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Kjetil Dohlen, Pascal Vola, Zalpha Challita, Tim Morris, Jean-Francois Sauvage, et al.. HARMONI at ELT: Towards a final design for the natural guide star sensors system. Proceedings SPIE Modeling, Systems Engineering, and Project Management for Astronomy X, Jul 2022, Montréal, Canada. pp.50, 10.1117/12.2628938 . hal-03795796

HAL Id: hal-03795796

<https://hal.science/hal-03795796>

Submitted on 4 Oct 2022

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HARMONI at ELT: Towards a final design for the Natural Guide Star Sensors system

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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 review (FDR).

The Natural Guide Star Sensors (NGSS) system of HARMONI provides wavefront and image stabilisation sensing for each of the four observing modes of the instrument, LTAO, SCAO, HCAO, and NOAO. It consists of five subsystems, three of which provide wavefront sensing (LOWFS, SCAOS and HCM), the remaining two (ESE and ISB) providing thermal and mechanical functions. To limit thermal background and to ensure the required stability, the sensors operate in a cold, thermally stabilized, dry gas environment. This paper presents the overall design of the system with emphasis on system analysis, assembly and test, and maintenance.

Keywords: ELT HARMONI, Adaptive Optics, Opto-Mechanics, wavefront sensors, AIT, SCAO, LTAO, HCAO

1. INTRODUCTION

HARMONI [1],[2] is a visible and near-infrared integral field spectrograph providing the ELT's core spectroscopic capability. It uses image slicers to provide spectra for each one of its 204x152 spaxels covering a single contiguous field. Spaxel scale is adjustable from 4x4 mas, Shannon sampling the NIR diffraction limit, to 60x30mas, for wide-field, near seeing-limited operation. The instrument will exploit the specific scientific niche opened by the ELT, starting at first light.

To benefit fully from the sensitivity and spatial resolution offered by the nearly 40 m diameter pupil of this giant telescope, HARMONI will be able to work at the diffraction limited thanks to its two complementary adaptive optics observing modes [3], SCAO (Single Conjugate AO) and LTAO (Laser Tomographic AO). In a third AO mode, HCAO, a high-contrast facility extends the SCAO capabilities to allow for exo-planet characterisation. Finally, a fourth mode, NoAO, allows operation assisted only by secondary guiding allowing coarse-scale imaging with minimal guide-star requirements.

While the deformable mirror performing real-time correction of the atmospheric disturbances is located within the telescope itself, HARMONI is 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 are contained within the LGSS system [4], located at the entrance of the instrument and fed by a dichroic beam splitter reflecting the sodium line. The various natural guide star sensors are contained within another system, the NGSS, object of this paper, located close to the science focal plane. LTAO, in addition to laser guide-star sensors, requires natural guide stars for fast sensing of tip-tilt and focus and for disentangling the effects of slowly varying non-common path errors. These are provided by the Low-Order Wavefront Sensors (LOWFS) subsystem [5]. A high-order pyramid wavefront sensor, aided by a slow, low-order Shack-Hartmann sensor and a low-order deformable mirror, offering HARMONI's cutting-edge single conjugate AO operation, is provided by the SCAOS subsystem [6]. Additional, slow, high-order, and ultra-sensitive wavefront sensing as required for high contrast imaging, together with a pupil apodization capacity, is provided by the HCM subsystem [7]. These various sensor subsystems are maintained precisely positioned and at a fixed and stable temperature on top of the IFS cryostat thanks to the mechanical subsystems ESE (External Structure and Enclosure) and ISB (Internal Support Bench).

In this paper, we present the current status of the final design process for the NGSS system, at about a year from its critical design review (CDR). Emphasis is given to aspects of system engineering, assembly and alignment, transportation, and maintenance, as well as to the description and evolution of subsystem designs. We also include discussions about ongoing design modifications imposed by the Red Flag process to which HARMONI is currently exposed. This process, which has led to deep interactions and discussions between members of the HARMONI design teams and ESO staff, has given rise to a certain number of requirement modifications for which resulting design changes are currently under study.

2. SYSTEM ANALYSIS

2.1 Instrument Product Break-down and interfaces

The HARMONI instrument (Figure 1) is built up of four main hardware systems [2]. The integral field spectrograph (IFS) consists of a 4 m high and 3.25 m 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 located at the entrance of the instrument, 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 (LGSS), working on artificial laser guide stars, and the other (NGSS) working on natural guide stars.

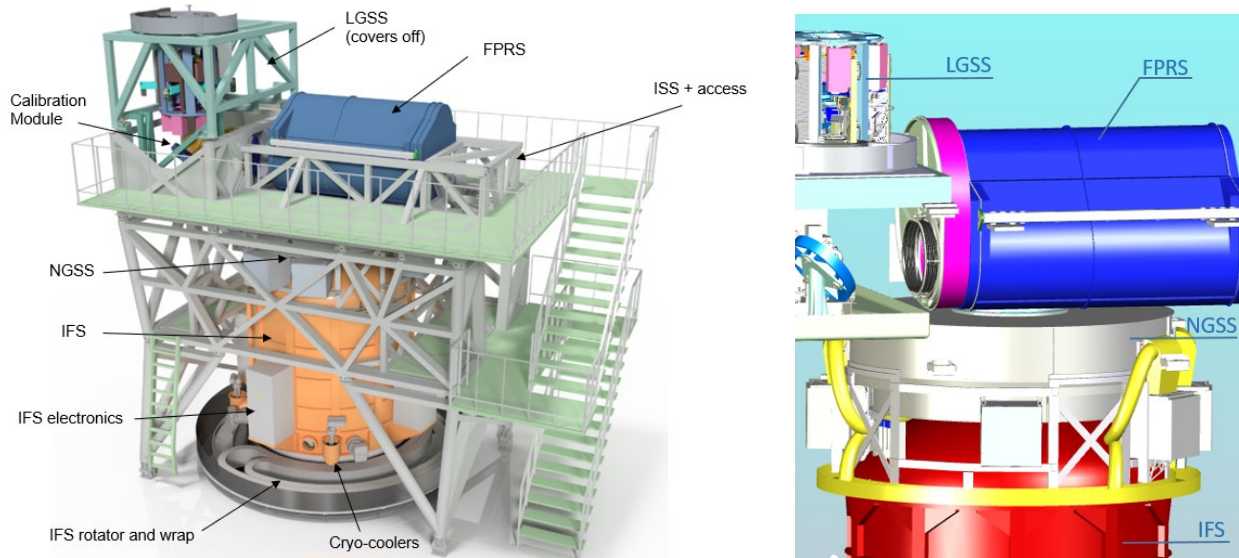


Figure 1. 3D rendering of the HARMONI instrument indicating major systems and components (left). Composite view of the main opto-mechanical elements of HARMONI with instrument structure removed (right)

While the LGSS is supported by the ISS, interfacing optically via a dichroic beam splitter located 1 m downstream of the telescope focus, the NGSS is mounted on top of the IFS cryostat and rotates together with the science field, allowing for maintaining the alignment between science and natural star sensors to within a fraction of a resolution element.

2.2 NGSS functionalities

In addition to transmitting science light to the IFS spectrograph system and providing natural-star wavefront sensing for each of the instrument's observing modes, the NGSS system needs to provide numerous additional functionalities. In particular, it operates directly on the scientific beam in the HCAO mode, where the light is deviated into a relay providing a slight rescaling to ensure Shannon sampling across the full NIR observing band and the possibility to insert shaped-pupil apodizers [8] in order to eliminate the telescope's diffraction features within the 1 arcsecond-diameter observable FOV.

In terms of overall design of the system, it is required to block any unwanted light from entering the beam during night-time observations, but also during day-time calibrations, and to limit thermal background. These requirements have led to the implementation of a light-tight and nearly hermetic, well-insulated enclosure with built-in cooling lines [9].

While the controlled internal temperature of NGSS ensures the required lateral stability required for precise stabilization of the science field, axial (focus) stability is hampered by the long chain of interfaces between the NGSS, mounted on top of the IFS cryostat whose temperature varies with ambient, and the IFS internal optical train, maintained at a stable cryogenic temperature. The resulting focus variation of up to 1.2 mm across the operational temperature range (0 to 15°C) is fully predictable, however, and leads to the additional functional requirement on the NGSS wavefront sensors to enable open-loop compensation of the corresponding focus error.

Finally, additional functionalities related to alignment, commissioning, and maintenance have been defined. While the wavefront sensors for LTAO and SCAO operation are equipped with navigation functionalities in order to select guide objects separated from the science object and are therefore tolerant to absolute lateral alignment between IFS and NGSS, the imaging relay of the HCM providing the specific high-contrast capabilities has little margin on its field of view. Instrument alignment budgets do predict sufficiently good alignment between these two systems, but it is still required that the NGSS provide a means for re-alignment during on-platform tests of the instrument as a risk mitigation. Additional features have been added to allow for this, see Sec. 3.4. Also, the inclusion of a commissioning camera is required, allowing efficient characterization of AO performance beyond what is possible using the IFS imaging capabilities and pipeline.

Allowing for maintenance throughout the lifetime of the instrument is essential, in particular for the AO wavefront sensor systems contained within NGSS relying on numerous electro-mechanical and electro-optical devices. While these devices are selected as far as possible with excellent lifetime and MTBF predictions, the risk of failure is non-zero and the requirement for maintenance access for each and every active device has been enforced strongly throughout the design process for this system.

2.3 Internal and external interfaces

To allow independent development of systems and subsystems, rigorous development of interfaces has been a priority of the HARMONI instrument from the start. Preliminary versions were signed off by the PDR, and well-developed versions were all, except for control interfaces, signed off by the beginning of the FDR process, in January 2021. Any change occurring since then goes through a change request process, as described in the project's product assurance plan.

Figure 2 shows the maps of external (a) and internal (b) interfaces. External interfaces are numerically dominated by control interfaces due to the separation of electronics and software control functionalities into a separate system, the HARMONI Control System (HCS). These are being defined in close collaboration between members of the NGSS and the HCS teams. The NGSS interfaces optically with both FPRS, at the input, and IFS, at the output of the system. FPRS provides the 2 arcminute-diameter patrol field, of which NGSS transmits the 12 arcsecond-diameter central part to IFS.

Mechanically, the system is structurally attached to the IFS, and it carries the lower part of the rotating seal towards the FPRS, with which it shares the cooled environment. The cooled environment of FPRS and NGSS minimizes thermal background radiation, and by keeping the temperature stable to within ± 1 K, it allows for the required dimensional stability of the wavefront sensors.

Internal interfaces reflect the hierarchical build-up of the system. The three opto-mechanical subsystems, SCAOS, HCM and LOWFS, are all independently mounted to the ISB, which is in turn mounted into the ESE. One breach to this rule is the HCM pick-off module (HPO) which is carried by the SCAOS dichroic exchange mechanism. The fluid distribution manifold, which is part of the ESE subsystem, is also carried by the ISB, making it possible to fully implement both electrical and fluid connections of the internal NGSS elements before installing it as a unit into the ESE structure and covers. Cables and pipes ensuring connections to the chiller and control electronics, all housed in specially designed cabinets mounted to the outside of the ESE, will be installed directly into cable paths and feed-through boxes provided by

ESE. Mounting (and dismounting) the ISB into the ESE can therefore be effectuated with a minimum of internal wiring activities.

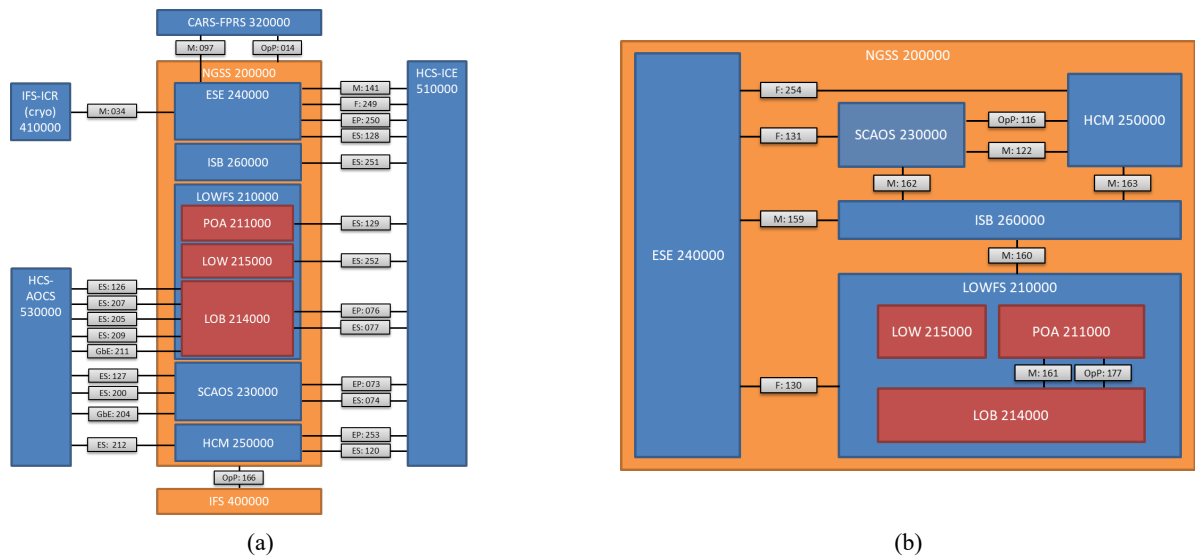


Figure 2. External (a) and internal (b) interface maps for the NGSS system, indicating subsystem names and PBS codes, and interface types: Physical optics (OpP), Mechanical (M), Fluid (F), electrical power (EP), electrical signals (ES), gigabyte network (GbE).

2.4 The NGSS state machine

As indicated in Figure 3, the main states of NGSS are Stand-by and Operational; this is where the instrument will be during the quasi-totality of its lifetime. In Stand-by mode, the instrument control system is running, instrument functions have been properly initialized, and the system is ready to operate. When switched to Operational (or Online), control functions are started and the instrument is ready to observe. In both these modes, all monitoring functions are available.

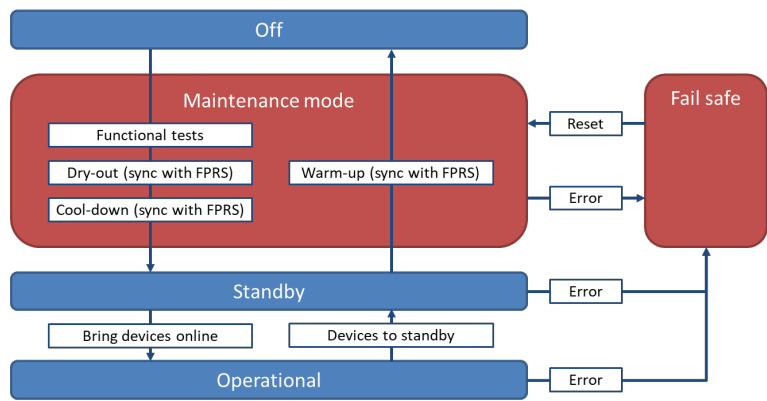


Figure 3. Global NGSS state diagram.

Whenever an error is detected, the system falls into a Fail-safe mode, from which a reset action moves it into the Maintenance mode. In this mode, access to all engineering activities are available, including functional tests as well as dry-out (flushing) of the internal volume before cool-down, cool-down, and warm-up activities. The Maintenance mode hence also allows transition between Stand-by and Off states. Any specific operations during testing, maintenance or repair interventions are done in this mode.

3. SYSTEM AND SUBSYSTEM DESIGN

3.1 NGSS Product breakdown structure

The NGSS system is broken down into subsystems as described in the top-level PBS shown in Figure 4, and the block diagram of Figure 5 illustrates the inter-relationship between these products in terms of optical signals. In most cases, the NGSS lets the science light (brown arrows) pass through unaffected, the various sensors only being fed by light from non-scientific guide stars (green arrows). Only in the case of the high-contrast module, science light is deviated and even taxed by a small quantity to feed the additional high-order Zeldas sensor.

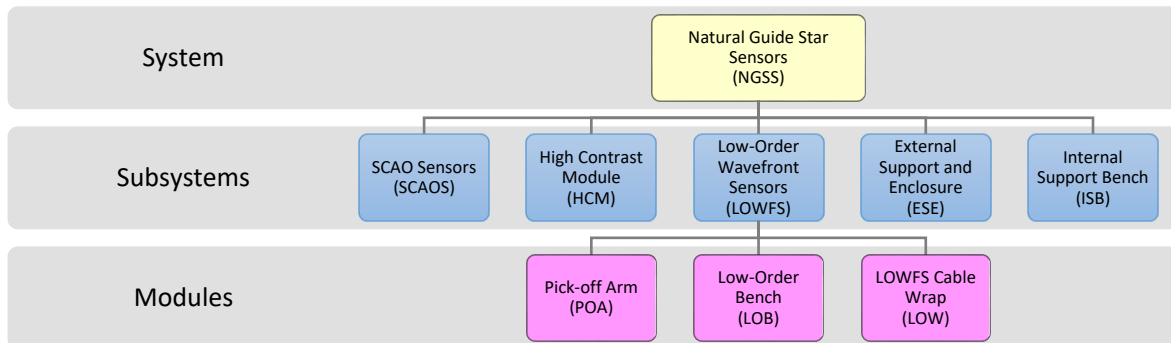


Figure 4. Top-level product break-down structure of the NGSS system.

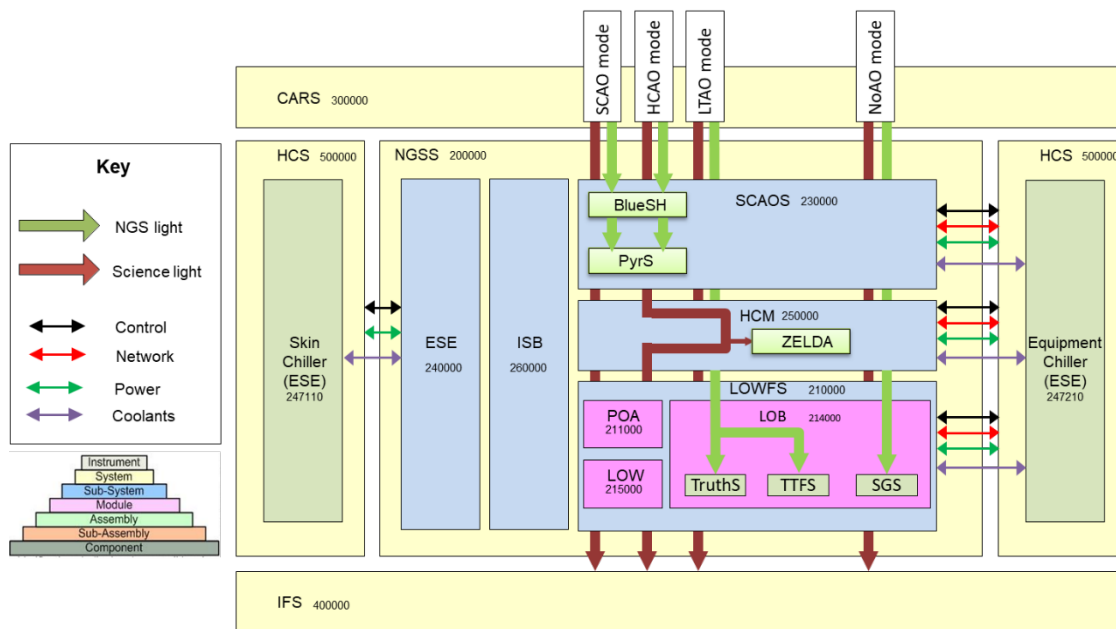


Figure 5. NGSS block diagram.

3.2 Global opto-mechanical design of NGSS

To respond to its functional requirements, all the NGSS wavefront sensors are enclosed within a light-tight and near-hermetic, insulated, and actively cooled box, as seen in Figure 1 (right). This box, together with structural elements allowing for external and internal interfaces and the chiller and chilled-fluid distribution elements, constitutes the ESE subsystem. Taking the top lid off the box, as seen in Figure 6, exposes some of the internal subsystems, mounted onto the ISB internal structure from the top: the SCAOS bench and associated dichroic exchange mechanism, the vertical bench of the HCM, and the manifold box. The LOWFS subsystem is mounted to the lower side of the ISB and requires removal of the ISB from the ESE to be fully accessed.

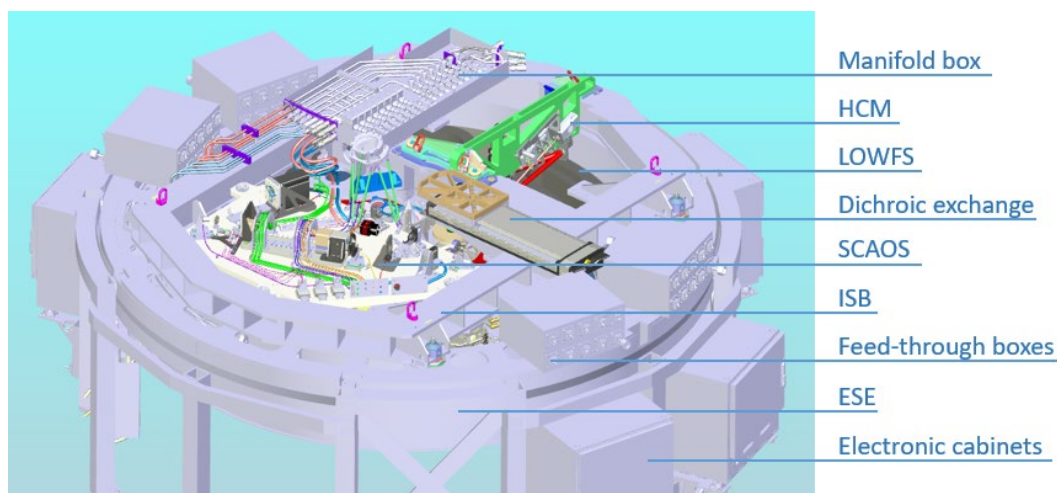


Figure 6. Global view of the NGSS system. The ESE top cover has been removed to show the interior subsystems.

3.3 ESE subsystem

The External Support and Enclosure (ESE) subsystem contains all the elements allowing NGSS to fulfil its environmental and interface functional requirements. Its light-tight, near-hermetic, and thermally insulated and controlled covers protects the science path from external optical and thermal disturbances. It also ensures dimensional stability of the housed wavefront sensors, and allows evacuation of any power dissipated within the volume. To this end, ESE is equipped with solid-state, vibration-free chillers providing chilled glycol for two independent cooling circuits, one serving the network of pipes bonded to the inner skin of the enclosure, ensuring cooling of the internal volume, and one providing individual cooling to every active device for which local cooling is required. In parallel with the cooling systems, an air flushing system is implemented to ensure both the humidity control required within a chilled environment, and the air cleanliness ensuring minimal dust deposition over the lifetime of the instrument. Compressed air provided by the telescope is filtered and adjusted for humidity within a specially-conceived unit. Further, in-depth description of the chiller system is presented at this conference [9].

The ESE plays a particularly important role in terms of maintenance since it provides access ports to all active devices of the interior wavefront sensor subsystems. Careful planning and interaction between design teams has been conducted in order to make such access available, on the conceptual level, and in terms of implementing design adjustments both of ESE and of the other subsystems.

The currently ongoing Red Flag process has identified cold operation at atmospheric pressure as a high-risk item in terms of icing and condensation, device failures, AIT duration, etc. The discussion, which has included interaction with the science team in terms of evaluating the loss in sensitivity due to increased thermal background, has led to an increase in operating temperature from -15°C as originally planned, to $+2^{\circ}\text{C}$. While the benefit in terms of risk mitigation of this modification is evident, the design of ESE remains essentially unchanged because the temperature stability requirement remains as before. Still, the opportunity to reduce the number of chillers from two to one is being studied.

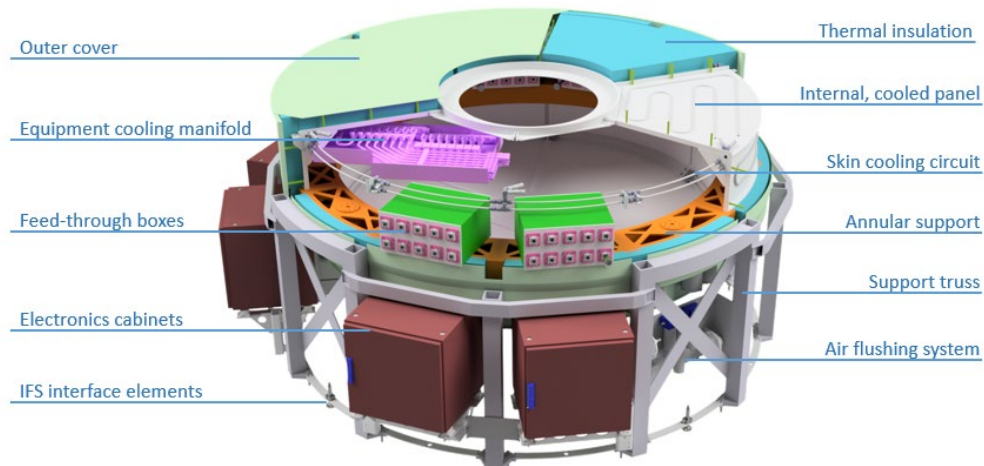


Figure 7. Cut-away view of the ESE subsystem, showing its main elements.

3.4 ISB subsystem

Separating out the Internal Support Bench (ISB) from the external support structure was a major decision for the NGSS system, allowing clean separation between the general services, provided by ESE, and the specific services related to support and internal alignment provided by ISB. This separation also allows for an important division in terms of the assembly process, allowing the interior subsystems to be integrated and mutually aligned, constituting the NGSS Optical Assembly (NOA), before integration into the ESE. Indeed, once integrated into the 4-m diameter ESE, and before installing the fully equipped NGSS within the HARMONI structure, access to interior organs will be extremely difficult.

As mentioned above, an important functional requirement for NGSS is to enable on-platform fine realignment between NGSS and IFS. The optimal way to implement this was found to be allowing the fully equipped ISB to be translated within the ESE. This process, which implies no mutual re-alignment between sensor subsystems, is implemented by including a system of air jacks, see Figure 8, permanently installed but disconnected during normal operation, which lifts the entire ISB by about 100 μm , sufficient for friction-free adjustment of lateral position. A detailed procedure involving several rotations of the IFS rotator is defined.

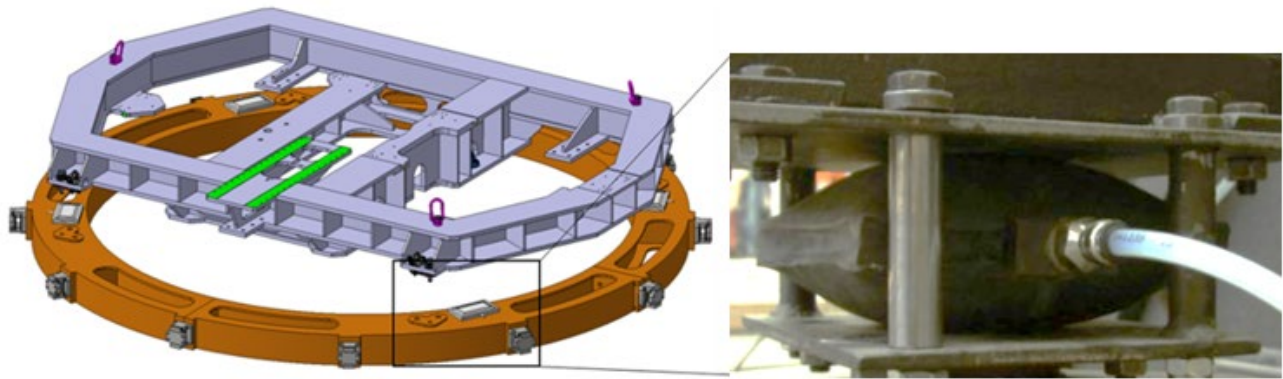


Figure 8. Exploded view of the ISB and the ESE annular support, indicating the presence of air jacks next to each of the four mounting points.

Structural analysis has been done to study deflections and ensure integrity in case of earthquake of the fully loaded subsystem, as illustrated in Figure 9 where the deflection of the system with its 1360 kg load is found to reach 566 μm in the presence of gravity. Another important analysis concerns stability of the optical axis of each subsystem as a function of temperature. While all efforts were made to ensure symmetry, inevitable asymmetries of the detailed design are found

to impose a $19\text{ }\mu\text{m}$ shift of the large LOWFS bearing for a temperature change of 35°C , corresponding to the worst-case shift between ambient and operational temperatures, see Figure 10. Insignificant in terms of initial adjustment, this sensitivity remains insignificant in terms of the $\pm 1^\circ\text{C}$ margin for internal operating temperature.

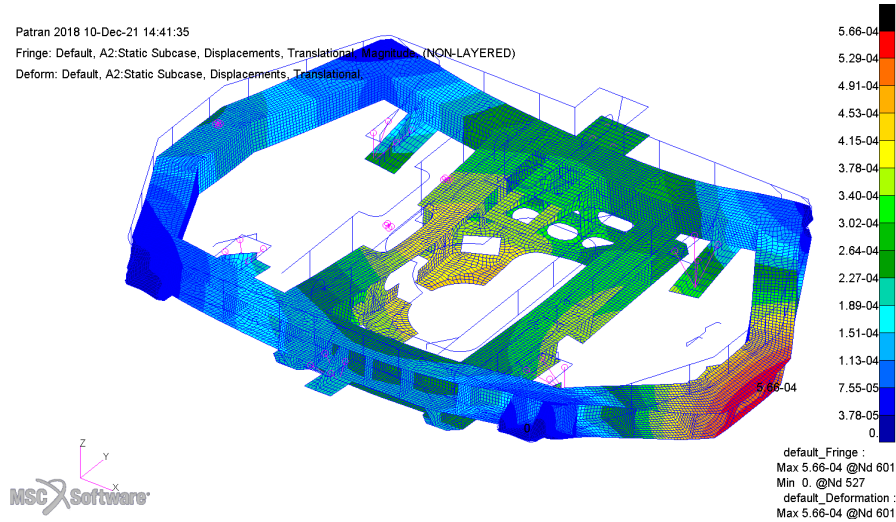


Figure 9. Deflection of the fully populated ISB in the presence of gravity (sub-systems are hidden for clarity but present in the model).

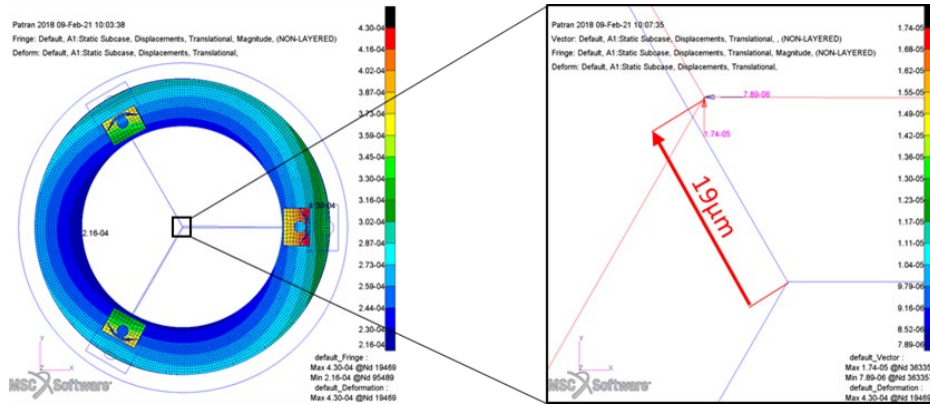


Figure 10. Centre shift of LOWFS primary bearing axis when temperature changes by -35°C .

3.5 SCAOS subsystem

The main function of the SCAOS subsystem [10], see Figure 11, is to provide pyramid wavefront sensing [11] for the Single Conjugate Adaptive Optics (SCAO) observing mode of HARMONI. An achromatic, double pyramid prism is combined with an OCAM2k electron multiplying (EMCCD) low-noise camera and a modulator mirror to constitute the state-of-the art pyramid sensor (PyrS) capable of reaching the required performance in terms of sensitivity and Strehl ratio [3]. To stabilize the pupil onto the sensor and to overcome the sensitivity of the pyramid sensor to non-common path errors (NCPA), additional equipment is added in the optical path upstream of the sensor. In addition to the classical, laterally activated lens which allows closed-loop pupil stabilization and a K-mirror derotator fixing the pupil orientation, a linear atmospheric dispersion corrector (ADC) is implemented. Less classically, a pupil zoom system based on three axially moving lenses offer control of pupil size [12], and a low-order loop (LOL) consisting of a low-order (10x10) Shack-Hartmann wavefront sensor is implemented in conjunction with a similarly low-order deformable mirror (LODM). Taxing

the blue end of the available spectrum around 650 nm, this "Blue Shack-Hartmann" (BlueSH) detects the position of the guide object as well as its low-order aberrations at a slow rate ($\sim 1\text{Hz}$) but with high precision before the beam enters any of the afore-mentioned correcting elements, where absolute position and wavefront information is lost due to inevitable wobble and manufacturing defects. Deviations from the fiducial position and wavefront shape are fed forwards to the LODM, and immediately detected by the PyrS which passes the information on to the science-path deformable mirror, the telescope M4. This "feed-forward feed-back" loop structure is directly inherited from the SAXO AO system of SPHERE [13] where such a loop structure is used for differential tip-tilt control.

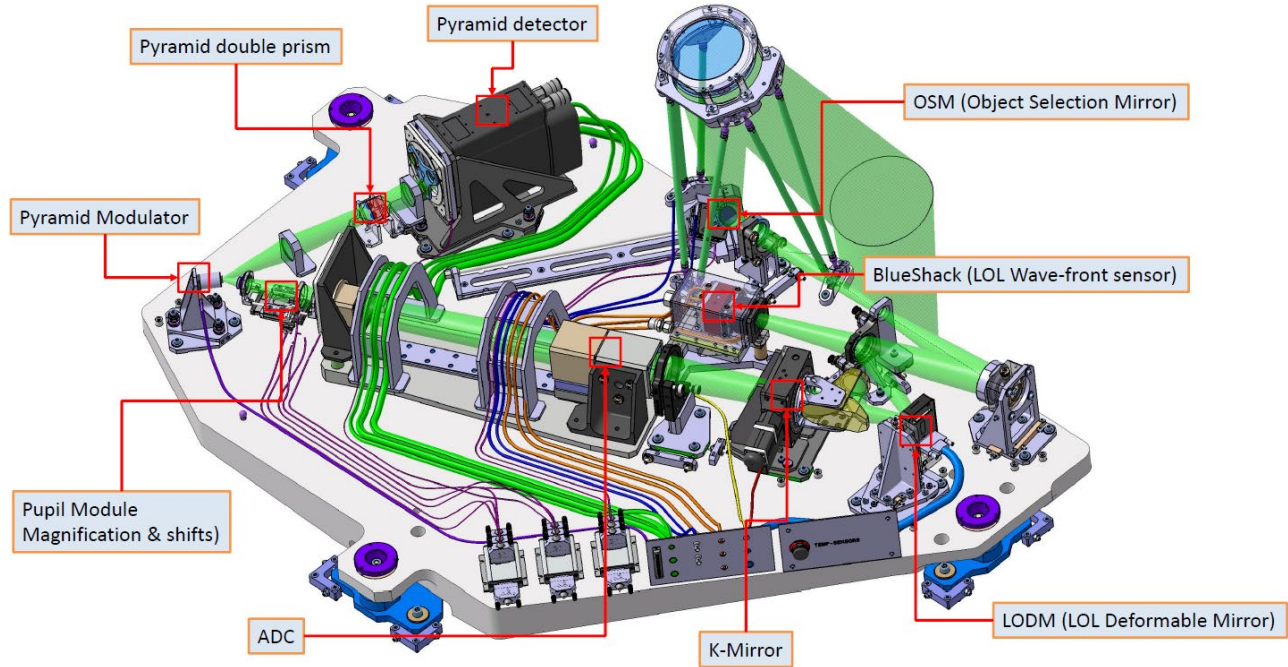


Figure 11. The SCAOS wavefront sensor subsystem indicating its main active devices.

Another feature of the SCAOS subsystem is its capacity to select a guide star anywhere within a radius of $15''$ of the science object, equivalent to the isoplanatic patch. For this, an object selection mirror (OSM) is implemented in a pupil plane created at the entrance of the system. Requiring mas-level navigation precision, this mechanism constitutes a major challenge. Several actuator types have been experimented [14], including the building of an in-house, fully-fledged prototype mechanism based on precision gear-head linear actuators, see Figure 12 (top). While all design features, including the motors, performed to specifications, the final product revealed itself insufficient because of high-frequency features in the calibration curve, an order of magnitude larger than expected. The finally chosen option uses piezo-driven goniometer stages from SmarAct [15]. While testing and fine tuning is still ongoing, this option is close to reaching the required performance, see Figure 12 (bottom).

In terms of maintainability, all devices are accessible either for complete extraction or, in the case of the largest stages, for intervention on the motorization. Two particular accessibility difficulties have been encountered during the development of the subsystem. The dichroic exchange mechanism was originally implemented in the form of a rotary mechanism fixed to the underside of the bench. Since no access could be found for intervention on this mechanism, and even though a particularly sturdy mechanism was chosen, the risk of experiencing a fatal event for the entire instrument due to the mechanism being stuck in an intermediate position, it was decided to replace this mechanism with a linear stage mounted directly to the ISB, as seen in Figure 6. While this complicates interfaces and violates the principle of fully independent subsystems, the gain in maintainability is overriding. The other difficulty is posed by the location of the OSM very close to the optical axis. Since this location is too far in to be directly accessible, an extraction rail has been implemented, as can be seen in Figure 11.

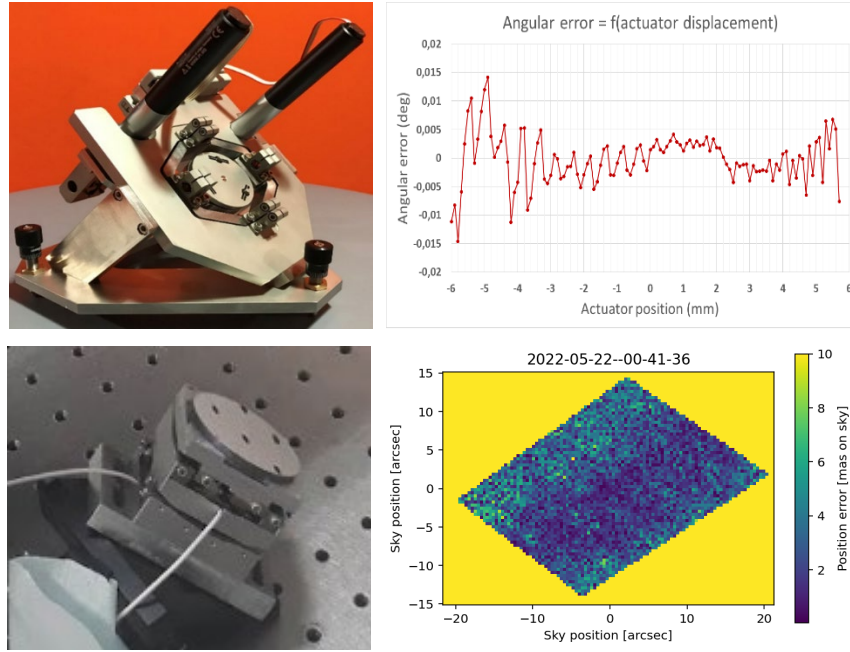


Figure 12. The in-house prototype (top left) developed for the Object Selection Mechanism (OSM) and its insufficient performance in terms of calibration capability (top right). The SmarAct-based current prototype (bottom left) is close to reaching required performance (bottom right), pending fine tuning of the mechanical setup and the calibration algorithm.

3.6 HCM subsystem

Maybe the most exciting aspect of the NGSS is the implementation of a high-contrast imaging facility for the HARMONI instrument. Not originally part of the instrument's science cases, it was felt that adding such a capability, based on the presence of the high-end pyramid-based SCAO mode and diffraction-limited integral field spectroscopy, would not only be possible but scientifically highly competitive [8]. While both pupil and image planes are available within the science path inside the IFS cryostat, these are incompatible with the fine position control required, both for image and pupil masks, for high-end coronagraphic imaging. The idea of creating an additional pupil plane within the NGSS therefore emerged, combining a specially tailored shaped pupil coronagraph [18], see Figure 13, precisely located within the image of the telescope pupil thanks to feed-forward active control, with a high-precision Zernike wavefront sensor (Zelda, [16],[17]), transmitting high-frequency NCPA wavefront maps measured at wavelength close to the observing wavelength to the SCAO system. An anti-saturation focal plane mask is located in the entrance focus of the IFS, but thanks to the deep apodization of the shaped pupil, its precise position is not critical. Also, no Lyot stop is required [19].

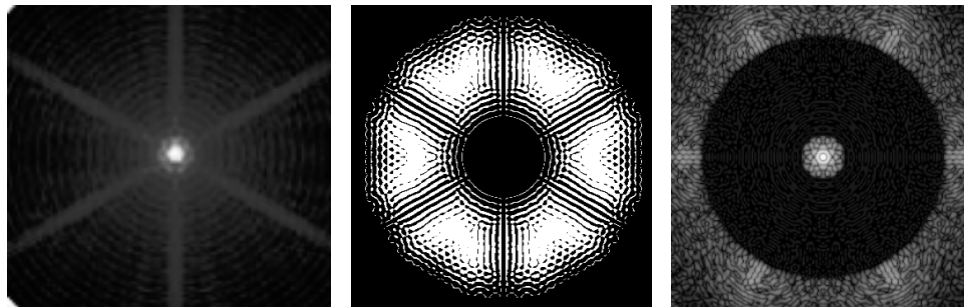


Figure 13. Unapodized PSF (left), shaped-pupil apodizer transmission map (centre), apodized PSF (right).

The HCM is presented in the form of a vertical optical bench, see Figure 14, one face of which carries the optical relay, the other, receiving a part of the beam separated off the main path by the aid of a dichroic beamsplitter, carrying the Zelda wavefront sensor. In addition to lenses and mirrors, the science path includes a fixed ADC, ensuring a sufficiently low residual dispersion within the range of Zenith angles considered. Indeed, since operation of HCM requires the IFS rotator to stabilize the pupil rather than the field, the dispersion vector has a fixed orientation, making such a fixed ADC viable. Downstream of the Zelda dichroic plate, the science path encounters one of two selectable apodizer masks. These are mounted on an x-y stage allowing mask selection but also fine position adjustment. Assuming sufficient stability between the apodizer plane and the Zelda sensor detector plane, the apodizer position is controlled in open loop by determining the movement of the pupil image on the Zelda sensor. Calibration of the two planes is done using the IFS pupil imaging mode.

On the Zelda side of the bench, the Zernike phase mask is located within a three-axis stage allowing both lateral and axial displacements. While the axial displacement is controlled in order to compensate known, thermally induced focus error (see Sec. 2.2), lateral displacements are set during calibration such as to center the image of the mask onto the IFS FOV. The wavefront maps derived from the Zelda sensor are fed back into the SCAO loop, either, for low spatial frequencies, in the form of offset slopes for the BlueSH sensor, or, for high spatial frequencies, in the form of offset slopes for the PyrS.

Impressive work is being done in prototyping both apodizers and the Zelda sensor. Closed-loop operation of the sensor is being experimented with great success [17], leading to good confidence in the capacity to reach the contrast levels the instrument is being designed for.

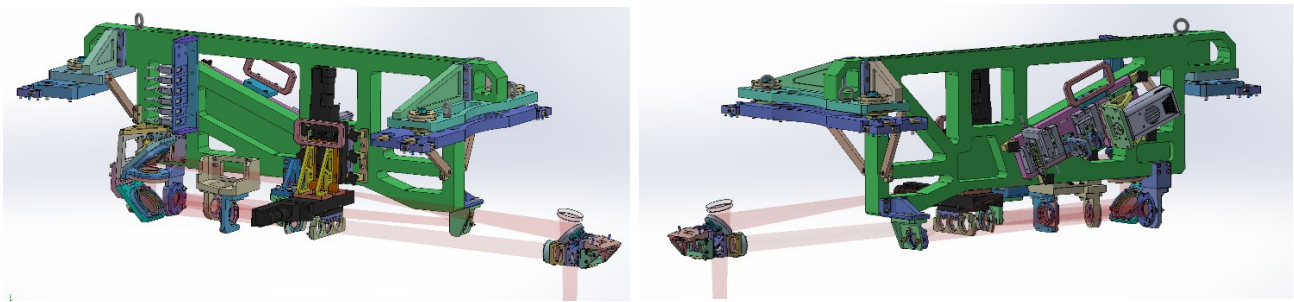


Figure 14. Two sides of the HCM optical bench: science path (left) and Zelda path (right).

3.7 LOWFS subsystem

The Low-Order Wavefront Sensor subsystem [10] of NGSS contains the sensors required for on-line calibration of the laser-tomographic adaptive optics (LTAO) observing mode. A guide star located within a distance of 1' from the science object is analyzed in terms of its low-order aberrations in order to determine corrections to be added to the loop closed between the laser guide star tomography and the telescope's DM. Tip-tilt and focus, for which the laser stars do not provide useful signals, are measured at a fast rate (500 Hz) using a 2x2 Shack-Hartmann sensors referred to as the Tip-Tilt Focus Sensor (TTFS). To reach the sensitivity necessary to achieve close to 100% sky coverage, an open-loop deformable mirror (OLDM), also driven by the laser tomography, is implemented within the TTFS optical path. Other low orders are measured using a slow (1 Hz) 10x10 S-H sensor referred to as the Truth Sensor (TruthS). Both sensors are alimented by a pick-off mirror precisely positioned within the patrol field by a Pick-Off Arm (POA).

One of the main issues raised during the Red Flag process was the risk of insufficient guiding accuracy due to the use of a single guide object. While the project's error budget indicated the capacity to reach sufficient accuracy, it was found that recent re-evaluations of telescope-related errors such as flexure-induced variations in plate scale and field rotation, significantly increased the guiding error budget. To mitigate this risk, it was agreed that the addition of a second guide arm would be mandatory.

Since the original, well advanced, singe-armed LOWFS design [5], see Figure 15, used up every cubic centimeter of the allowable space, adding a second arm required seriously rethinking the concept. Maintainability is an additional constraint, already to some degree compromised in the original concept. Since a large part of the volume was occupied by the cable

wrap, imposed by the concept of a rotating optical bench carried by a large bearing, it was natural to question this scheme. It had appeared in the pioneering days of NGSS as a natural candidate due to its inherent capacity to always point towards the pupil, hence providing a fixed pupil image in spite of the finite pupil distance. Seeing that other factors, such as telescope flexures and FPRS distortions also impose pupil movements, the addition of a pupil centering mechanism could therefore be seen as an advantage. The idea of a fixed optical bench hosting two identical navigation arms therefor emerged, potentially providing both volume and mass savings.

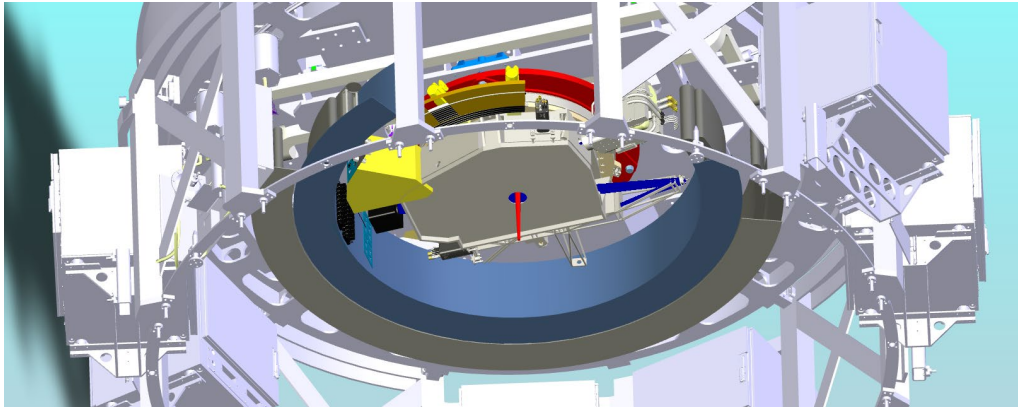


Figure 15. Original LOWFS concept based on an optical bench carried by a large bearing, surrounded by a cable wrap.

This is the starting point that is currently on the table for upcoming design efforts. A tentative implementation has recently been presented, see Figure 16, but great challenges lie ahead to evolve this into a final design compatible with the current project schedule. Making this concept compatible with on-site maintenance actually constitutes an opportunity for removing the LOWFS from the critical path of the AIT activities. The idea here is to extract the complete LOWFS Optical Bench (LOB) for maintenance, see Figure 17, rather than reaching in or extracting individual devices as for the original concept. If this scheme can be implemented, one can imagine also to insert the LOB into the NGSS during system AIT without needing to dismount the entire system.

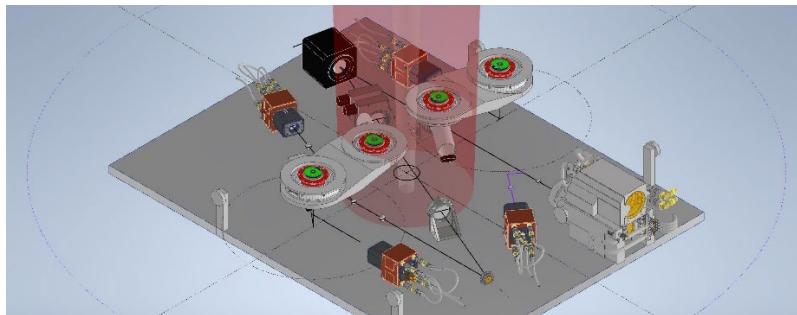


Figure 16. Current starting point for a fixed-bench, dual arm version of the LOWFS.

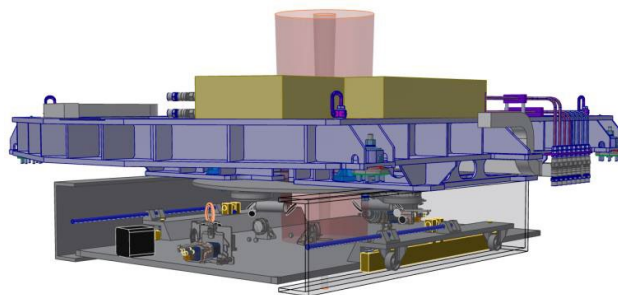


Figure 17. Possible implementation of the LOB extraction mechanism.

4. AIT, SHIPPING, AND MAINTENANCE

Each subsystem will be fully mounted and tested at the premises of the institute responsible for its development before delivery to LAM, where the assembly, integration and tests (AIT) of the complete NGSS system will take place. This is also where the AIT of the Top End of the HARMONI instrument, constituted by parts of the instrument structure, the FPRS relay, the LGSS, the NGSS, and the calibration module, takes place. The route of NGSS towards preliminary acceptance in Europe (PAE) can therefore be seen in three parts:

- Acceptance, integration and alignment of subsystems
- Testing of the NGSS in stand-alone mode
- Testing of NGSS within the Top End

Figure 18 illustrates the NGSS integration process and Figure 19 shows the current view of this process in terms of tentative dates. Conducting this process is a major challenge for the LAM laboratory because of the sheer dimensions of each element. To prepare these operations, plans for reorganizing parts of the facilities are under way, and walk-through sessions using 3-D printed mockups are being organized, see Figure 20.

Among the AIT tools for alignment and stand-alone testing of NGSS is an optical axis projector, allowing representing the optical axis, with materialization of both image and pupil planes, at all the wavelengths used by NGSS subsystems. This will allow co-alignment of each subsystem to a common reference, and materialize that reference with respect to mechanical interfaces. Another important AIT tool is the ESE subsystem handling carriage, allowing safe mounting, and storage, of the system outside of the instrument. It is likely that this tool will also be used for transportation of the system between the integration hall and the Top End testing facility, as well as to provide the rudimentary rotation capability required for testing in the Top End context. Taking optimal benefit from the existing ESE structure, the current plan is to use a fairly stiff annular structure representing the IFS top ring, equipped with a series of caster wheels and spokes towards a central hub where the rotation axis can be defined, as illustrated in Figure 21.

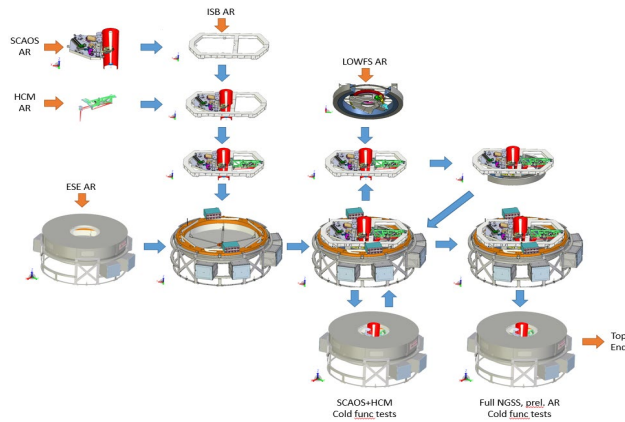


Figure 18. Cartoon illustrating the integration of subsystems into the NGSS system. Orange arrows indicate passage through acceptance reviews, blue arrows indicate passage from one build state to the next.

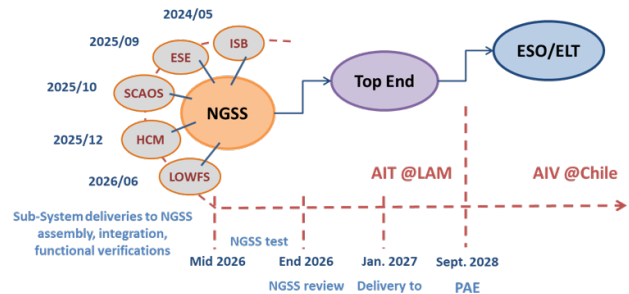


Figure 19. Current view of the NGSS AIT/AIV planning.

Transportation of NGSS from Europe to Chile is likely to happen by sea, although the risk of damage from salt water contamination is still to be evaluated. Three options for packing are being considered: sufficient dismounting to fit in standard containers, shipment as a single, fully mounted unit, or shipment as two separate units, where the NOA optical assembly is shipped separately from the ESE. While the first option was assumed at PDR, it becomes clear that this approach, classically used for shipment of VLT-sized instruments like SPHERE, will lead to an excessive work load in terms of dismounting, remounting, requalification testing, etc. Among the two other options, the latter is likely to be the most cost-effective since the most critical parts, contained within the NOA, requires a considerably smaller box than if

they were to be transported within the ESE. Also, the ESE shipped alone can be fitted into a less protected box than if it were to be fully equipped. Of course, the ESE transportation box would also serve for the shipment between UK-ATC in Edinburgh, responsible for the subsystem, and LAM, providing further time savings.

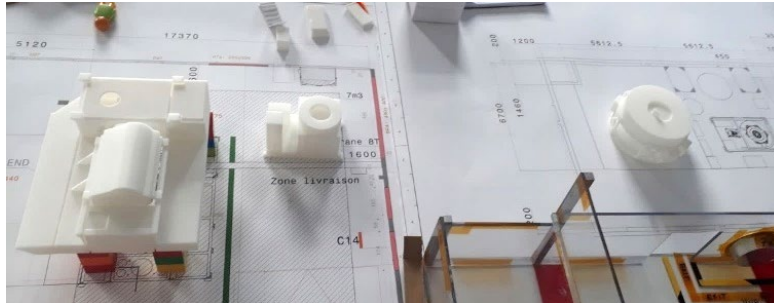


Figure 20. 3-D printed mock-ups used during one of the walk-through sessions organised in preparation for AIT activities at LAM.

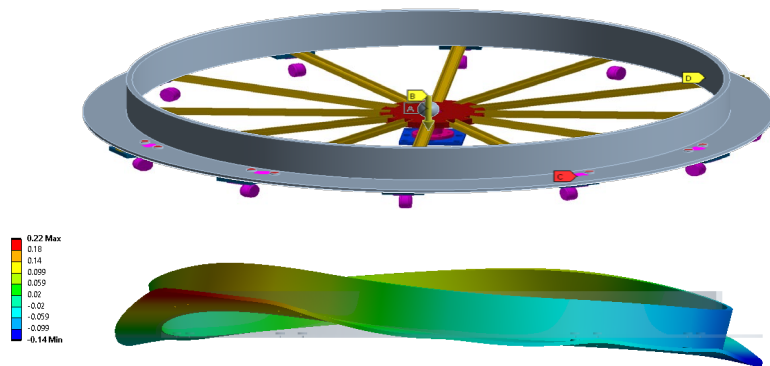


Figure 21. Preliminary design of the ESE system handling carriage (top) and finite element simulation of ring deformations (bottom).

Rebuilding and testing activities at the telescope in Chile will contain a minimum of alignment verifications and functional tests to ensure no damage was suffered during shipment. The most critical part of these pre-commissioning activities at Armazones as far as NGSS is concerned, is its very first encounter as a fully-fledged system with the IFS system. While fit checks are planned between ESE and the cryostat dome before ESE leaves Edinburgh, no alignment verification between the inner organs of the two systems will have happened in Europe. Interface transfer equipment will have been devised and exchanged between the teams, so the risk of any great surprise is rather small, and as explained in Sec. 3.4, risk mitigations are implemented in case misalignments do appear. Still, mating these two monsters will provide excitement in years to come.

Arguably even more exciting though is the question of lifetime of the numerous devices from which this particularly complex system is built up. Cutting edge equipment such as super-fast infrared cameras and open-loop deformable mirrors do not have sufficient run-time today to guarantee the required 15-year lifetime requirement. It is therefore of utmost importance to ensure access to all the devices through a possible, if not comfortable, route. For this, the top cover of ESE is made up of six individually removable panels, allowing access through a hatch in the instrument structure to each and every device of SCAOS and HCM, see Figure 22, left. Access to LOWFS, mounted to the lower side of the ISB, is ensured by a removable panel in the bottom cover of ESE, located where no electronics cabinets are mounted, see Figure 22, right. In the original LOWFS concept, access to various devices was obtained by the aid of the rotator. In the absence of rotator, the new, dual-arm concept is likely to provide access by sliding the entire bench out through this hatch.

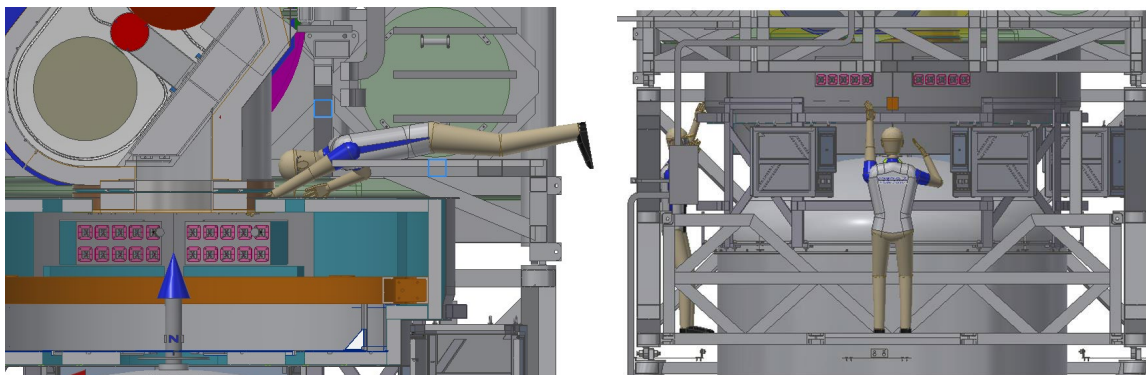


Figure 22. Access paths to NGSS sensor subsystems from the top (left) and from below (right).

5. CONCLUSION

We have described the design status of the NGSS system of HARMONI as we approach final design review, currently planned for mid-2023. A particularly complex system containing numerous cutting-edge opto-electro-mechanical devices in order to reach the challenging mas-level navigation and stability levels required and to provide the state of the art wavefront sensing capacities needed to run every one of the four AO-based observing modes of the instrument. Rigorous system analysis has led to the development of a hierarchically built up system with clearly defined boundaries and interfaces, leading to clear work-package distributions and allowing for an AIT process where individual parts are fully testable before transfer to the next level up. Subsystem designs have been outlined, and system-level AIT, transportation, and maintenance philosophies have been described.

Great challenges lie ahead, both in terms of a tight plan for reaching FDR and in terms of the team's capacity to build and qualify this large machine, part of an instrument of unprecedented dimension for an even more gigantic telescope. Every member of the NGSS team is proud of being part of such a magnificent adventure, looking forwards to the day when the final product can be handed over to science.

ACKNOWLEDGEMENTS

This work benefited from the support of 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 Commission Spécialisée Astronomie-Astrophysique (CSAA) and 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) and STIC AmSud (21-STIC-09).

REFERENCES

- [1] Thatte, N. A., et al., "HARMONI at ELT: Overview of the capabilities and expected performance of the ELT's first light, adaptive optics assisted integral field spectrograph.," this conference, 12184-71
- [2] Thatte, N. A., et al., "HARMONI: first light spectroscopy for the ELT: instrument final design and quantitative performance predictions". In Ground-based and Airborne Instrumentation for Astronomy VIII. SPIE, Volume 11447 (2020).
- [3] B. Neichel et al, "HARMONI at ELT: Getting to the Diffraction limit!" this conference, 12185-41.
- [4] A. Costille et al., "HARMONI at ELT: designing a laser guide star wavefront sensors for the ELT," this conference, 12185-172

- [5] A. Estrada et al., "HARMONI at ELT: Pick-Off Arm module design status and prototype results," this conference, 12188-133
- [6] E. Renault et al., "HARMONI at ELT: SCAO optical design," this conference, 12185-190
- [7] L. Jocou et al. , "HARMONI at ELT: development of the High Contrast module," this conference, 12185-171
- [8] A. Carlotti, François B. Hénault, et al., "System analysis and expected performance of a high contrast module for HARMONI." This conference, 10702-352.
- [9] T. Louth et al, "HARMONI at ELT: cooled environment for focal plane relay optics and guide star sensors; design ahead of FDR," this conference, 12184-95.
- [10] K. Dohlen, et al., "Opto-mechanical designs for the HARMONI adaptive optics systems," Proc. SPIE. 10703, Adaptive Optics Systems VI (2018)
- [11] R. Ragazzoni, J. Mod. Opt. 43, 289 (1996).
- [12] Miks and Novak, Applied Optics 51, 5231 (2012)
- [13] Fusco, T. et al., Optics Express, 14, 7515 (2006)
- [14] K. El Hadi et al., " HARMONI at ELT: Prototyping for Single-Conjugate AO Sensor subsystem," this conference, 12185-187
- [15] <https://www.smaract.com/goniometer-stages>
- [16] M. N'Diaye, K. Dohlen, T. Fusco and B. Paul, "Calibration of quasi-static aberrations in exoplanet direct-imaging instruments with a Zernike phase-mask sensor," A&A 555, A94 (2013).
- [17] A. Hours et al., "HARMONI at ELT: A Zernike wavefront sensor for the high-contrast module - Testbed results with realistic observation conditions," this conference 12185-86.
- [18] Carlotti, R. Vanderbei, and N. J. Kasdin, "Optimal pupil apodizations of arbitrary apertures for high-contrast imaging," Opt. Express 19, 26796–26809 (2011).
- [19] M. N'Diaye, K. Dohlen, S. Cuevas, "Apodized Pupil Lyot Coronagraph, working without Lyot stopworking without Lyot stop," Proceedings of the conference In the Spirit of Bernard Lyot: The Direct Detection of Planets and Circumstellar Disks in the 21st Century. Paul Kalas (ed), id. 40 (2007).