedback on the experiment plan.

In a second stage, the recorded data will be used to first validate the numerical simulation code results and second identified the key parameters to be considered as inputs in the future numerical simulations for the instrument design.

3 The proposed on-sky experiment

The experiment principle is presented on the sketch of figure 1. We propose to use as the source the compact and transportable LGS unit developed by ESO including the 20W CW 589nm laser based on Raman Fiber Amplifiers and the 300mm launch telescope. It will be installed at an off-axis distance up to 40m from the receiving telescope. We propose to use CANARY on the WHT as the receiver bench to implement the Na LGS WFS. The advantage of using CANARY is to benefit from the modular infrastructure already in place as other WFS, AO mirrors and RTC. The 4.2m telescope will only correspond to an off-axis part of the E-ELT pupil.

An example of SH spot pattern, as it will be recorded on CANARY for the maximum off-axis angle, is given in Figure 2. CANARY will observe the Na LGS and at least one NGS in the field. It will allow to acquire synchronous NGS WFS data with the LGS WFS ones.

Additionally, a profiler located further away allows to accurately monitor the LGS plume in parallel.

4 Experiment configuration

We propose to use 60cm sub-apertures leading to 7x7 pupil sampling for the Na LGS WFS as the CANARY NGS WFS. The frame rate could be varied from 150 to 250 Hz. A WFS camera with 240x240 pixels is well suited to allow a 20″ field of view per subaperture (minimizing

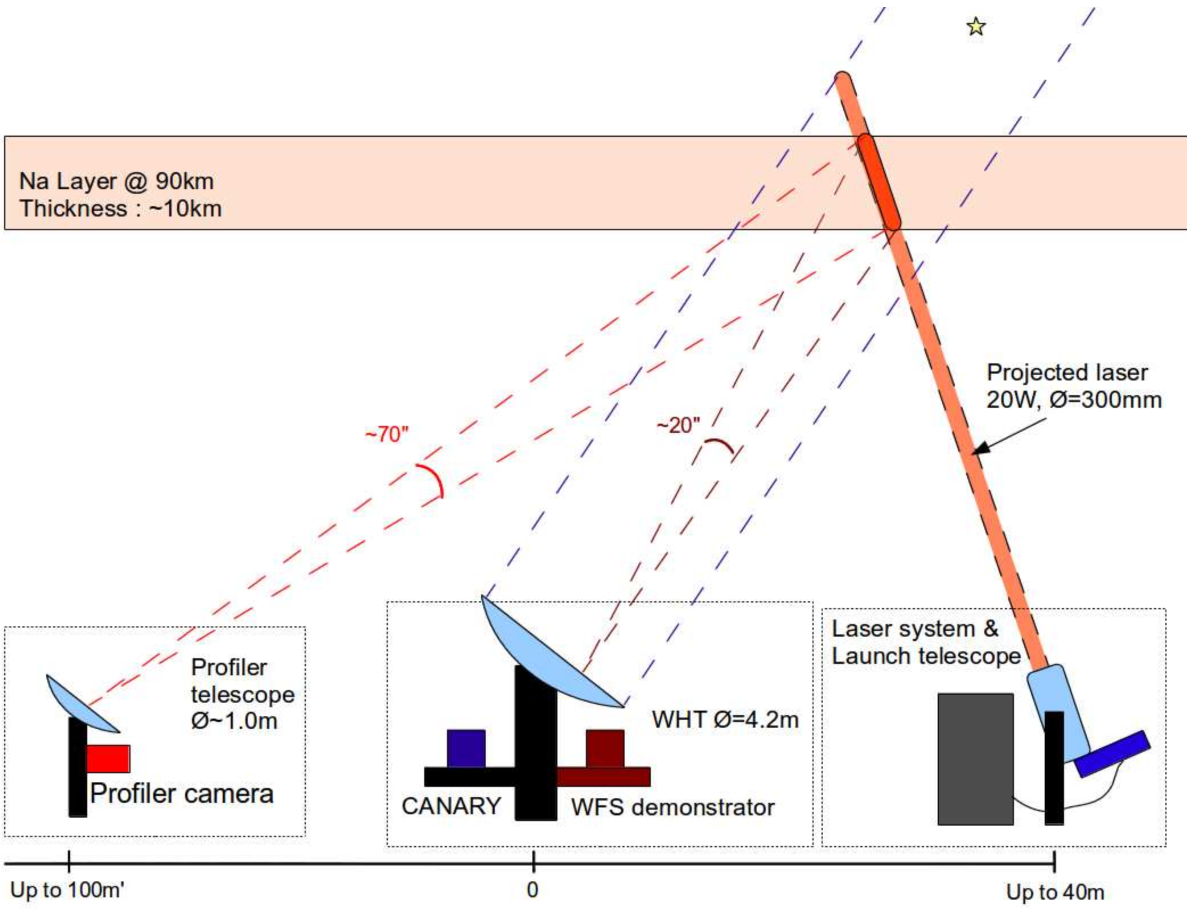

Fig. 1. The various components of the proposed experiment.

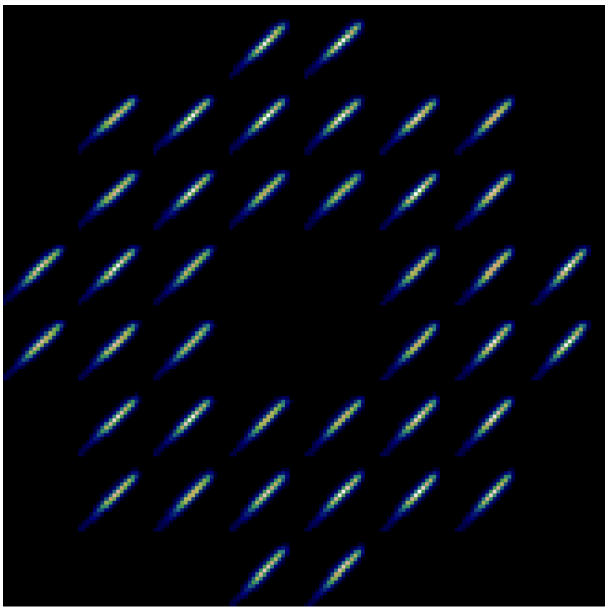

Fig. 2. An example of SH spot pattern, as it will be recorded on CANARY for the maximum off-axis angle.

the truncation) leading to a pixel scale of 0.59″ (keeping a proper sampling of the LGS spot).

This scaling could be adjusted depending on the final selected camera. The camera will be synchronized to the other NGS WFS cameras of CANARY.

In the first experiment the Laser will be pointed to a bright NGS, CANARY will observe on-axis both the LGS and the NGS and close the AO loop on the bright NGS with the Truth Sensor. We will have to implement the compensation of the laser jitter in the optical path of the LGS WFS. In addition a dithering of the laser beam will be also implemented to provide a convenient complementary tool for centroid gain estimation. The data reduction will compare the LGS WFS measurements to the NGS ones.

A second experiment will be to use the potential of the tomographic analysis of CANARY, using off-axis NGS in addition to the central one. Here the laser will be pointing to one of the already observed CANARY asterisms. The NGS magnitudes will here be higher than in the first experiment. The existing identification and calibration procedures of CANARY will be used to retrieve the phase perturbation in the full volume and correlate it to the Na LGS measurements to evaluate the cone effect anisoplanatism. We could also envisioned to engage the loop on the off-axis WFS of CANARY with the proper tomographic reconstructor to mimic cone effect compensation. The LGS measurements will include the following main error terms: cone effect anisoplanatism, aliasing, detection noise, non linearity error and LGS beam differential quasi-static telescope aberrations. The non linearity error to be quantified can be modeled in first approximation by a bias term and a gain on the centroid estimation linked to the misknowledge of the Na profile reference image used in the centroid algorithm. In addition, field truncation and pixel under-sampling will also contribute to the non linearity error. Anisoplanatism will be mitigated by the tomographic approach. Aliasing by the estimation of r_0. Detection noise are uncorrelated between the sub-apertures and in time. The telescope differential aberration amplitudes will have to be analytically quantified and are slowly evolving in any case.

5 Numerical simulation of expected results

We ran representative simulations of a WFS located at increasing distance from the Laser launch telescope (10 to 40m) and with a sub-aperture size of 60cm. Hence, we sample the E-ELT pupil at various distance with respect to the launch telescope. We define the phase error (in nm) as the difference between the LGS and a bright NGS under the same conditions. Centroiding is done here using the weighted center of gravity method. While the LGS spot is built using a profile measured on sky (black curve, figure below), the weighting function is taken as a Gaussian of equivalent FWHM (red curve, figure below) so as to simulate an imperfect knowledge of the spot. The results are displayed in the figure below. As predicted, the error is correlated between the sub-apertures and increases with the axis distance quite dramatically.

These results are totally consistent (qualitatively and quantitatively) with our previous study on measurement errors, as shown by the bottom right panel of this figure in which we displayed the value of the bias in arcsec for this WFS when the LLT is located 40m away, as estimated using the analytical approach developed in [4]. Indeed, we predict an almost constant bias of $0.2''$ which 0.6μm leads to a global tilt of about 3μm RMS as observed with the end-to-end simulation.

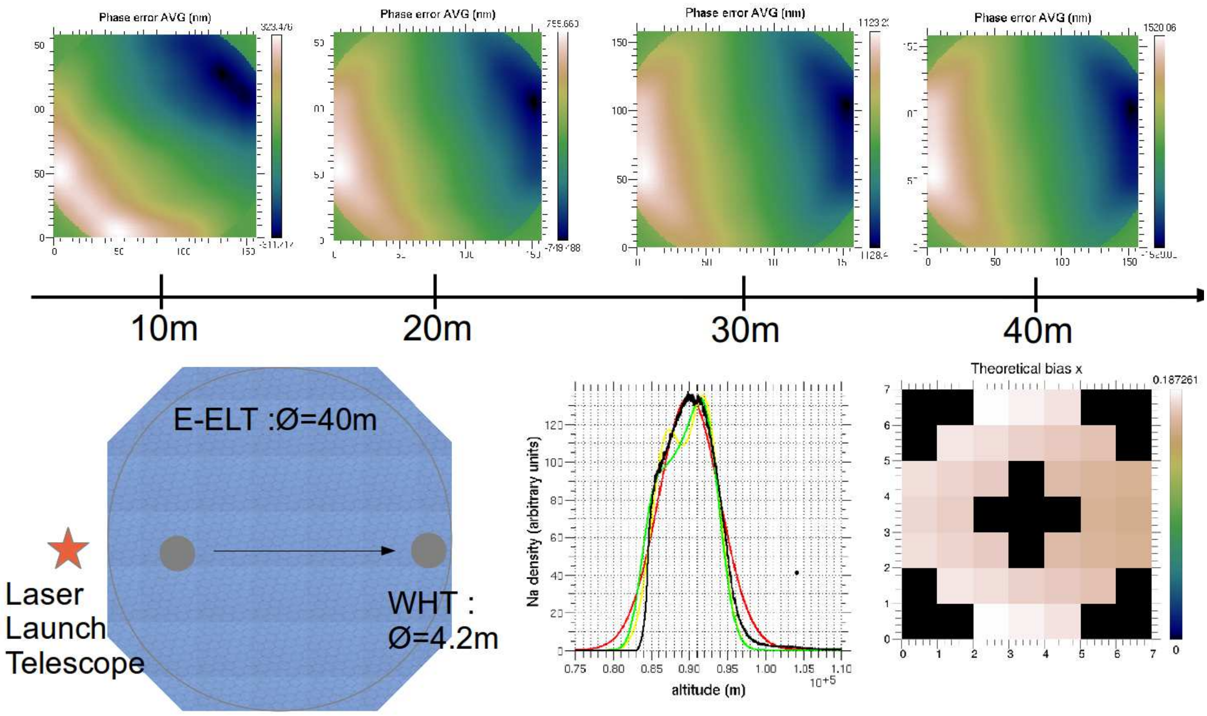

Fig. 3. Top: average reconstructed phase error in nm RMS for various off-axis distances from 10 to 40m. Bottom : Sketch clarifying the simulation conditions (left), examples of Sodium profiles used (center) and Theoretical value of the centroiding bias in arcsec for a 40m off-axis launch under the simulation conditions

6 Conclusion

In this paper, we present the objectives and the design of an on-sky experiment for a Na LGS wavefront (WF) sensing at the scale of the E-ELT. This experiment will provide unique and relevant spatial and temporal WF measurements on a true LGS, perturbed by the atmospheric turbulence and mesospheric Na variability. These data are mandatory to validate the potential performance of Na WF sensing at the ELT scale. We detail our strategy in terms of experimental setup and data reduction. We take advantage of both the ESO transportable Na laser and launch telescope and the CANARY AO experiment installed at the WHT in the Canaries Islands. A global error budget for the whole experiment is derived and spin-offs for the adequate dimensioning of E-ELT LGS-AO modules WFS are demonstrated.

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