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Laboratory prototype for the demonstration of sodium laser guide star wavefront sensing on the E-ELT

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Abstract. The new class of Extremely Large Telescopes (ELT) relies on Sodium Laser Guide Stars (LGS) to improve the Adaptive Optics performance in terms of correction quality and sky coverage. The time instability and the vertical extension of the atmospheric Sodium layer density have a potential significant impact on the wavefront sensing accuracy. We describe a laboratory prototype which has been developed with the goal to investigate specific algorithms for wavefront sensing with these artificial sources under different conditions of sodium layer density profile, parallactic effects due to laser launch geometry and atmospheric turbulence. The prototype can emulate realistic elongated spots on the focal plane of a Shack-Hartmann wavefront sensor (SHWFS), including their intensity variations due to the time variability of the Sodium density vertical profile. In addition, multiple LGSs can be simulated, one at a time, and a two-layer atmospheric turbulence model is available. Herein we report the verification of prototype performances, including optical performance, accuracy of emulated Sodium density profiles and atmospheric turbulence features.

Key words. Adaptive Optics – Laser Guide Stars – Wave front sensors – EELT

1. Introduction

The LGS wavefront sensor (WFS) prototype was developed at INAF-OABo in the framework of phase A of the Multi Conjugate Adaptive Optics Relay (MAORY) instrument project.

The prototype reproduces the expected conditions, in the ELT case, when measuring the wavefront of LGS by means of a SHWFS. A simplified version of the prototype was successfully integrated and tested in 2010 (M. Lombini, 2011) and it has been upgraded to realistically reproduce the time variable Sodium layer density vertical profile and to simulate, one at a time, a multiple LGS launching system. To introduce a differential wavefront aberration according to the azimuth angle of the LGS and simulate the time evolution of the turbulence, a two layers turbulence model has been implemented. All these features can be remotely controlled during data acquisition.

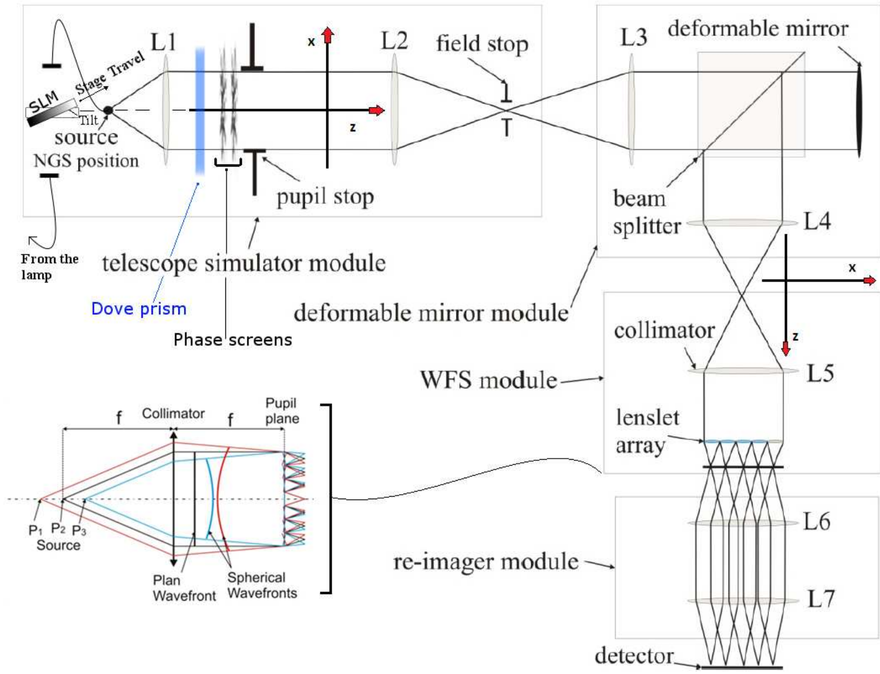

Fig. 1. The concept of LGS Prototype. The images moves in the sub-apertures due to source position along the optical axis (z). The central sub-aperture does not detect a perspective elongation but just a small blur.

1.1. Prototype requirements

In order to reproduce the LGS features, some fundamental requirements have to be fulfilled by the LGS WFS Prototype. These are:

a) 'Seeing limited' source;
b) Variable Sodium layer density profile;
c) Spot elongation pattern geometry on a SHWF in case of LGS launcher behind the secondary telescope mirror or on the edge of the primary mirror;
d) Different LGS launcher positions around the primary mirror;
e) A layered model of atmospheric turbulence and its time evolution;
f) The footprint of an LGS on the turbulent layer depending on the layer altitude and on the LGS azimuth and zenith angle;
g) The spot truncation effect.

1.2. Design description

The Prototype is composed by four modules (see Figure 1):

1. the telescope simulator reproduces the source, the turbulence and the telescope aperture. The module collects light coming from an output fiber beam which has been modulated in intensity by the spatial light modulator (SLM). This makes possible to generate the desired Sodium layer density profile. The source is placed on a motorized linear stage moving along the optical axis. By integrating the light during the source movement, the elongated spots are formed on the SHWFS. The non radial elongation pattern, which is typical of a side-launch geometry of the LGS, is produced by tilting the motorized linear stage travel axis with respect to the optical axis. The Dove prism, placed after abjective lens L1, emulates

multiple LGSs (though not simultaneously) by means of its rotation. The reproduced LGS can intercept the proper phase footprint on the phase screens, placed before the pupil stop, simulating a given launching angle. The prototype is not able to simulate the cone effect, so the footprint diameters do not change with the atmospheric layer altitude. The variations of the turbulence caused by a single layer can be modeled by a 'frozen' pattern, that is transported across the aperture by the wind in that layer (F. Roddier, 1999). Following the procedure described by (S. Thomas, 2014) plastic screens and hair spray are used to emulate atmospheric turbulence whose production is quite empirical and took several attempts. The high altitude layer phase screen can be shifted in x and y axes (orthogonal to the optical axis) using two motorized linear stages while the ground layer phase screen can be only shifted in x. The field stop (FS), placed at the end, is a diaphragm which sets the SH sub-apertures FoV
2. the deformable mirror (DM) module introduces low order WF modes by means of a DM and it is an a-focal relay (lenses L3 and L4) that replicates the source image.
3. the WFS module re-images the pupil through a collimator (lens L5) and produces an array of images of the source by a lenslet array (LA)
4. the re-imager module is an a-focal relay (lenses L6 and L7) whose magnification permits to fit the LA pitch with an integer and even number of detector pixels per subaperture leaving a convenient back-focal distance for the camera.

1.3. Sodium density profile simulation

The SLM, moving through the z direction, settles the light transmissivity as a function of the source axial position and can be programmed before any run. So, according to the chosen profile, the SLM simulates any feature of realistic sodium profile. The light beam, coming from a 50/125μm multi-mode fiber and collected by a 50mm f/2.5 lens, illuminates different SLM pixels in line with the stage movement. The modulated beam is finally driven by another 50/125μm multi-mode fiber on the motorized linear stage which generates a defocus signal on the Prototype focal plane.

2. LGS WFS prototype verification results

All tests are performed with a narrow band source centered at the wavelength of 630nm. Each test is in high signal-to-noise ratio regime to obtain a negligible background contamination and optimize data reduction. The main indicators of prototype performances are the repeatability tests whose purpose is to evaluate the system precision. We also expect to detect systematic errors whose nature is internal to the system or linked to the environment that affect the prototype accuracy. If systematic errors were identified, they could be minimized with careful analysis and design of the test conditions and procedure or by the experimental investigation of specific algorithms and calibration strategies.

2.1. Repeatability tests

The prototype was aligned under a controlled room temperature to avoid thermal effects that impact the system performance. During operations, the air conditioning system generates a periodic variation within 1 ^{o}C. Besides, the Dove prism and its mechanical bearing are critical components for the prototype accuracy. Fabrication errors related to optical surfaces, the mechanical bearing and alignment errors limit the translation and angular co-alignment of the prism with the optical axis of the system. The main goal of the tests is to quantify the WF errors introduced by Dove prism rotation and the errors introduced by temperature variation. The analysis of collected data shows a periodic offset of the SH spots pattern (Figure 2).

Even if the room temperature has reached its nominal value, the system needs a certain

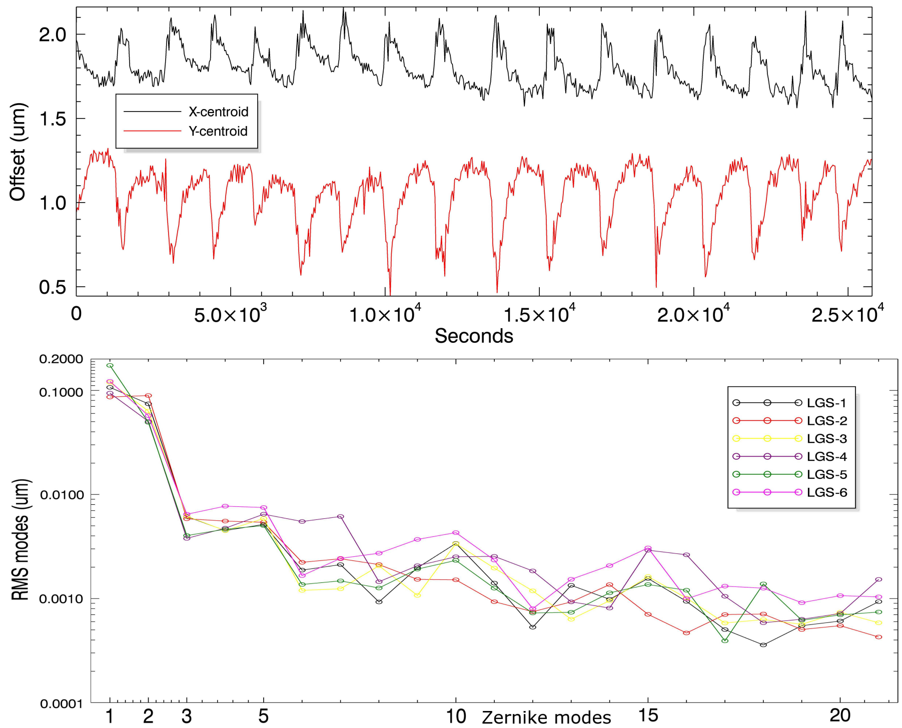

Fig. 2. Mean spot centroids offset, expressed in microns and RMS of repeated measures for 6 simulated LGSs (Y scale is logarithmic)

thermal relaxation time after which a maximum spot offset per sub-aperture is about $0.75\mu m$ on timescales of about 15 minutes. This systematic error is reproducible but the x-y offset zero point cannot be predicted a priori and requires a preliminary series of frames acquisitions in order to calibrate the experimental procedure upon this reference quantity. The WF distortions are expandend in terms of 21 Zernike modes. The systematic error decreases the accuracy in measurement of Tip and Tilt terms of the incoming WF. Considering all the following modes, the prototype precision is below $\lambda/20$ WFE RMS. Due to prism position during the rotation, in addition to the temperature-dependent image drift, the main introduced WFEs are the Tip-Tilt terms. High order modes variations among different LGSs are introduced but they are a factor 8 smaller than Tip-Tilt. Since the dependency of these modes on thermal effects is negligible, they are reproducible and, being known a priori, easy to calibrate.

2.2. SLM tests

In order to fulfill the prototype requirement b) and c) listed in section 1.1, the goal of SLM tests is to meet the foreseen features when reproducing the sodium layer profiles and LGS perspective elongation pattern. There is a linear relation between the source travel through the prototype optical axis and the elongated spot generation. For 1 pixel spot displacement on the detector, the source linear stage has to move of about 0.5mm. The spot FWHM gradually increases away from the zero defocus position (±14% deviation from the mean) and considering the mean FWHM of 1.8 pixels along the stage travel range, the SLM has to move of about 0.9mm in order to obtain the minimum resolvable distance of sodium features. In the case of E-ELT (Diameter ≃39m) for the most elongated sub-aperture FoV ≃1 arcsec, when the sodium layer altitude is equal to 90Km, the projected layer width is Δh≃1Km. In our prototype scale, a LGS "seeing limited" size of about 1.5 arcsec, corresponds to 1.8 CCD pixels. Thus, 24 CCD pixels, for the most elongated sub-aperture, reproduce a simulated layer width of Δh≃20 Km. The source image made by the 50mm focal length lens on the SLM screen has a geometrical size of ≈ 90μm, corresponding to ≈3 SLM pixels. This is the PSF of the optics that collect light from the fiber output convolved with the SLM pixels. Following the same proportion to the E-ELT scale, our resolution in sampling the Sodium density layer corresponds to a simulated width of about 150m.

2.3. Atmospheric turbulence characterization

The phase measurements of plastic screens were done by using the Prototype itself and, from the slopes offset in the sub-apertures, we reconstructed the phase map corresponding to different and casual screen coordinates. The strategy is to take a series of images for each phase screen at random positions of their corresponding linear stage. The fitting of the data with the Kolmogorov theoretical curve produced a coherence length r_0 ranging from 0.168mm to 0.19mm for the ground altitude layer (corresponding to ≈0.6 sub-aperture size) and from 0.43mm to 1mm for the high altitude layer (varying within ≈3.5 sub-apertures size).

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