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► **To cite this version:**

Anne Costille, Edgard Renault, Anne Bonnefoi, William Ceria, Kjetil Dohlen, et al.. Design and challenges for the HARMONI Laser Guide Star Sensors. Adaptive Optics for Extremely Large Telescopes 7th Edition, ONERA, Jun 2023, Avignon, France. 10.13009/AO4ELT7-2023-010 . hal-04402840

HAL Id: hal-04402840

<https://hal.science/hal-04402840v1>

Submitted on 18 Jan 2024

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Design and challenges for the HARMONI Laser Guide Star Sensors

Anne Costille^{*a}, Edgard Renault^a, Anne Bonnefoi^a, William Ceria^a, Kjetil Dohlen^a, Zoltan Hubert^b, Jean-Jacques Correia^b, Thibaut Moulin^b, Patrick Rabou^b, Saul Menendez^c, Benoit Neichel^a, Thierry Fusco^d, Kacem El Hadi^a, Stephane Curaba^b, Fraser Clarke^e, Dave Melotte^f, Niranjana Thatte^e

^aAix Marseille Univ, CNRS, CNES, LAM, Marseille, France

^bUniv. Grenoble Alpes, CNRS, IPAG, 38000 Grenoble, France

^cInstituto de Astrofísica de Canarias

^dONERA, B.P.72, 92322 Chatillon, France

^eDepartment of Physic, University of Oxford, Oxford OX1 3RH, United Kingdom

^fUKATC, Royal Observatory Edinburgh Blackford Hill, Edinburgh EH9 3HJ, United Kingdom

ABSTRACT

HARMONI is the first light visible and near-IR integral field spectrograph for the ELT. It covers a large spectral range from 450nm to 2450nm with resolving powers from 3500 to 18000 and spatial sampling from 60mas to 4mas. It can operate in two Adaptive Optics modes - SCAO (including a High Contrast capability) and LTAO - or with NOAO. The project is preparing for Final Design Reviews. The laser Tomographic AO (LTAO) system provides AO correction with very high sky-coverage and it is supported by two systems: the Laser Guide Star Sensors (LGSS) and the Natural Guide Star Sensors (NGSS). The LGSS analyse the wavefront coming from 6 laser guide stars (LGS) created by the ELT; light that is picked up at the at the very entrance of the instrument with a dichroic mirror. LTAO is complemented with NGSS that probe the wavefront on natural guide star for tip, tilt, focus determination. The LGSS is made of 6 independent wavefront sensor (WFS) modules mounted on a rotator of 1100 mm diameter to stabilise the pupil onto the microlens array in front of the detector with an accuracy of 90". Each LGS WFS is designed to compensate variations of the LGS mean layer centroid from 75 km to 92 km altitude at zenith angles from 0° to 60° with a dedicated mechanism in each module. We present the optical and mechanical design of the LGSS proposed for FDR. The optical design is based on the use of freeform lenses to minimize the numbers of optical components, to accommodate for the diversity of sodium layer configurations and to ensure a small amount of aberrations in each LGS path. The WFS itself is based on a CMOS detector from SONY: it provides a large number of pixels to accept elongated spots up to 16 arcsec without truncation and to sample the pupil with 68 sub-apertures with a pixel size of 1.15". The trade-off of the mechanical design is also presented to illustrate how materials (carbon benches) have been carefully selected to ensure resistance to earthquake with a reduced mass to obtain a complete system smaller than 3 tons and with a first mode larger than 12Hz. The current challenge of the design relies on the choice of the microlens array technology to minimize the transmission loss.

Keywords: ELT Harmoni, Adaptive Optics, Opto-Mechanics, LTAO, laser guide star, wavefront sensors

INTRODUCTION

HARMONI [1] is a visible and near-infrared integral field spectrograph providing the ELT's core spectroscopic capability. It will exploit the ELT's scientific niche in its early years, starting at first light planned in 2029. To get the full sensitivity and spatial resolution gain, HARMONI will work at diffraction limited scales. This will be possible thanks to two complementary adaptive optics systems [2], fully integrated within HARMONI. The first is a Single Conjugate AO (SCAO) system offering high performance for a limited sky coverage. The second is a Laser

*E-mail: anne.costille@lam.fr

Tomographic AO (LTAO) system, providing AO correction with a very high sky-coverage. Both AO modes for HARMONI have gone through Preliminary Design Review at the end of 2017, and enter their Final Design phase starting in 2018 ending in 2024.

While the deformable mirror performing real-time correction of the atmospheric disturbances is located within the telescope itself, instruments are in charge of providing the wavefront measurements controlling this correction. To this end, HARMONI contains a suite of state-of-the-art and innovative wavefront sensor systems. These are distributed within the instrument according to their various functions. The Laser Guide Star Sensors (LGSS) are located at the entrance of the instrument and fed by a dichroic beam splitter reflecting the sodium line and holds by the optical relay at the entrance of the instrument. The various natural guide star sensors (NGSS) are located close to the science focal plane. LTAO requires natural guide stars for fast sensing of tip-tilt and focus and for disentangling the effects of slowly varying non-common path errors.

In this paper, we present the current design of the LGSS system and we focus on its optical design constraints and performance.

LASER GUIDE STAR SENSORS DESIGN OVERVIEW

2.1. HARMONI Instrument

The HARMONI instrument (Figure 1) is built up of four main hardware systems. The Integral Field Spectrograph (IFS) [3] consists of a 4m high and 3.25m diameter cylindrical cryostat vessel sitting on a rotator, housing scale-changing optics, image slicer units and spectrograph modules. The Calibration And Relay System (CARS) consists of a relay system (FPRS) in the form of a cooled Offner relay producing a vertical optical axis and a focal plane at the entrance of the IFS, a calibration unit, and the instrument structure (ISS) allowing to present these elements to the telescope optical axis, 6m above the Nasmyth platform. The two remaining systems are the wavefront sensor systems, one working on artificial Laser Guide Stars (LGS), and the other working on Natural Guide Stars (NGS).

To implement the LTAO operational mode, HARMONI instrument uses the laser guide stars sensors provided by the LGSS together with the appropriate natural guide start sensor (LOWF subsystem part of NGSS (Natural Guide Star Sensors)), the ELT corrective optical components (tip-tilt mirror (M4) and deformable mirror (M5)) together with the Adaptive Optics Control System (AOCS) to configure the instrument. Once configure, LTAO operation mode is used to correct the incoming wavefront, stabilize the science focal plane and communicate with the ELT to track the science object of interest across the sky.

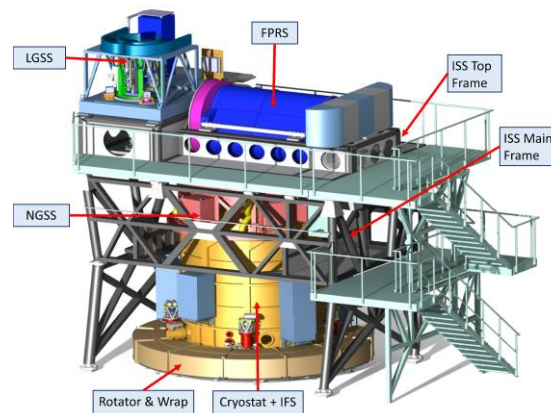


Figure 1. 3D rendering of the HARMONI instrument indicating major systems and components.

2.2. Laser guide star sensors design overview

LGSS system is using six laser guide stars produced by the ELT on an asterism radius of 34". Located at the entrance of HARMONI, it receives the laser light reflected off a large dichroic beam splitter located 1m downstream of the telescope focus. A fold mirror sends the 6 laser beams vertically upwards where they are individually intercepted by the six LGS

Wavefront sensor Modules (LWM). These are mounted in a rotating core structure, controlled such as to maintain the pupil stabilized within the wavefront sensors.

The LGSS system is made of three main sub-systems:

- The LGS support frame (PBS ID 110000) that contains all the mechanical elements that compose the structure of the LGSS. It includes a rotator to allow the stabilization of the pupil onto the microlens array and a cable wrap to allow the cables to move properly. It holds the LGSS cabinets and the service routing that provides power, signal and glycol to the different parts of LGSS. Design of the rotator is still under analysis with a trade-off on the use of two motors working in opposition as in MICADO design [4] or using a direct drive motor. The picture shown below is based on the two motors solution;
- The LGS fold mirror (PBS ID 120000) that reflects the light of the laser vertically and that is directly installed onto the ISS of HARMONI. It is a large mirror (600 x 900mm) with a lightweight structure;
- The LGS rotating sub-system (PBS ID 130000) that holds the six optical benches of the LGSS. This is the opto-mechanical core of the system where the WFS are installed and analyzed the light coming from the LGS. The LGS rotating sub-system is also structure in three main modules:
 - The LGS core structure (LCS 131000) that is made in stainless steel and aligned to the rotator axis. It holds 6 WFS benches
 - The LGS WFS modules (LWM 132000) that holds the optical component to focus the light and conjugate the pupil plane on to the detector array
 - The LGS Detector Modules (LDM 133000) that is made of a microlens array, a focal plane relay and a detector. The interface between the LWM and the LDM is the pupil plane.

The total mass of the system, including its cabinet, shall be below 3 tons.

Figure 2 shows the current CAD model of the LGSS and its sub-system. Figure 3 presents the CAD model of the LGS WFS modules, which are duplicated six time into the core structure. More details on the design choice and their description can be found in [5].

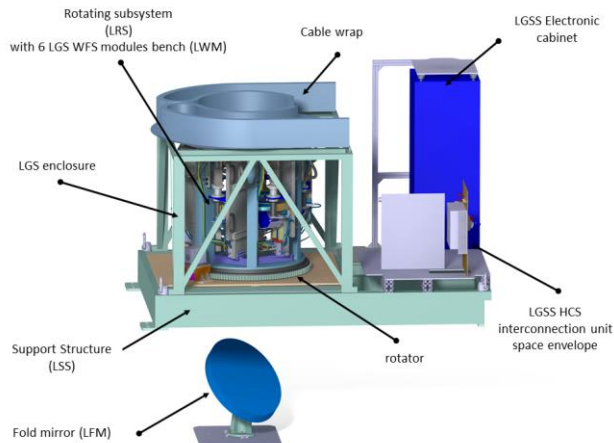


Figure 2: LGSS system overview

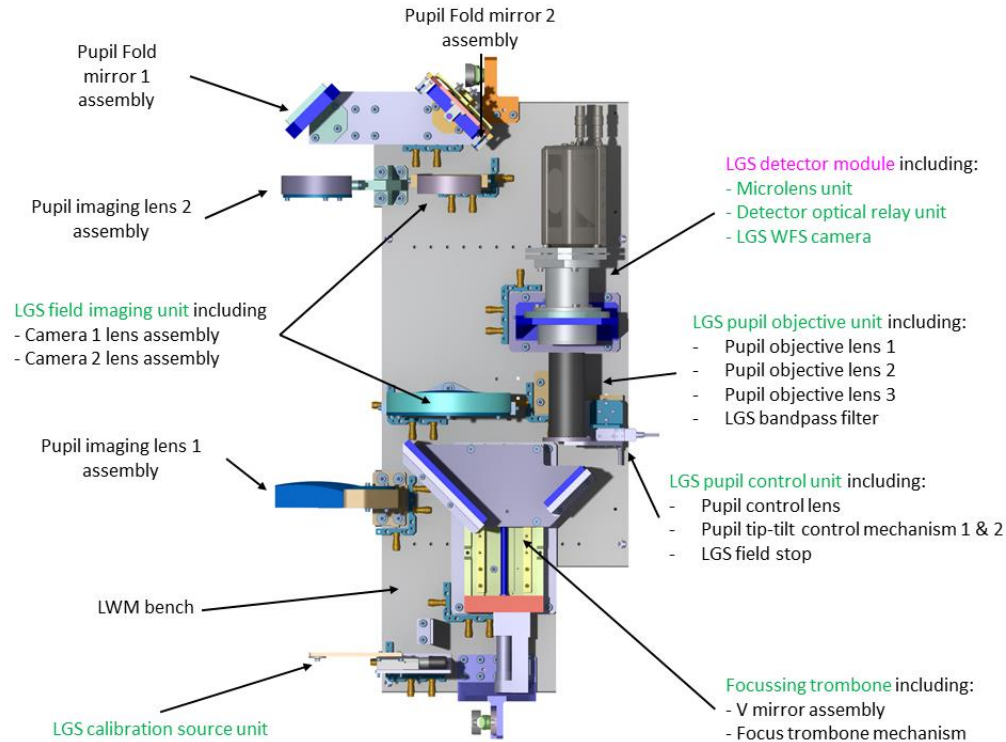


Figure 3: the optical bench assembly including the LGS detector module.

LGSS OPTICAL DESIGN PERFORMANCE

3.1. LGSS optical design description

The most critical part of the optical design for LGSS are the pupil imaging lenses at the entrance. They need to produce well-corrected images at vastly different object distances (the laser focus moves by several meters when going from Zenith to 30 degrees from the horizon). An appropriate design has been found using four free-form lenses as shown in Figure 4, staying within the required wavefront error budget of 120nm rms and 0.1% pupil distortion. The LGSS design needs to accommodate for:

- Sodium layer medium altitude above telescope: 87.8km +/- 2km at $Z_a = 0^\circ$
- Sodium layer thickness: +/-11km
- Pupil conjugation with microlens array: M1 mirror with entrance pupil size: 38542mm
- Exit pupil distance: 37849mm
- Telescope Zenith angle: 0 to 60°
- Compatibility with a fixed astigmatism of 34'' radius
- Provide a field of view non vignettted $\leq 16''$. A field stop shall be implemented
- Providing focus correction for layers ≥ 84.8 km and ≤ 92 km at $Z_a = 0^\circ$
 - Layer < 84.8km will be decentered on the WFS but not vignettted
 - Layers >184km will be decentered on the WFS but not vignette
 - The rest of the layer altitude will be truncated
- Providing a pupil stabilization with an accuracy of 0.03 sub-apertures
- Providing a bandapss filter of 589nm +/-5nm
- Capacity to handle the non-common path errors with respect to science path
- Global transmission $\geq 45\%$ (detector quantum efficiency included)

According to the requirements described below, an optical design has been proposed for the LGSS system. Light of the LGS is received in the horizontal plane coming from the dichroic beam splitter which is part of the CARS system. A large folding flat which is part of LGSS redirects the beam vertically into the rotating structure holding the six LGS WFS modules (LWM). The optical design of each LWM is composed of the following elements:

- Field optics, placed in the space between the infinite conjugate focus and the LGS focus. Creates a pupil image and reduce the focal distance in order to fit with the volume allocation Freeform lenses are needed to achieve the requested image quality.
- Folding mirrors to fold the optical beam and fit the optical design in the LWM dimensions
- Camera optics to create a telecentric beam with a unique focal ratio. Two freeform lenses are implemented to control pupil distortion
- Focussing trombone with a mechanism to compensate the focus difference between zenith and 60° pointing. The maximal shift (between these two pointing angles) is 97mm.
- A Pupil Control lens to align accurately the pupil onto the microlens array
- A square Field Stop defines the FoV (16" on sky) and orients according to the WFS camera orientation
- Pupil Objective Lenses to create a pupil of 22.58 mm diameter at the microlens array.
- Detector module made of the microlens array, a relay optics and a SONY detector. Raytracing diagrams

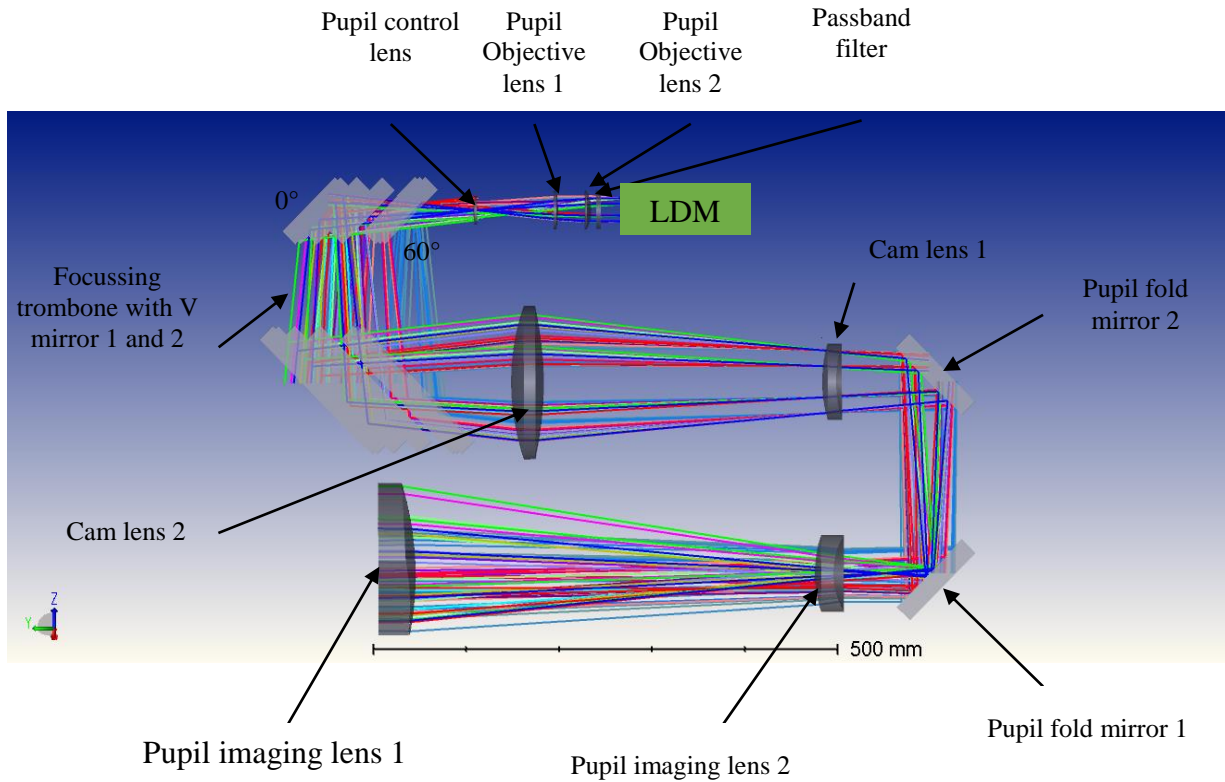


Figure 4: Ray tracing diagram of the LWM up to the microlens array. The fold mirror is not shown.

Table 1: LGSS optical components detailed description

	PBS number	Diameter in mm	Thickness in mm	Surface Shape	Edges Shapes
LGSS Fold Mirror	123000-0000	600x840		Plane	Elliptical

Pupil Imaging Lens 1	132111-0000	200	40	Plane-convex R1 = infinity R2 = -325.211 mm (freeform) Z6 = - 1.7238.10 ⁻⁴ Z7 = - 9.6342.10 ⁻⁴ Z11 = 0.075 Z22 = - 7.3204.10 ⁻⁴ Z37 = - 1.1063.10 ⁻⁵ Z56 = - 3.1099.10 ⁻⁵ Z79 = 7.3937.10 ⁻⁶	Circular Cuted
Pupil Imaging Lens 2	132121-0000	80	20	Meniscal R1 = 120 mm (freeform) Z6 = - 2.3455.10 ⁻³ Z7 = - 6.4832.10 ⁻⁴ Z11 = 0.0695 Z22 = - 4.4033.10 ⁻⁴ Z37 = - 6.4014.10 ⁻⁴ R2 = 75.675 mm	Circular
Pupil Fold Mirror 1	132131-0000	80x100	20	Plane	Rectangular
Pupil Fold Mirror 2	132141-0000	80x100	20	Plane	Rectangular
CAM 1 Lens	132311-0000	80	15	Meniscal R1 = - 130.502 mm R2 = - 138.769 mm (freeform) Radius norm 40mm Z6 = -1.1619.10 ⁻³ Z7 = -1.4388.10 ⁻⁴ Z11 = 1.4817.10 ⁻³ Z22 = 1.3422.10 ⁻⁴	Circular
CAM 2 Lens	132321-0000	160	35	Biconvex R1 = 369.590 mm (freeform) Radius norm 95 mm Z6 = -2.6466.10 ⁻³ Z7 = 3.7039.10 ⁻⁴ Z11 = -0.143 Z22 = 8.9050.10 ⁻³ Z37 = 3.3286.10 ⁻³ Z56 = 8.144.10 ⁻⁴ Z79 = 1.0393.10 ⁻⁴ R2 = - 240.755 mm	Circular
V Mirror 1	132411-0000	120x170	20	Plane	Rectangular
V Mirror 2	132421-0000	80x80	20	Plane	Rectangular
Pupil Control Lens	132510-0000	30	4	Convex_Plane R1 = 90 mm R2 = infinity	Circular
LGSS Field Stop	132550-0000	40x40 13.2x13.2 (hole)	200 μm (TBC)	Plane	Square
Pupil Objectif Lens 1	132610-0000	40	5	Plano convex R1 = infinity R2 = 120 mm (aspheric) 2nd : -6.3011.10 ⁻⁴ 4th : 2.2715.10 ⁻⁶ 6th : 6.8956.10 ⁻¹⁰	Circular
Pupil Objectif Lens 2	132630-0000	40	5	Meniscus R1 = -87.1876 R2 = -41.9138	Circular
Na Filter	133600-0000	40	5	Plane	Circular

3.2. Performance and analysis of the optical design

Performance analysis of the optical design has been done thanks to Zemax software. In order to check the Wavefront Error at the Microlenses level, we add a paraxial lens and we observe the spot diagram (referenced to the centroid) at its

focus. We use several configurations to analyse the performance for different zenith angle, and for different thickness of the sodium layer. The Paraxial focal length is adapted for each configuration in order to keep the same aperture. Analysis of the WFE is done for the mean layer first. The calculation of the Zernike coefficient is only possible for the centred and focused Laser Guide Stars. For the other fields, like upper and lower Na layers, the pupil is vignetted, then the projection onto the Zernike polynomials is not providing consistent result. This is a major difficulty of the analysis of the LGSS performance to analyse a result on a vignetted pupil.

Figure 5 shows the rms value of the WFE for the mean layer with respect to zenith angle variation. In conclusion, all the centred configurations (ie mean layer centred and focused) for each zenithal distances are within the specification in term of WFE as all WFE are below 60 nm rms.

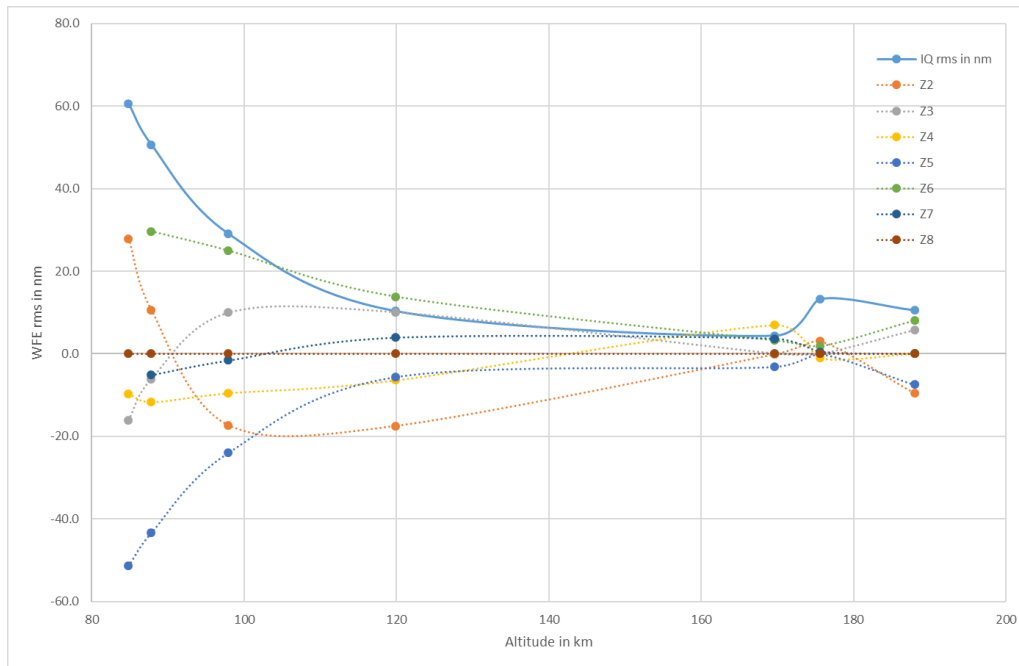


Figure 5: WFE of the mean layer with respect to zenith angle (Na layer distance)

To analyse the impact of the aberrations along the sodium layer, it is not possible to use directly the Zemax software due to the pupil vignetting. In fact the aberrations from the sodium layer will be seen as non-common aberrations and shall be kept under a certain level (45nm rms) to limit their impact on the LTAO performance. The analysis that has been done evaluate the impact of these aberrations as followed:

- Phase map of the medium layer is calculated (evaluation of the rms, phase map)
- For the altitude along the sodium layer, we calculate the residual phase map of the aberrations by subtracting for each phase map the mean layer contribution
- We calculate the sum of the phase map along the sodium layer: for this residual phase map we calculate the PV and rms value
- We apply the 7 sodium layer profile provided by ESO to this residual phase map and we calculate the resulting phase map (rms value).
- We look at the propagation of the aberrations in a GLAO configuration by calculating the residual phase map of the 6 LGS resulting map (we only consider here the worst case scenario)
- We check that the rms value of the GLAO configuration is below 45nm rms.

This analysis is done for the 6 different Zenith angles for the 3 LGS configurations. In this document we present the detailed steps for $Z_a = 30^\circ$ and the results obtained in the GLAO configuration for all zenith angles. From the results presented below, one can see that the resulting map shows 14.5nm rms of aberrations. The optical design is not introducing residual aberrations.

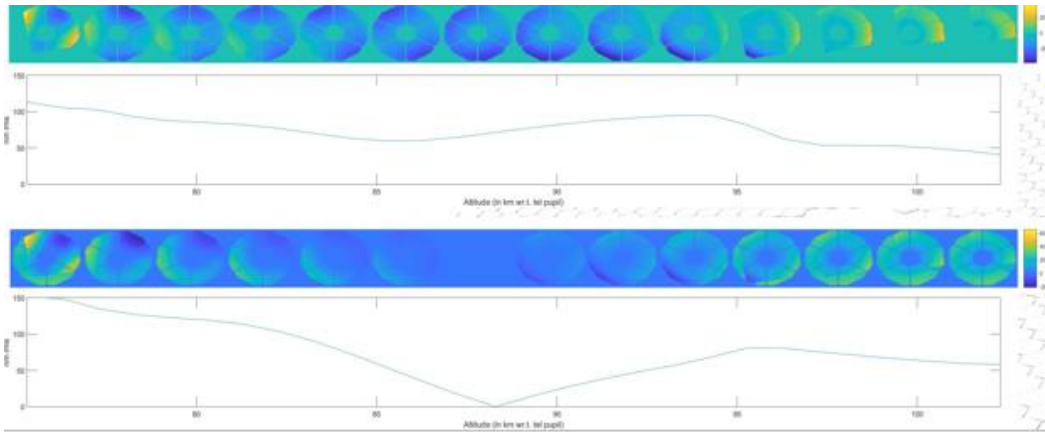


Figure 6: top : phase map along the sodium layer (+/-11 km). Bottom : phase map after subtraction of the mean layer

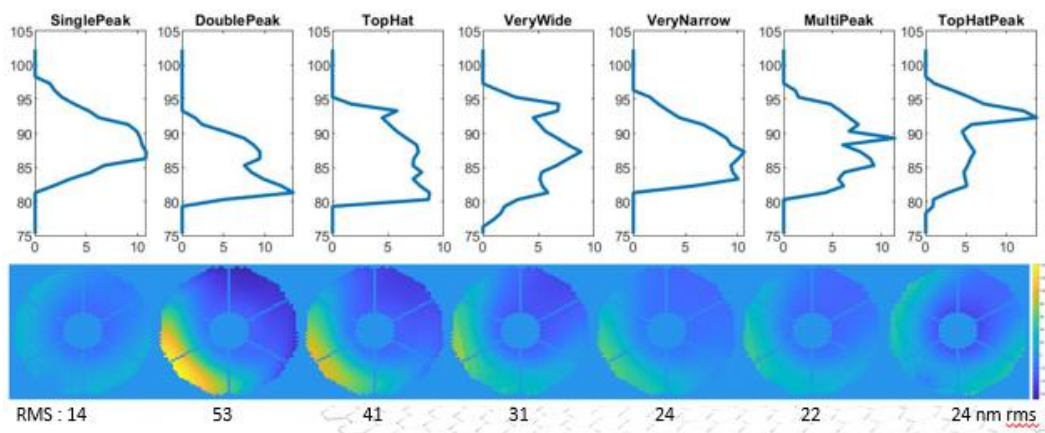


Figure 7: Resulting map with different sodium profile

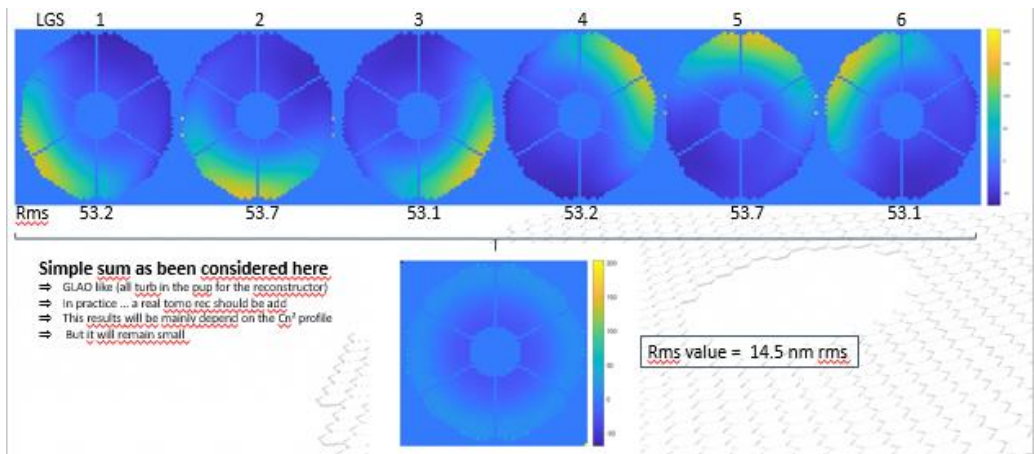


Figure 8: Resulting map with GLAO like calculation.

3.3. LGSS detector module description

The LGSS Detector Module (LDM) contains a microlens array, relay optics, and a camera package. The detector module is developed by IPAG, with a joint effort and analysis with MORFEO project. The baseline for the LGSS design is to use a SONY detector, delivered in a C-BLUE 1 camera [6]. The current design of LGSS provides a detector module directly installed on the optical bench modules. The main characteristics of the detector module are:

- 68x68 sub-apertures in the pupil
- Minimum useful FoV per sub-aperture: 16''
- PSF sampling on the detector $> 1.1''/\text{pixel}$
- Double-sided microlens array to limit the angle of acceptance on the detector
- Optical relay: Due to the wide field required for LGS wavefront sensors, the microlens focal length is very short. To avoid implementing a microlens inside the detector chip, it is therefore mandatory to implement a relay system to reimage the Shack-Hartmann spots onto the detector. This problem is common with other ELT instruments, and an agreement is made with the MORFEO team to develop common detector system module: microlens, relay, camera. Figure 9 shows ray paths traced through the design of a relay with a C-BLUE 1 camera. The length of this system is about 150 mm, from lenslet array to detector.

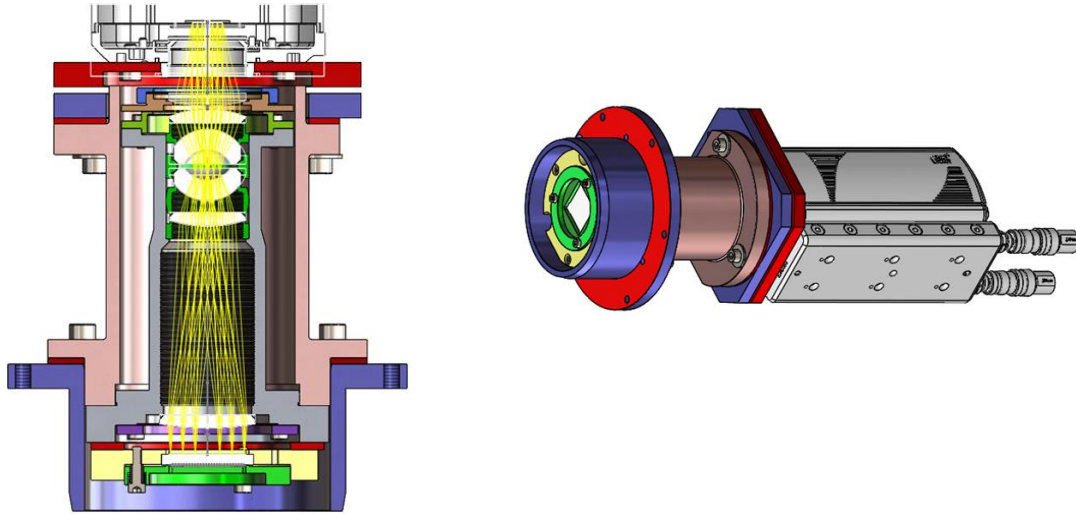


Figure 9. Left: ray tracing and opto-mechanical concept of the LDM. Right: global CAD view of the LDM with the CBLUE1 camera.

4. CONCLUSION

We have described the opto-mechanical designs of the Laser Guide Star Sensors for HARMONI and present the optical performance of our design. This system holds the six wavefront sensors used to sense the light from the LGS of the ELT. The description given in this paper are representative of the design done for the Final Design Review that is on going, with a review in 2024.

ACKNOWLEDGEMENTS

HARMONI is an instrument designed and built by a consortium of British, French and Spanish institutes in collaboration with ESO. This work benefited from the support of the the French National Research Agency (ANR) with WOLF (ANR-18-CE31-0018), APPLY (ANR-19-CE31-0011) and LabEx FOCUS (ANR-11-LABX-0013); the Programme Investissement Avenir F-CELT (ANR-21-ESRE-0008), the Action Spécifique Haute Résolution Angulaire (ASHRA) of CNRS/INSU co-funded by CNES, the ECOS-CONYCIT France-Chile cooperation (C20E02), the ORP-H2020 Framework Programme of the European Commission's (Grant number 101004719), STIC AmSud (21-STIC-09), the Région Sud and the french government under the France 2030 investment plan, as part of the Initiative d'Excellence d'Aix-Marseille Université -A*MIDEX, program number AMX-22-RE-AB-151.

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