Sodium layer density anisotropies as a reference for tip-tilt measurement in Laser Guide Stars

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ABSTRACT

Nowadays the ultimate limit for high-spatial resolution observations is increasingly related with the availability of a natural star bright enough to provide the tip-tilt information. This problem is especially relevant for telescopes in the 40m range due to the small technical field they consider. From our experience measuring sodium layer profiles at the Observatorio del Teide we realise that the sodium layer could present anisotropies in the 1" range, which eventually might become in a low-contrast image when illuminated by a laser beam designed with a proper width. By tracking such image in close loop from the launching subsystem, a static laser guide star will be generated, that could be used by the receiving adaptive optics system to measure the tip-tilt and all others components of the wavefront aberration caused by the turbulence. Wavefront sensing of the anisotropy images ideally needs a sensor adequate for extended objects, like the plenoptic camera, using correlation-based calculations. Simulations of the computed tip-tilt by a plenoptic wavefront sensor are presented (OOMAO Toolbox), showing the expected quality result as a function of both the photon return and the contrast of the extended laser guide image generated. To confirm and characterize sodium layer anisotropies and also to verify the viability of this tip-tilt measurement system, both the design and simulation results are the cornerstone for planning a measurement campaign, at the Observatorio del Teide.

Keywords: Laser Guide Star, Plenoptic, Sodium, Tip Tilt

1. INTRODUCTION

Laser Guide Stars (LGSs) are artificial references for the adaptive optics systems, which are used to cope with the lack of natural stars up on the area of interest. They are produced by laser beams projected to the atmosphere to create focused spots of light as if they were a natural point-source. The artificial stars are created either at the upper layers of the atmosphere (Rayleigh LGS) or at the Sodium layer, at 90km above the ground.

Once the necessary reference on the sky has been found, it is essential to have the proper instrumentation to measure and quantify the atmospheric phase at a time instant t. Wavefront sensing is the first step in the atmospheric turbulence correction. Indirect wavefront sensors measure either local slope (dW/dy or dW/dx) or differential wavefront (dW) as a function of pupil coordinates,[1] and instead of using the explicit information of the phase, they translate it into signals which will be used to compensate the wavefront itself. This methodology is the one that rules sensors as the plenoptic camera.

The plenoptic camera consists of a detector and a lenslet array placed at its focal distance from the first one. When placing the plenoptic camera at the telescope focal plane, it generates pupil images from as many different viewpoints as microlenses building the array, which can be processed to generate the aperture images associated to each viewpoint direction and by computing their relative displacement, estimate the wavefront slope.

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As LGSs are projected upwards and their light travels downwards towards the telescope, the laser is deflected twice through nearly the same path but in different direction. Therefore, tip and tilt compensate almost completely, creating a quasi-stable LGS image in the telescope focal plane (a fast steering mirror is still necessary to correct for the TT fraction induced by the slight difference in the optical path of the upwards and the downwards propagated beam, as launch and receiver aperture have usually different sizes); consequently, the atmospheric TT cannot be retrieved from the Laser Guide Star. Current AO systems use Natural Guide Stars to solve this problem, although this paper proposes a novel solution still in low Technology Readiness Level (TRL), which needs to be further investigated.

2. SYSTEM MODELLING

The presented methodology has been simulated using the OOMAO simulator, a Matlab toolbox which has been developed by[2] with the aim of simulating the behaviour of a complete AO system.

The system was modelled by considering an extended illuminated area in the Sodium layer of 1-arcminute diameter, over which the anisotropies of the Na could be tracked in order to compute the tip-tilt from the LGS itself. This extended area would be illuminated by propagating a ring-shaped beam to the Sodium, without focusing the laser at 90 km, but higher, using an axicon device to generate this shape and the entire telescope aperture for the launch. Figure 1 illustrates the idea.

The ring shape in the Na layer needs to be large enough to keep the central area, and the anisotropies in it, always illuminated; in this way, the displacement of the beam due to the uplink TT would not affect this central illumination and the Sodium anisotropies would present some apparent movement as a consequence of only the downlink tip-tilt, making possible its reconstruction by the WFS. The Sodium layer needs to be uniformly illuminated in order to properly detect the movement of the anisotropies; this uniformity would be achieved by the pre-compensation of the upwards propagated laser beam, which would reduce its scintillation, as it has been previously proven.

The simulation parameters are gathered in Table 1.

Table 1. TT retrieval from Na-layer: Simulation Framework

Atmosphere	5cm; 8cm; 10cm; 12cm; 15cm (photon flux calculation); 18cm
Telescope	OGS Telescope optical parameters
Laser Guide Star	$\lambda = 589$nm Height = 90km Extensively illuminated = Ring shape
WFS	Plenoptic camera Lenslet array = 12x12 Sensor resolution = 144x144 pixels Readout noise = 0.3 e^-
Operation Frequency	100Hz

Synthetic images with five different contrast for the Na anisotropies were implemented in the simulation (Figure 2) with the purpose of proving the performance dependency on the contrast of the plenoptic frame. The

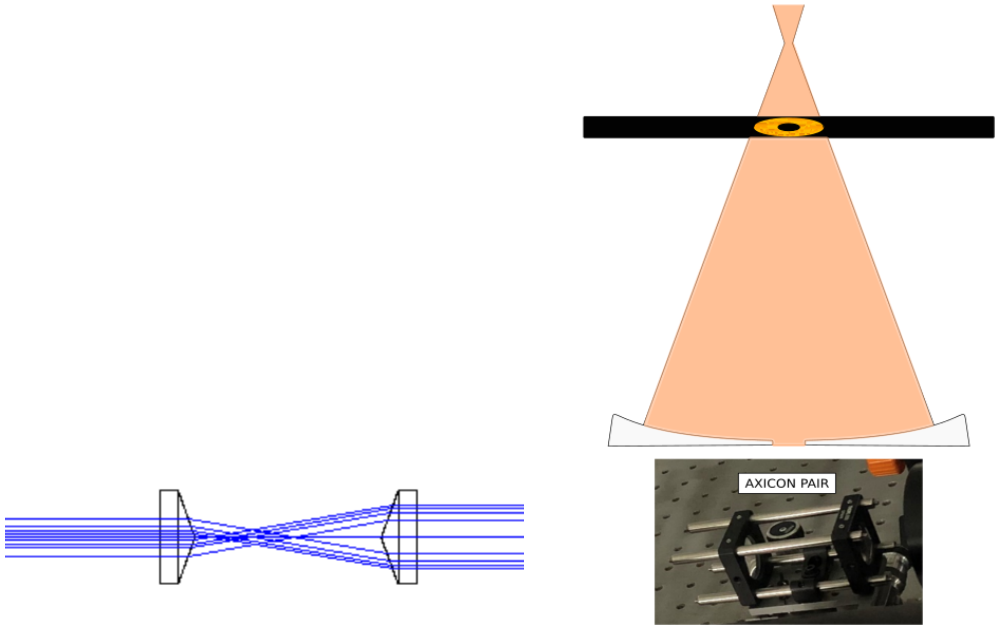

Figure 1. The axicon device could be use to generate a ring shape in the Sodium layer.

RMS contrast of the synthetic images was calculated equivalently as in solar granulation images; the $rms_{contrast}$ is defined as the squared root of the variance of the normalized observed brightness fluctuations[3] (Eq. 1).

$$rms^2_{contrast} = \frac{\sum_{i=1}^{N}(I - \bar{I})^2}{N\bar{I}^2}, \tag{1}$$

where $\bar{I}$ is the mean intensity of the observed image and N is the number of pixels in it.

Tip and tilt coefficients were retrieved from the plenoptic images at different atmospheric cases by using the described contrast levels. Later on, the J similarity index between the real and the computed wavefront (Eq. 2) was calculated and represented for each contrast value at each atmospheric scenario.

$$J(Real, Reconstructed) = 1 - \frac{TT_{real} - TT_{reconst}}{mean(TT_{real})} \tag{2}$$

3. RESULTS

Simulations of the computed tip-tilt by a plenoptic wavefront sensor are presented in Figure 3, showing the expected quality result as a function of the contrast of the generated extended laser guide image.

Additionally, the photon flux of the WFS image was gradually reduced with the aim of detecting the minimum power necessary to illuminate 1' ring up on the Na layer and to reconstruct properly the TT. Simulation of minimum photon flux return from the Sodium inhomogeneities were carried out only for the 15cm seeing atmosphere and the best possible contrast in the Na anisotropies, as this result was considered to be just a rough estimation of the required laser power. Figure 4 presents the method behaviour when decreasing the Signal-to-Noise Ratio; it shows the similarity between the real atmospheric TT, used in the simulation, and the estimated one, when decreasing the photon flux per frame at 100Hz and maintaining the readout and photon noise of the plenoptic camera. For comparison purposes with ESO Wendelstein LGS unit, its photon flux per frame at this operation rate was also added to the graph (photon flux return extracted from[4]).

4. CONCLUSIONS

Results show that the TT information could be extracted from Sodium contrast images by the plenoptic sensor, although this part of the research needs to be further studied, especially whether those anisotropies eventually exist.
The main limitation of the proposed method is the spatial structure of the Sodium anisotropies: they have to be large enough and with the proper contrast to be detected by the wavefront sensor; future experiments will be perform to measure the anisotropies structure. Additionally, the stability of this structure in time needs to be larger than the atmospheric coherence time; it can evolve in time, but slower than the atmosphere itself.

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REFERENCES

[1] R. K. Tyson, "Adaptive optics engineering handbook," 2000.
[2] R. Conan and C. Correia, "Object-oriented matlab adaptive optics toolbox," 2014.
[3] T. Roudier and R. Muller, "Structure of the solar granulation," *Solar Physics* **107**, pp. 11–26, Mar 1986.
[4] R. Holzlöhner, D. B. Calia, D. Bello, D. Budker, M. Centrone, I. Guidolin, W. Hackenberg, S. Lewis, G. Lombardi, I. Montilla, F. Pedichini, F. P. Bustos, T. Pfrommer, M. R. G. Talavera, and S. Rochester, "Comparison between observation and simulation of sodium lgs return flux with a 20w cw laser on tenerife," 2016.

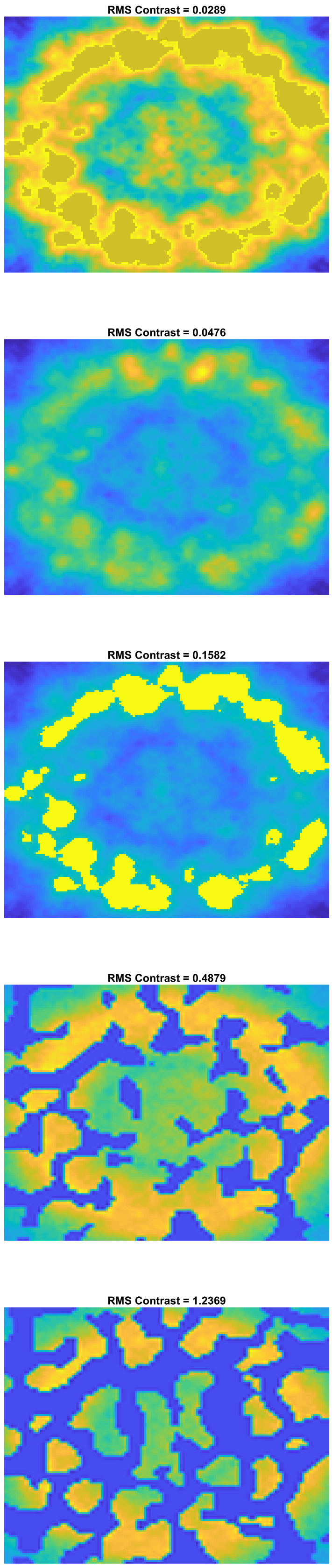

Figure 2. Synthetic images of the anisotropies in the Sodium layer, ranging from lower to larger RMS contrast.

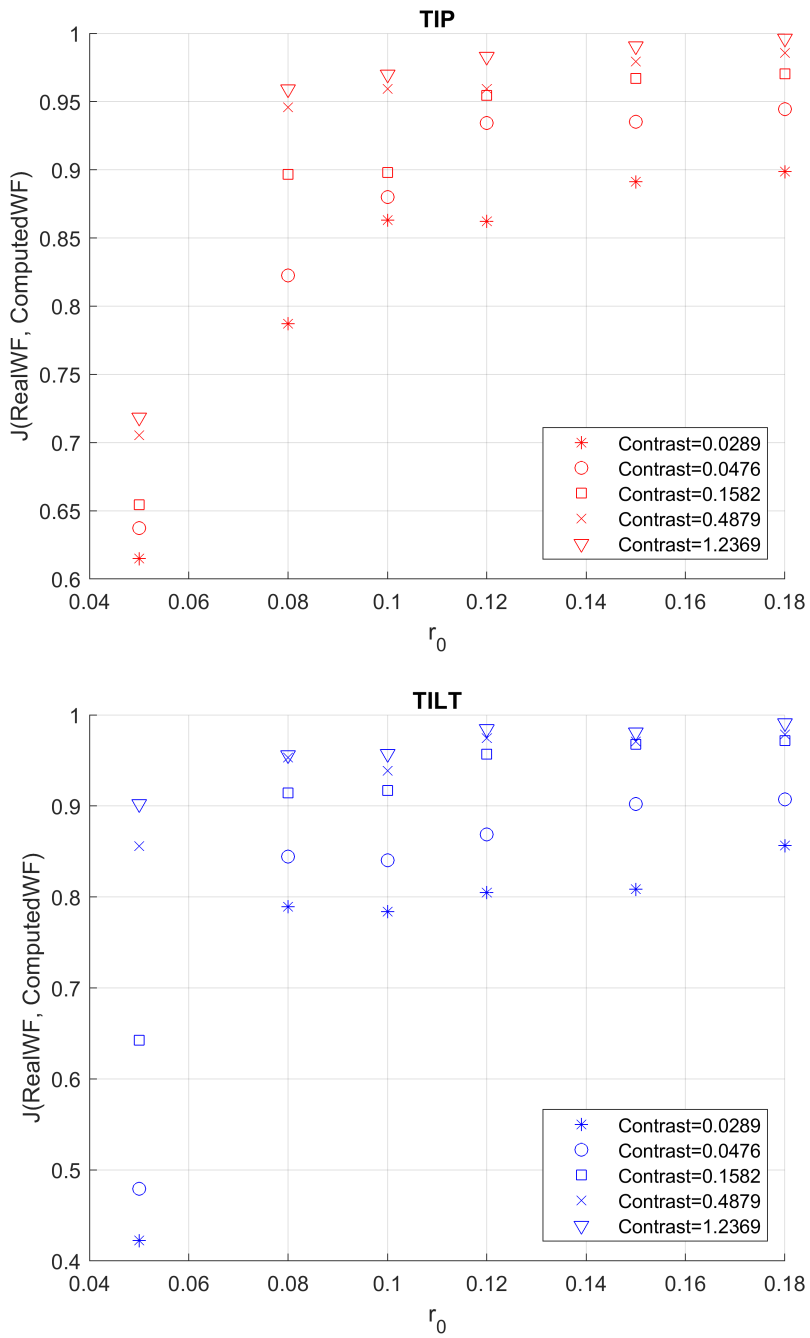

Figure 3. Similarity index between the real atmospheric tip-tilt and the estimated TT by the plenoptic WFS. Results are analysed for several atmospheric turbulence strength and RMS contrast in the Na anisotropies.

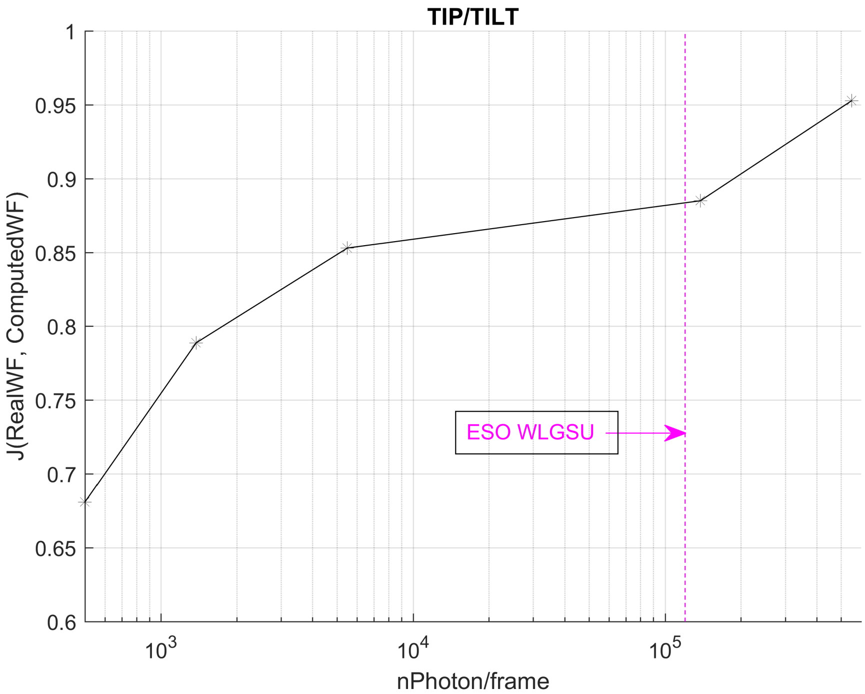

Figure 4. Similarity index between the real atmospheric tip-tilt and the estimated TT by the plenoptic WFS and the effect of decreasing the SNR in the measurements.