AO4ELT7 - June 2023 - Avignon

A pupil-plane LGS wavefront sensor for the next-generation telescopes: the Ingot WFS

Elisa Portaluri[a,b], Kalyan Kumar Radhakrishnan Santhakumari[c,b], Roberto Ragazzoni[d,c,b], Davide Greggio[c,b], Carmelo Arcidiacono[c,b], Maria Bergomi[c,b], Simone Di Filippo[c,b], Marco Dima[c,b], Jacopo Farinato[c,b], Tania Sofia Gomes Machado[d], Demetrio Magrin[c,b], and Valentina Viotto[c,b]

[a]INAF-Osservatorio Astronomico d'Abruzzo, via Mentore Maggini, I-64100 Teramo, Italy
[b]ADONI - Laboratorio Nazionale Ottiche Adattive - Italy
[c]INAF-Osservatorio Astronomico di Padova, vicolo dell'Osservatorio 5, I-35122 Padova, Italy
[d]Dipartimento di Fisica e Astronomia "G. Galilei", Università di Padova, vicolo dell'Osservatorio 3, I-35122 Padova, Italy

ABSTRACT

We present a well-known concept of pupil-plane WFS, proposed 20 years ago, but developed recently to cope with some typical limitations and problems of using LGS, especially on 40m-class telescopes. The main advantages will be to overcome the truncation problem, to be sensitive to the island effects and, not as a secondary aspect, to be opto-mechanically compatible with the vast part of the existing WFS-LGS system and doable with a smaller format detector. We called it "Ingot", looking at its final design, even if we started from a more complicated initial 6 faces concept and here we describe the possible combinations and configurations. We also focus on the characterization of the LGS in the focal volume and the optical/geometrical description of the Ingot WFS. Then we provide a first order comparative analysis with other approaches, by using some relationships to quantify its sensitivity. Finally, we describe the project and the progress of each work-package, in terms of numerical simulations, lab activity and preparation for validation.

Keywords: Adaptive Optics, Wavefront Sensing, Ingot WFS, LGS, Sodium Laser Guide Star, Na, ELT, extended sources

Further author information: (Send correspondence to EPO)
EPO: E-mail: elisa.portaluri@inaf.it

1. INTRODUCTION

To achieve diffraction-limited imaging on large ground-based telescopes, Adaptive Optics (AO) plays a key role, correcting the field of view by using multiple corrector systems that has been proven to work on the sky from more than a decade. This compensation is achieved in a portion of the sky, close to the references used to sense the turbulence, then the sky coverage is an important parameter to be considered when selecting the AO system. Together with the effort in finding a way to select and use natural references on a larger area [13, 9, 8], a great support on this field was done by introducing artificial sources [18] from the propagation of light beams from the ground [4].

However, the current examples of AO systems encompassing LGSs are "common" WaveFront Sensor (WFS) adapted to these peculiar reference sources (location, wavelength), that are usually called "stars", but are quite different from unresolved sources located at infinity distance.

Moreover, the indeterminate absolute position in the sky of the artificial reference is one of the reasons why natural sources remains fundamental.

The appropriate and more efficient WFS should be designed tailoring to the specific case, treating LGS as a sort of cylindrical emitting volumes, with a variable spatial light distribution, placed at a finite distance and thus considering the 3D volume. All these considerations go in the direction of achieving diffraction-limited images on a large ground-based telescope, by eliminating the defocus on the focus plane that will have a big impact.

One of these approach, already described in the literature and tested, although in open loop, on the sky, is the so-called z-invariant class of WFSs [12]. That earliest concept was now extended, considering a roof-like wavefront sensor, coupled with the Sodium LGS, and enlarging its ability to provide information in both the directions [16, 15, 17]. We derived some useful relations and we analyze by which amount its sensitivity can be larger than other selected approaches in order to provide a first order comparative analysis. All the details are described in a forthcoming paper [14], while here we resume the main results and the state of the art of the project.

2. A NEW WFS

Here we consider the configuration where a LGS propagated from a side of the telescope, as in the ELT case, where a laser launcher telescope (LTT) fires the LGS. The case behind the cage of a secondary mirror, in a typical two-mirrors telescope, is not considered and will lead to a different dissertation.

2.1 LGS geometry

A generic point C located in the nominal range at the Sodium layer (Figure 1), will be re-imaged well behind the focal plane (where astronomical objects are focused). The detailed position is indicated by h' and s':

$$\frac{s'}{h'} = \frac{s}{h} \tag{1}$$

where s (and s') is the distance from the optical axis of the system and the point (image), while h (and h') the one between the focal axis and the point (image). A generic point P on top of the Sodium layer (δh) will be reimaged:

$$\frac{\delta s'}{\delta h'} = \frac{s}{f} \tag{2}$$

where f is the focus of the telescope, $\delta s'$ and δh' are the parallel and orthogonal projections of the image with respect the focal plane.

The loci of the points where the image of the elongated LGS is lying are inclined with respect to the optical axis: this is the so-called Scheimpflug principle. Of course, the principle can be applied to a generic position and line of sight of the LGS projector. We recall here that we consider only projectors that are located outside of the telescope pupil (as in the ELT and TMT case). And this principle shows that the illuminating beams will never embed the LGS image itself.

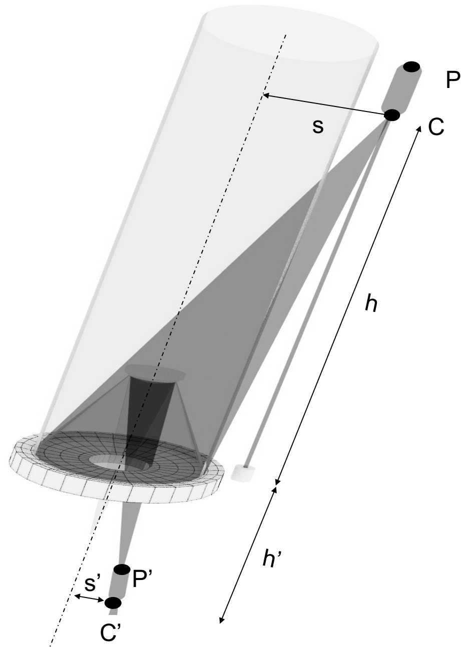


Figure 1. LGS in the focal volume: propagation parallel to the optical axis.

2.2 WFS geometry

There are many possibilities for the geometry of the ingot, depending on the needs of the system (and number of detector pixels available), including combination of only reflective, only refractive, a combination of both, depending which region of the LGS images is being considered. We started form a work done by Ragazzoni et al. [12], considering the Rayleigh beacon and adapting to the Sodium LGS (see Figure 2).

We believe that the maximum useful number of regions is 6 [15] and, after an initial investigation of the 6-faces configuration, given the requirements of the next-generation ELT telescopes, we focus on the geometry having 3 faces: 2 reflecting and one where the light is totally transmitted. Table 1 shows a list of possibilities including how slicing the source and the shape of the prism.

The geometrical characterization using a ray-tracing approach is described in a paper that will be submitted soon [14], where the ingot is properly dimensioned accounting an ELT-like telescope.

3. THE PROJECT AND THE TEAM

The project is ongoing and the subsequent steps are well defined, accounting for numerical simulations, lab experiments, the prototyping and, finally the verification on sky. The team is composed by about 15 researchers organized in 2 main work-packages with the aim of demonstrating the ingot performance with (1) laboratory experiments and (2) through simulations. Several phases of experimentation with considerable technological, theoretical effort and testing are required. The details of the feasibility study and the current status of the project, are reported in Portaluri et al. [10].

3.1 Lab Activity

We set up the first test bench at the INAF-OAPD laboratory mimicking the ELT characteristics to test the optical design [2] and analyze the sensitivity of the prism [11].

We developed and tested a fully automated Python-code alignment procedure [3]. Also, movements of the ingot in its various degrees of freedom and corresponding WFS slope measurements were compared to that of the simulations along with the sensitivity analysis.

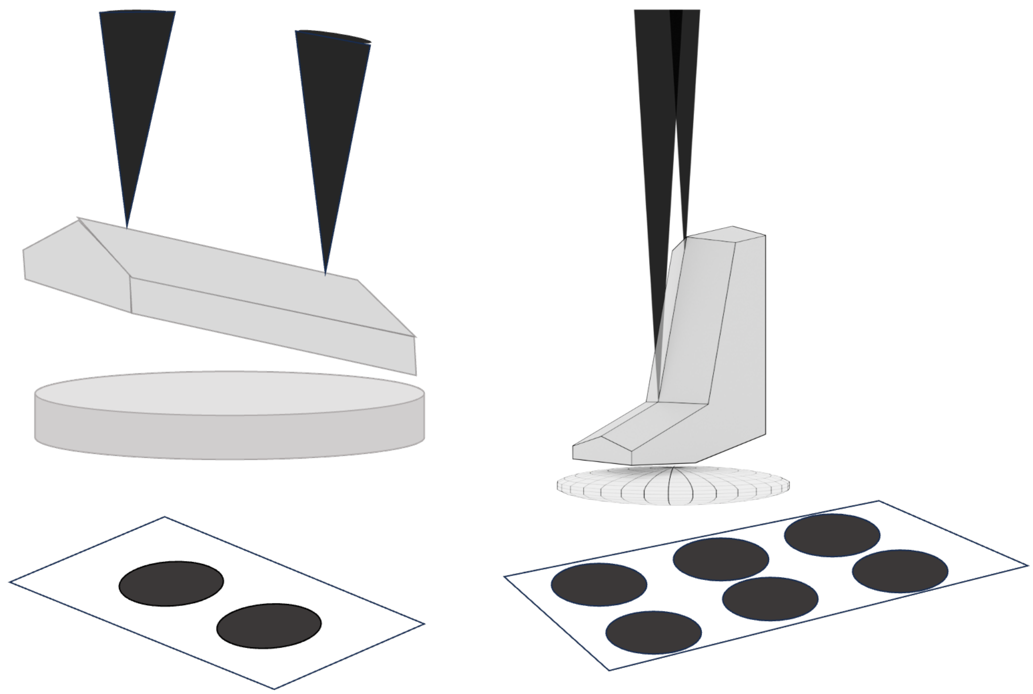


Figure 2. Prisms geometry showing the different configurations, depending on number of faces needed and thus producing the same number of pupils in the focal plane.

Using the LOOPS bench at the Laboratoire d'Astrophysique de Marseille, we verified the working of the 2D version of the ingot in a quasi-real Adaptive Optics closed loop scenario [1], where the the Ingot WFS is approximated with a set of 2D phase masks using an SLM.

The recent updates from the laboratory are described in the paper by Gomes Machado et al. [5] (this conference). More detailed testing and analysis of the alignment procedure of the ingot to the LGS source and several sensitivity analysis are described in this work. In short, the work explains the acquisition of an OLED Screen used for simulating an LGS source in a fast and effective way, to make an operational friendly Ingot WFS.

3.2 Simulations

To test the ingot WFS performance in a close loop regime [7], we also developed a simulation tool [19] which uses both a pure ray-tracing and a Fourier-technique [20] as we need to manage how to deal with the 3 dimensional E2E simulations. We investigated different parameters, adopting several models for ingot prism, and correlated measurements of the slopes [6].

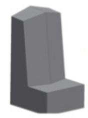
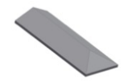
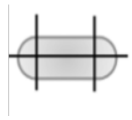
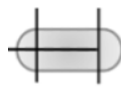
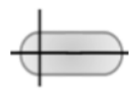
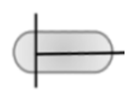
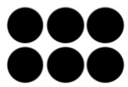
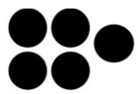
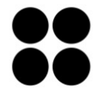
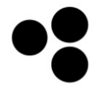
We were able to close the loop in different configurations and we plan to compare the results with those obtained considering a common WFS. The results will be published in a further paper.

3.3 Preparation for validation

As the Ingot WFS can be considered as a risk mitigation for the next generation of ELTs equipped with LGS launchers from the side of the primary mirror, we need to persuade the community that we will have important advantage using the ingot WFS replacing a common conventional WFS.

To do so, we will verify the performance on a stand-alone opto-mechanical system in the Laser Laboratory at INAF-OAR, provided by a LGS simulator and possible a turbulence generator. Then we plan to study the feasibility on sky, applying for having some time at a telescope with an AO system, adapting interfaces and organizing the on-sky verification. One possibility we want to explore is to participate to the call at ESO Wendelstein Laser Guide Star Unit (WLGSU) @William Hershel Telescope where we will have the perfect match with the future ELT.

Table 1. Different configurations of the prism, sensing different regions of the LGS and producing the corresponding pupils.

N. faces	6	5	4	3
Prism geometry				
LGS geometry				
N. pupils				

4. CONCLUSIONS

In this paper we presented the geometrical justification for a new class of WFSs called "Ingot", which are thought to be coupled with an LGS-AO system of the new generation telescopes (with the laser launcher on the side of the telescope) and can be adapted to the needs and the characteristics of the system itself. We also presented an overview of the project: several phases of experimentation and testing are required and described, of considerable technological and theoretical effort.

Our goal is to develop the sensor that allows to optimize the performance of the AO correction overcoming some well-known limits, related to the use of LGS: truncation, sensitivity to island issue, opto-mechanically compatible with existing WFS-LGS systems, doable with a smaller format detector.

Ragazzoni et al. (2023, [14]) will present the complete and exhaustive analysis and the rationale of thw Ingot WFS. Moreover, further papers ready to come will show the results of the laboratory experiments and of the simulations

ACKNOWLEDGMENTS

We acknowledge the ADONI Laboratory for the support in the development of this project.

Funding to support the lab activities described in this paper came also from the INAF Progetto Premiale "Ottica Adattiva Made in Italy per i grandi telescopi del futuro".

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