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The Ingot WFS ON an ELT-like telescope: the project and simulations

Portaluri E.[a,b], Di Filippo S.[c,b], Viotto V. [c,b], Ragazzoni R.[d,b], Arcidiacono C.[c,b], Greggio D.[c,b], Radhakrishnan Santhakumari K. K.[c,b], Bergomi M.[c,b], Marafatto L. [c,b], Dima M.,[c,b], Farinato J.[c,b], Magrin D.[c,b], Di Rico G.[a,b], Centrone M.[e,b], and Bonaccini D.[f,b]

[a]INAF - Osservatorio Astronomico d'Abruzzo, Via Mentore Maggini, I-64100 Teramo, Italy
[b]ADONI, Laboratorio Nazionale di Ottica Adattiva, Italy
[c]INAF - Osservatorio Astronomico di Padova, Vicolo dell'Osservatorio 5, I-35122 Padova, Italy
[d]Dipartimento di Fisica e Astronomia, Università degli Studi di Padova, Vicolo dell'Osservatorio 3, I-35122 Padova, Italy
[e]INAF - Osservatorio Astronomico Roma, Via Frascati 33, I-00078, Monte Porzio Catone (RM)
[f]European Southern Observatory, Karl-Schwarzschildstr. 2, 85748 Garching, Germany

ABSTRACT

The Ingot WFS represents an innovative and indispensable class of sensors conceived to overcome some limitations due to the LGSs geometry, which is significantly different from the point-object originated by a NGS. Here we overview the project, aiming at investigating the performance of an ELT-like telescope equipped with the Ingot WFS, facing different aspects of the program: the needs for numerical simulations and laboratory experiments, the prototype and, finally the future plan for the verification on sky.

Keywords: Instrumentation: adaptive optics, Adaptive Optics for ELT, Ingot WFS, Wavefront Sensing, Elongation

1. INTRODUCTION

The next generation of extremely large telescopes (ELTs, i.e. the European Extremely Large Telescope,[1] ELT, and the Giant Magellan Telescope[2]) MCAO modules are going to be fed by artificial sources, fired by launchers located at the side of the telescope that excites the Sodium layer. Being generated at around 90 km from the ground, e.g. at a finite distance, and on a stratum that has a variable thickness, these sources are not point-like objects, but something similar to "cigars". The Ingot wavefront sensor (I-WFS[3–5]), shaped like an prism, is designed to cope with this typical elongation and thus overcoming such a limitation in order to improve the Adaptive Optics (AO) correction.[6,7]

The project here described is an *R&D* study aimed at the investigation of the feasibility of this innovative and ground-breaking wavefront sensor, reminding that its advancement can be considered as a risk mitigator for the AO systems of the future ELTs, whose baselines foresee only the use of "conventional" sensors with such elongated sources. It is developed by a passionate group of young researchers (∼15), belonging to INAF institutes of Padova, Teramo and Rome and accounts for numerical simulations, lab experiments, the prototype and, finally, the verification on sky at the CANARY facility of the William Herschel Telescope (WHT) in La Palma.

Here, we present the current status of the project, reporting the operations we are setting out to explore how the sensor can be implemented on large telescopes to fully exploit their extraordinary sensitivity and resolution capabilities. In particular, we focus on the description of the overall architecture and results of ongoing activities: the simulations we set out to investigate the performance of the I-WFS on an ELT-like telescope (Section 2) and the laboratory tests we made to study the response of the sensor (Section 3). Then we discuss the plan for

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

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the future, accounting for the test of the sensor on the Laser Laboratory @ the Astronomical Observatory of Rome and, finally, the verification on sky (Section 4) at the ESO Wendelstein Laser Guide Star Unit (WLGSU) @ WHT.

2. NUMERICAL SIMULATIONS

We developed a simulation tool to evaluate the impact of the ingot WFS and test its performance.

The peculiarity of the project lies precisely in the different approach we use to face an old problem: for the first time we have to deal with E2E simulations that would consider a 3D space, as the Fourier (2D) method, commonly used, would not enhance the advantages of the sensor, designed to couple the geometric characteristics of the LGS.[8,9]

The tool accepts a list of input parameters that describe the configuration whose final performance the user wants to estimate. These parameters include atmospheric assumptions, telescope and system characteristics, and purely ingot aspects, as shown in Figure 1 and are fully described in previous papers.[10,11] Therefore, assuming a given geometry of the system and an appropriate LGS asterism, accounting for the cone effect and for an input atmosphere, the simulator will retrieve the incoming wavefront. It is then translated into the focal plane, through the ingot, to the pupil plane, where the 3 pupils are re-imaged and then used to compute signals,[11] calculated with different options.

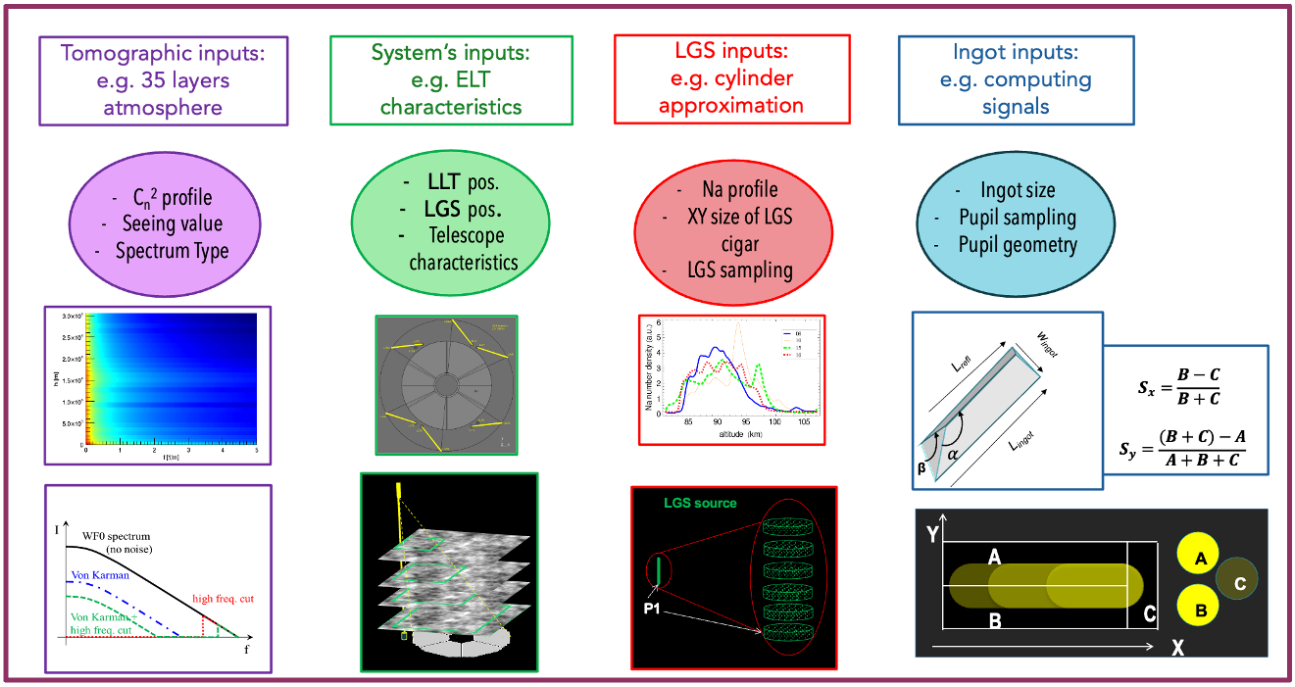


Figure 1. List of the 4 main categories that the software accounts for: tomography, system, LGS and ingot geometry. For each of them some examples of inputs are listed and shown with a figure or plot.

The software works in a closed-loop fashion, aiming at the reconstruction of the incoming turbulent wavefront using a modal approach. In particular, we use a Zernike modal basis to compute the interaction matrix and the relative reconstructor, which is calculated and then used to retrieve the output wavefront from signals. The outcome is the achievable SR, which can be compared with the one expected for the next generation of instruments in the same conditions and used to quantify the gain reachable in many cases, also considering the science applications.

At the moment, we are working in a "comfortable zone", using a frozen atmosphere and first 100 Zernike modes, performing first loops in low-resolution mode. However, the first results are encouraging: we were able to

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properly close the loop and obtain very good performance, reconstructing the incoming wavefront with an error less than 2%.[11]

A great effort and a lot of time time have been dedicated to overcome computational and memory issues in order to work (in the future) in the high-resolution regime (as an example, the high pupil sampling is a bottle neck) and, currently, we are ready to improve the description of the performance improving the input parameters as resolution, sampling, number of modes and dynamical disturbance and, at the end, to compare the results with those obtained using a SH-WFS.

Then, the plan is to explore the range of parameters to find which one mostly influences the response of the sensor, then to reproduce:

- the laboratory configuration in order to compare the results (Section 3)
- the ELT configuration as much as possible in order to compare the prediction of the AO correction, with the outcome of the I-WFS.

As the simulations are proceeding in parallel with first experiments on the laboratory[12,13] (Section 3) and also with tests in the Fourier environment,[14] at the end we will have a complete view of the response of the sensor. Their comparison will be necessary in order to properly evaluate the positive impact of such new sensor on an AO system, going towards the possibility to test it on sky (Section 4).

3. LABORATORY EXPERIMENTS

Laboratory experiments are required in order to have a hint of the effectiveness of the sensor, and they have to be close as much as possible to reality to properly couple the geometric characteristics of the LGS to the sensor itself: this translates on the fact that for the first time we had topay close attention to the 3rd dimension.

In short, we dedicated 2 setups to investigate different features of the I-WFS, performing:

- a test in a quasi-real Adaptive Optics Closed Loop scenario at the LOOPS bench @ LAM[14]
- a test of the alignment of the system and measurements of low-order static aberrations in an Open Loop scenario.[12,13,15]

In the first case, the I-WFS was approximated with a set of 2D phase masks and tested using different formulas for calculation of signals and configuration of the LGS elongation (Figure 2). The results were compared with the ones obtained with a 2D phase mask pyramid-like sensor and show the advantage of the I-WFS in the most elongated configuration.[14]

On the opposite side, following the second approach, we built an optical setup mimicking the ELT characteristics at the INAF-Observatory of Padova to test the I-WFS and its alignment procedure using an OLED screen to reproduce the LGS source, which is elongated along the optical axis, coupled with a real ingot prism.

Several simulations and tests were required to align the ingot prism to the LGS source, considering its 6 degrees of freedom. The procedure is now definitive, its working and efficacy is described in a previous paper[12] and now it is fully automatized[13] .

With this configuration we performed:

- Movements simulation analysis
- Sensitivity analysis
- Definition and automatization of the alignment procedures

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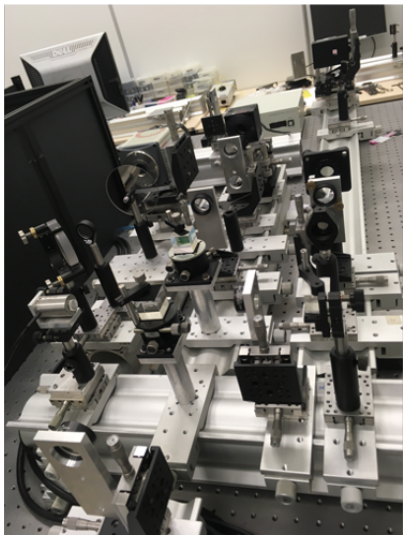


Figure 2. Ingot setup @LAM. For more details see Arcidiacono et al. 2020.

Currently we positioned a deformable lens (DL, aperture= 25mm, actuators=18) in the pupil plane in order to apply low order aberrations to the wavefront (Figure 3). In this way, we can apply a single value or combination of modes and actuators movements using our Python/Matlab procedure, which controls the system, to create known aberrations.[13]

However, the laboratory setup is evolving in time to accommodate new components: for example in the future we plan to use in the future a deformable mirror for the close-loop operations and eventually a "classical" WF sensor (a pyramid and/or a Shack-Hartmann) to compare the performances. As a further step, we plan to mimic as much as possible the real scenario by the introduction of the source profile, which takes into account the temporal and spatial variability of the Sodium layer. And finally, our goal is to reach an advanced phase (in the setup configuration and in the learned procedure) to make the laboratory results comparable the I-WFS performance obtained with the end-to-end simulations.[11]

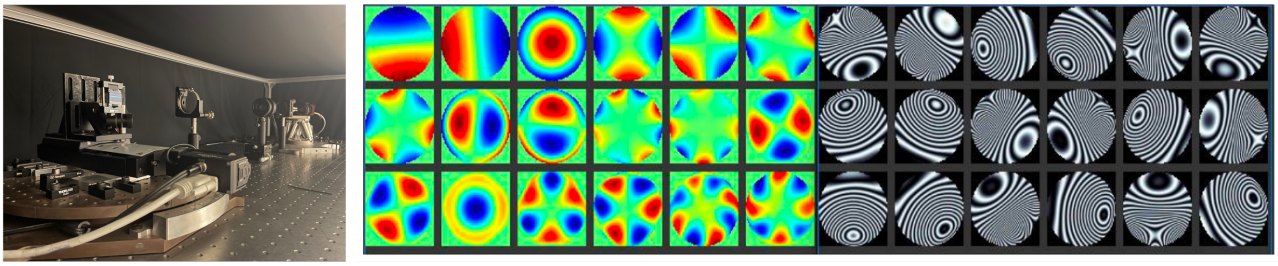


Figure 3. Left-hand panel: Ingot setup @INAF-Padova, including the DL. central Right-hand panel: aberration modes produced by the 18 actuators of the DL and corresponding WF.

4. FUTURE PROTOTYPE AND VERIFICATION

As already highlighted, the I-WFS can be considered in the strategy of risk mitigation for the next generation of ELTs equipped with LGS launchers (located at the side of the telescopes.) However, in order to demonstrate its feasibility and gain, we have to go in the direction of prototyping!

Once available, first, we will test the prototype and verify the performance on a stand-alone opto-mechanic system in the Laser Laboratory @ INAF-OAR, provided by a LGS simulator and possibly a turbulence generator.

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Figure 4. Laser Laboratory @ INAF-Rome.

Then we plan to study the real working instrument and participate to the next year call at ESO Wendelstein Laser Guide Star Unit (WLGSU) @ WHT, adapting interfaces and organizing the on-sky verification. The WLGSU is located 40 m from the WHT, and is used together with CANARY adaptive optics system on the WHT: a Sodium laser beam is launched from the WLGSU as part of laser guide star field tests for validating ELT laser guide star baseline performance.



Figure 5. WHT with the WLGSU facility. Credit: Obs.de Paris/Lisa Bardou.

5. STATUS OF THE PROJECT AND CONCLUSIONS

The Ingot *R&D* project has an ambitious goal: to develop a new type of sensor that allows to optimize the performance of the AO systems of the new generation telescopes, overcoming some well-known limits, related to the use of LGSs.

To achieve this goal, several phases of experimentation and testing are required (in laboratory and through simulations), all well defined, of considerable technological and theoretical effort. In fact, we remark here that the peculiarity of this study lies precisely in the different approach to manage a well-known problem: for the first time we have to carry out 3D tests in the laboratory (to couple the geometric characteristics of the LGS to the sensor itself), and managing how to deal with the E2E simulations as the 2D Fourier method, commonly used, would not enhance its advantages.

Until today we reached important results, which are documented in several reports, technical documents and proceedings (see Section 5) presented during conferences (SPIE, AO4ELT, WFS workshops) and/or during internal meetings. To resume:

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- The characteristics of the sensor are already defined thanks to a careful study that considered the configuration and the geometry of the ELT
- We conducted preliminary experiments in the laboratory using available materials, testing the response and the performance of the sensor and starting to contact the industry to upgrade the setup, making more suitable and compliant to the ELT expectations
- We concluded the tests @ LAM laboratory and analyzed several configurations of the couple LGS+Atmosphere, defining alignment procedures, data collection and analysis
- The simulation tool is already developed and we are working to speed up the operations and improve the compliance with the reality to run high-resolution simulations.

In the next future, to finalize the feasibility of the sensor, the project accounts for:

- the final development of the simulation tool to estimate the expected sensibility and the response of the system (in the ELT perspective) and its usability to the whole group;
- the publications of the results, in particular their comparison with the ones obtained using different types of sensors, (pyramid and Shack-Hartmann WFS) and the evaluation of the better performance;
- the final implementation of the laboratory setup @ INAF-Padova and publication of the tests made to learn the sensibility of the instrument and the definition of the common operations needed for the alignment of the whole system;
- the prototyping of the prism to draw attention to possible difficulties for the implementation and integration of the system;
- the definition of the design of an opto-mechanical system and possible realization of an LGS simulator with a turbulence generator in the context of the Laser Laboratory @ INAF-Rome to verify the performance of the prototype
- the feasibility study for an experiment @ the ESO instrument WLGSU and with the WHT AO module Canary.

Therefore, the next phases that have to be faced are sequential and their succession goes hand in hand with the knowledge of the sensor response and with the skills that the whole team acquires in a trade-off training process. We wish to develop the prototype soon and publish some exciting news once we will test it on sky.

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