



HAL
open science

HARMONI at ELT: development of the high-contrast module

Laurent Jocou, Patrick Rabou, Thibaut Moulin, Yves Magnard, Adrien Hours, Fabrice Panher, Sylvain Guieu, Alexis Carlotti, Alain Delboulbé, Maxime Vérove, et al.

► **To cite this version:**

Laurent Jocou, Patrick Rabou, Thibaut Moulin, Yves Magnard, Adrien Hours, et al.. HARMONI at ELT: development of the high-contrast module. Proceedings SPIE Adaptive Optics Systems VIII, Jul 2022, Montréal, Canada. pp.171, 10.1117/12.2626984 . hal-03796083

HAL Id: hal-03796083

<https://hal.science/hal-03796083v1>

Submitted on 4 Oct 2022

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

HARMONI at ELT: development of the High-Contrast module

Laurent Jocou^a, Patrick Rabou^a, Thibaut Moulin^a, Yves Magnard^a, Adrien Hours^a, Fabrice Pancher^a, Sylvain Guieu^a, Alexis Carlotti^a, Alain Delboulbé^a, Maxime Vérove^a, Eric Stadler^a, Didier Maurel^a, Sylvain Rochat^a, Francois Henault^a, K. Dohlen^b, N. Thatte^c, B. Neichel^b, P. Vola^b, F. Clarke^c, D. Melotte^c, M. Tecza^c, H. Schnetler^d, on behalf of the HARMONI consortium.

^a Univ. Grenoble Alpes, CNRS, IPAG, 414, rue de la piscine 38400 Saint Martin D’Heres; ^b Aix Marseille Univ., CNRS, France ; ^c Department of Physic, University of Oxford, Oxford OX1 3RH, United Kingdom, ^d UKATC, Royal Observatory Edinburgh Blackford Hill, Edinburgh EH9 3HJ, United Kingdom

ABSTRACT

HARMONI is the first light 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 (AO) modes – Single Conjugated AO (SCAO - including a High-Contrast capability) and Laser Tomography AO (LTAO) - or without AO (NOAO). The project is preparing for Final Design Reviews. In addition of the SCAO mode, the instrument includes a high-contrast imaging capability working in H and K band. This sub-system will be essential to spectrally characterize young giant exoplanets with contrast down to $1e-6$ and a separation from 0.1 to 0.3 arc second (goal: 0.05-0.3'') from their host star. It will also be used to characterize young circumstellar disks. The High-Contrast Module (HCM) is based on an apodized pupil coronagraph which lowers the intensity of the diffracted starlight to a planet-star contrast compatible with the dynamic range of the scientific detector. A dedicated Zernike wavefront sensor will internally calibrate non-common path aberrations at a 0.1Hz rate.

This paper therefore recalls the driver requirements before describing the optical, mechanical and control system designs. We then shortly describe the operation of the HCM. Section 3 addresses the main aspects of the system analysis while the last section is dedicated to the AIT aspects.

Keywords: HARMONI, High contrast, ELT, Adaptive optics

1. INTRODUCTION

HARMONI [1] is a near-infrared (NIR) integral field spectrograph dedicated to ESO’s Extremely Large Telescope (ELT) which will sit on top of Cerro Armazones. It is composed of five main systems: a Focal Plane Relay System (FPRS) that reimages the ELT focal plane at the entrance of the spectrograph, a Calibration Unit (CALUNIT), a Natural Guide Star System (NGSS) [2], a Laser Guide star System (LGSS) [3], and an Integral field Spectrograph (IFS) with a $R=3000-18000$ spectral resolution.

Three sub-systems are hosted in the NGSS: the Single Conjugate Adaptive Optics System (SCAOS) [4] which will provide diffraction-limited images in a narrow field, the Low Order Wavefront Sensor, complementary to LGSS, and the High-Contrast Module (HCM) which adds an essential high-contrast imaging capability for HARMONI to spectrally characterize young giant exoplanets and disks with flux ratio down to $1e-6$ at 0.1'' from their star. The HCM makes use of the apodized pupil coronagraph concept [5] to lower the intensity of the diffracted starlight and limit the dynamic range on the detector. It also includes an internal ZELDA [6] Wavefront Sensor (WFS) to calibrate Non-Common Path Aberrations (NCPA).

2. DESIGN DESCRIPTION

2.1 Requirements

The HARMONI technical specification defines that the instrument shall be able to detect a planet with a 10^{-6} flux ratio with a $M_v \leq 9$ star at $2.2\mu\text{m}$, and located at $0.2''$ from it, after post-processing of the data cube, and assuming a best quartile seeing ($0.43''$).

Managing the contrast

Most coronagraphs rely on a focal plane mask to attenuate the intensity of the diffracted light (classical Lyot coronagraph, apodized pupil Lyot coronagraph, vortex coronagraph, etc.). Using such a coronagraph requires an active correction of the atmospheric dispersion which is not implemented nor required in HARMONI. Since there is no chromatic beamshift in the pupil plane, we have chosen to use shaped pupil masks, i.e., apodizers that attenuate the intensity of the diffracted light of the star relative to the central peak intensity, in chosen regions of the image plane. These regions are referred to as high-contrast regions.

Two pupil masks will be implemented. The first attenuates the intensity of the diffracted light up to a $38\lambda/D$ outer working angle (the maximum separation limited by the M4 correction) and down to a minimal separation of about $7\lambda/D$. The second mask has a smaller inner working angle (IWA) of about $5\lambda/D$, and an OWA of about $11\lambda/D$.

Spectral range of operation

While our specification is given at $2.2\mu\text{m}$, HARMONI being able to cover a wider spectral range (from I to K band), the module is optimized for the range $[1.45\text{-}2.45\mu\text{m}]$. In practice, the HCM allows the observation down to $1.25\mu\text{m}$ to be able to observe spectral features such as the O_2 lines at $1.26\mu\text{m}$, and the Paschen- β lines at $1.27\mu\text{m}$, and up to $2.45\mu\text{m}$.

Tracking the pupil

A direct consequence of using a pupil apodization is that a sufficiently good enough positioning has to be ensured between the telescope pupil and the apodizers. This also assumes that the HCM will operate in pupil tracking mode, meaning that the field will rotate at the image level.

Correcting the quasi-static aberrations

SCAO will apply fast compensation for both atmospheric aberrations as well as aberrations induced by the optics of the telescope and of the instrument. The surfaces of the optics of the telescope and of the instrument induce quasi-static aberrations, i.e., intensity aberrations in the image (speckles) with a lifetime of few seconds to a few minutes which cannot be averaged out, nor be considered as purely static.

Given a target contrast of 10^{-6} after post-processing, the quasi-static speckles should not have a relative intensity higher than 10^{-5} . Figure 2-1 shows that this level of contrast induces a wavefront aberration of about 20 to 25nm at 200mas, and closer to 15nm if we want to maintain this performance at a smaller working angle.

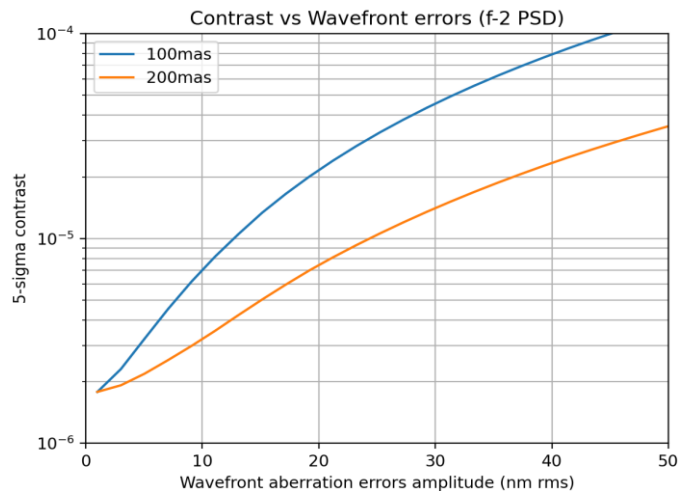


Figure 2-1: Contrast as a function of the wavefront aberrations for 100 and 200mas separations for f-2 PSD.

These quasi-static aberrations are also chromatic as their partial correction is limited by the difference between the sensing wavelength and the science wavelength. Finally, it is also important to understand the difference between common path, and non-common path aberrations (NCPA), i.e., aberrations that are not seen by the SCAO wavefront sensor but seen in the science detector plane, or vice-versa. As a consequence, there is a need to measure the wavefront in the HCM as close as possible to the focal plane in which we create the high-contrast image.

NGSS environment

Being hosted in the NGSS, the HCM needs to fulfill the environment requirements of the NGSS. In particular, the operating temperature is defined to be +2°C to limit the impact of the thermal background.

2.2 Functional analysis

The core functions of the HCM sub-system are:

Pick up the beam and redirect it: The beam comes out vertically from the HARMONI Relay (FPRS) up to the entrance focal plane of the spectrograph (IFS). A dedicated deployable pick-off optics (HPO) is therefore required to collect the converging beam before the IFS focus and fold it to feed a science channel and a WFS channel. Once apodized, the beam shall be redirected to the IFS at its nominal position.

Apodizing the pupil: As said previously, this is the main function of the bench as the high-contrast imaging field is obtained using this apodization. An apodizer mask has to be placed in the pupil of the system, and its alignment must be maintained whatever the pupil position. Moreover, since we are using two apodizers, we need to have a selection function.

Minimizing the impact of the atmospheric dispersion: HARMONI has no dispersion compensator as the capability is both complex to implement for a large field, and because it is not mandatory for the other science cases of HARMONI. The impact is high for the HCM since the PSF being elongated it forces the focal plane mask to be elongated also which increases the effective minimum separation, i.e., the ability of the mode to look at planets close to the star. We thus need ideally to fully cancel this atmospheric dispersion, or at least to minimize it as best as possible.

Attenuating the star light: the core of the apodized PSF still needs to be blocked or sufficiently attenuated to maximize the achievable dynamic range to characterize the planet. A strong attenuation has the advantage of enabling a secondary guiding to directly check the position of the star under the mask.

Calibrating the NCPA: as previously said, the requirement is to have a dedicated wavefront sensor in the HCM to measure the NCPA that exist between the SCAOS and the HCM, so that they can be continuously maintained at a level of ~20nm RMS. It is a low frame rate WFS as in that regime the quasi-static aberrations vary with a typical time of few tens of seconds.

In addition to these core functions, the HCM WFS has been given the task to measure the AO-corrected PSF during commissioning. While this capability is not planned to be used in operation, it will be essential to check the performance of the SCAO and LTAO modes.

2.3 Optical design

Layout description

Figure 2-2 shows the optical layout of the high-contrast module. It is roughly based on two channels: the science beam in green, which feeds the HARMONI spectrograph, and the internal WFS channel in blue.

The vertical converging beam comes from the HARMONI relay (FPRS). It first goes through a dichroic which feeds the SCAO sub-system and immediately enters the HCM to be picked-off by a first mirror that fold the beam, and directs it towards a relay system. This relay is composed of two folding mirrors and a collimation achromat which will form the

pupil that will be apodized. The HCM being integrated late in the project, several constraints (volume, number of controlled devices) forced us to choose a fixed ADC, i.e., an ADC designed to compensate dispersion for a single zenith distance, instead of a full one that would have required two more controlled devices. This component is located after the mirror M3, and it is also the last component of the common layout between both channels. At this level, few centimeters after the WFS dichroics, the pupil of the science beam is apodized before going to a second achromat which creates an image at the IFS entrance focal plane in which we place the focal plane mask (FPM) dedicated to attenuating the star light. Both achromats are designed to obtain a resulting magnification of ~ 1.13 to ensure the correct sampling of the PSF on the detector. Each are custom made and optimized for the spectral range $[1.25-2.45\mu\text{m}]$. The resulting pupil has a diameter of 29.7 mm.

Concerning the WFS channel, the beam is collected after the ADC by a dedicated dichroics, and the beam is sent to the wavefront sensor.

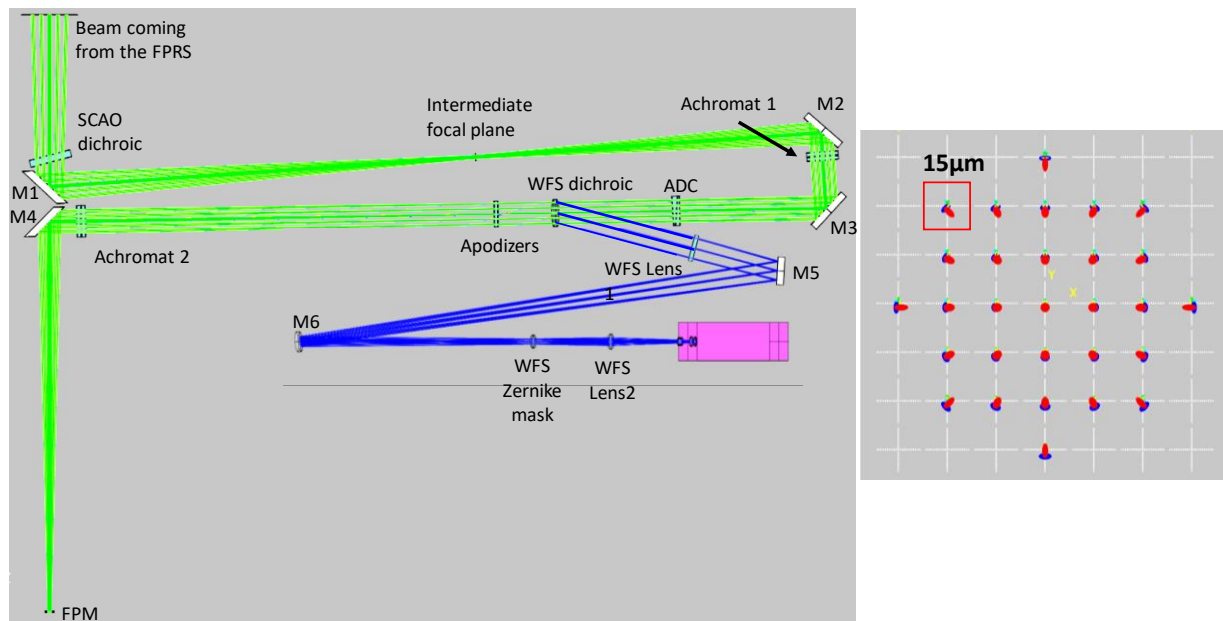


Figure 2-2: Left: Optical layout of the high control module. The green beam is the science channel that feeds the HARMONI spectrograph, while the blue one is the ZELDA WFS. Note that the original drawing has been modified to better show the WFS layout. In practice, the WFS dichroic reflects the beam towards the reader and then on the upper part (see the mechanical implantation in section 2.4). Right: image quality of the over the 1 arcsec field.

The Zernike wavefront sensor

The role of this WFS is first to calibrate the NCPA, including differential piston, between the SCAO sub-system and the HCM, ideally as close as possible to the FPM. In operation these NCPA will be compensated by the M4 through the AO Control System. The WFS shall moreover provide a measure over at least 160 points across the pupil, to take benefit of the M4 correction. Its dynamics could be low as we expect aberrations of the orders of a few tens of nm rms but it should be accurate at a level of few nm rms to ensure, according to the error budget, a WF aberration of 20nm RMS in the plane of the FPM. Finally, the spectral range of this WFS should be as close as possible from the science bandwidths to limit chromatic differential effects.

For these reasons, the ZELDA WFS (ZWFS) has been identified as the most suited WFS for the HCM. Its name stands for Zernike sensor for Extremely accurate measurements of Low-level Differential Aberrations. It is implemented in VLT-SPHERE, where it has been used to identify and characterize the low-wind effect, in addition to measuring NCPA [7].

This WFS returning a pupil-plane image of the WFE, it thus provides at the same time a measure the pupil position. This ensures that the NCPA map can be used as an offset for the reference slopes of the SCAO wavefront sensors with a sufficiently low lateral shift error. Additionally, it also enables the control in open loop of the apodizers position.

In the optical layout (see Figure 2-2), the HCM WFS channel picks up the shortest wavelengths from the science channel collimated beam before the apodizer with a dichroic beam-splitter, then a focusing Singlet (e_f= 1188 mm) forms an image at F/40 on the Zernike phase mask, and then a collimating Singlet (e_f = 120 mm) forms a pupil image (Φ WFS = 3 mm) spread over 200 pixels of the detector.

As the ZELDA WFS is sensitive to the PSF elongation produced by the residual atmospheric dispersion (see proceeding...), we have to make a trade-off between the flux and elongation and thus we limited the bandwidth within the range [1.15-1.2 μ m],

AO Commissioning camera

In the preliminary design of HARMONI, the commissioning of the AO system was planned to be done directly with the spectrograph detector, which allows only long exposures and is not well adapted in term of sampling. The implementation of the ZWFS has therefore been seen as an opportunity to add an imaging capability dedicated to the AO commissioning. A switchable lens has thus been inserted in the WFS, to change the pupil imaging into a field imaging with a sampling of about 2.5 pixels/(λ /D) over a field larger than 1 arcsec.

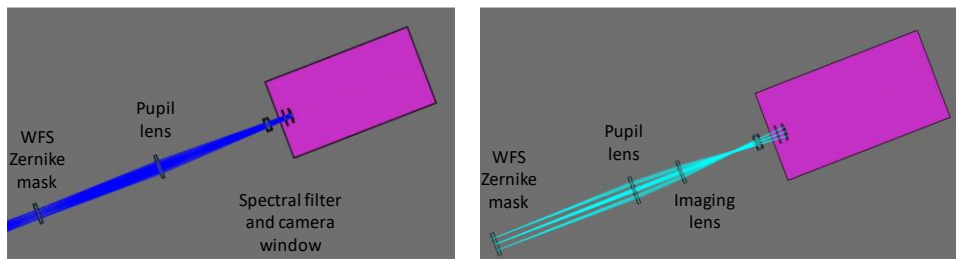


Figure 2-3: Pictures of the ZELDA WFS in mode HCM operation (Left) and in mode imaging for AO commissioning (Right)

2.4 Opto-mechanical design

The HCM is composed of three mains opto-mechanical components, 1/a pick-off module called HPO, 2/the main bench called high-contrast bench (HCB), and 3/the focal plane mask assembly (FPM). Each component is described hereafter. Note that the AIT being mostly done at ambient temperature, and the operation at +2°C, we need to manage the transition from ambient to cold temperature. This is done in the system using dedicated sets of shims for each environment.

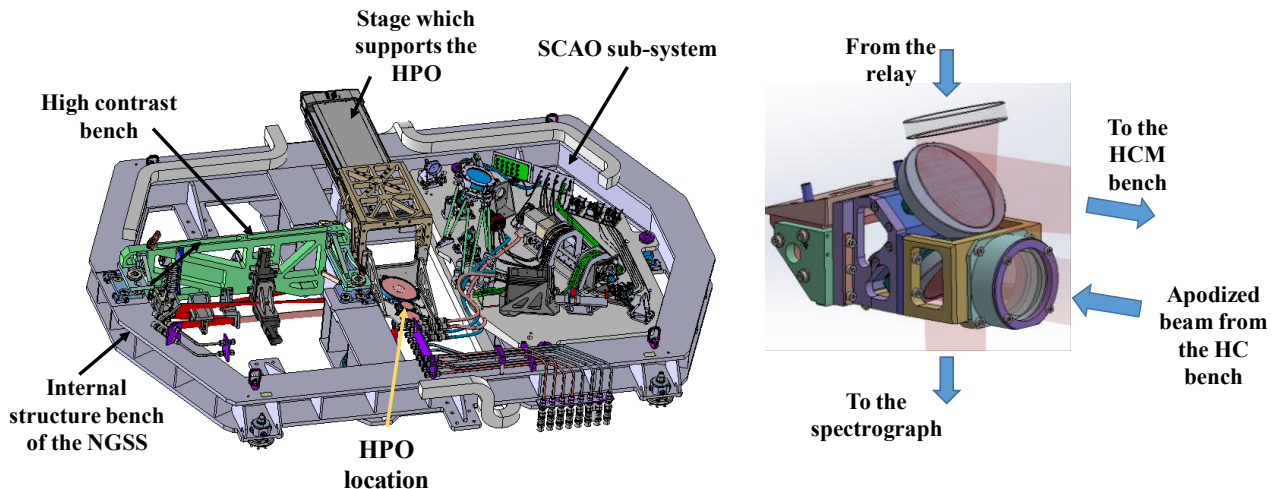


Figure 2-4: Left: location of the HCM in the NGSS. Right: Zoom on the HPO sub-assembly

The High-contrast Pick-Off Unit (HPO)

The HPO (see Figure 2-4) comprises two fold mirrors. The first one picks up the input beam and redirects it to the high-contrast bench (HCB). The second mirror receives the processed science beam and folds it to the IFS entrance. Considering the mechanical constraints of the system, this is the only location which can host the second achromat which reforms the image at the IFS entrance. As the system needs to be very compact, all the degrees of freedom are custom made. Note that in Figure 2-5, the HPO is in air because, since it is a deployable system, it is held by the translation stage supported by the main structure of the NGSS. The mass of the HPO is about 1 kg.

The high-contrast bench (HCB)

The HCB is built around a vertical bench which hosts one channel on each side (see Figure 2-5 and Figure 2-6). The components will be machined in aluminum 6082 to minimize the mass, and because this is the material used for the internal structure bench (ISB), i.e., the support structure of the HCM in the NGSS.

The mechanical interface between the HCM and the ISB will be done using a spherolinder system (G2 engineering) which allows a precise repositioning of the bench in case of maintenance.

Science channel

Once folded by the HPO, the beam forms an entrance focal plane (visible in Figure 2-2) before going to a trombone composed of two mirrors and the first achromat. These 3 components are mounted on the same support as, considering that constraints on the system, it is the only way to adjust the position of the pupil in the alignment process. Leaving the trombone, the beam goes through the fixed ADC and the ZELDA WFS dichroics which splits the beam in two. The science beam then travels to the apodizer assembly. This assembly is a system of two translation mechanisms which select the mask to use and adjust precisely its position to keep the alignment with the telescope pupil (measured by the ZELDA WFS, see section 2.3). This assembly provides three positions: two user-selectable apodizers to allow the users to optimize their observations, and a clear, i.e., non-apodized, pupil for the alignment. Once apodized, the collimated beam goes to the HPO to be sent to the IFS.

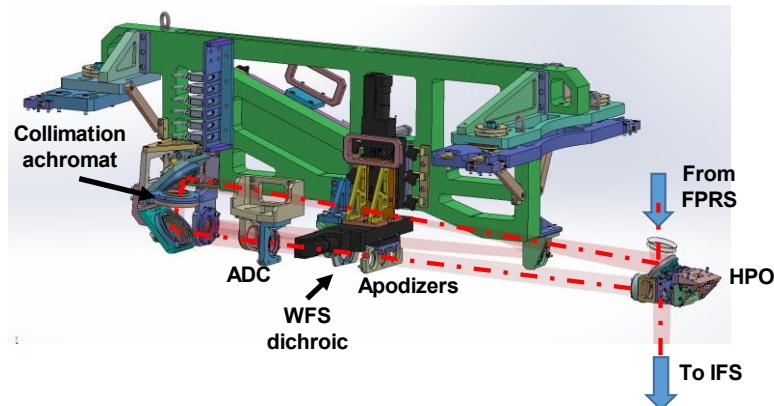


Figure 2-5: View of the science side of the HCM.

ZELDA WFS channel

The blue part of the collimated beam is reflected by the WFS dichroics before going through a single lens that forms an image on the ZELDA mask. The WFS dichroic and the ADC share the same mechanical support on the bench. The beam is then folded two times by M5 and M6 to be redirected to the WFS breadboard.

This breadboard is first composed of the Zernike mask which is mounted on a three stages system that is required to accurately position the mask on the PSF. After the mask, the diverging beam is finally collimated by a lens that images the pupil on an InGaAs camera (see section 2.5).

As described in section 2.3, the WFS assembly includes a functionality to transform the ZELDA WFS into a diffraction-limited imager for the AO commissioning. This is achieved by the aid of an additional linear stage that inserts a lens into the ZELDA beam to focus the image rather than the pupil onto the ZELDA camera. In this mode (called ComCam mode), the Zernike mask is taken out of the beam by the aid of the ZELDA positioning stage.

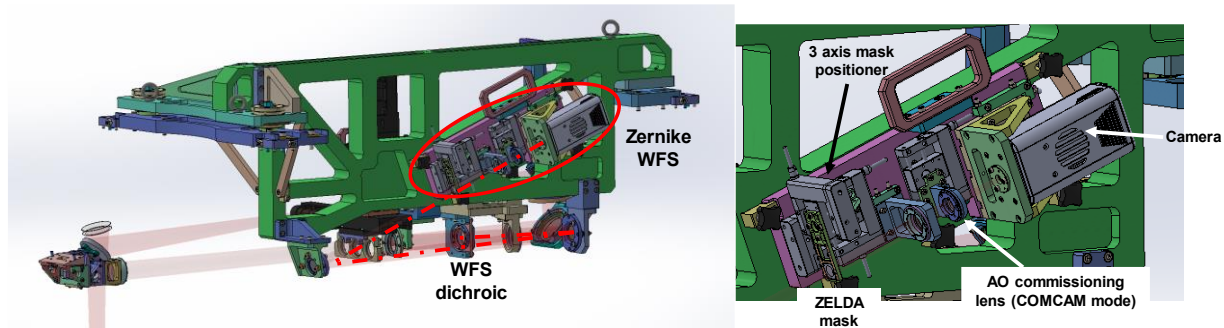


Figure 2-6: WFS channel. Left: the red dashed line shows the beam axis, and the red ellipse shows the ZWFS breadboard, also given in the Zoom on the right picture.

Focal plane masks (FPM)

The high-contrast image is formed at the entrance of the HARMONI spectrograph. The FPM is therefore not physically in the HCM main bench environment but integrated in the IFS pre-optics in the focal plane mask wheel (see Figure 2-7). Three masks will be used to cover both the H and K band operations with the two apodizers defined.

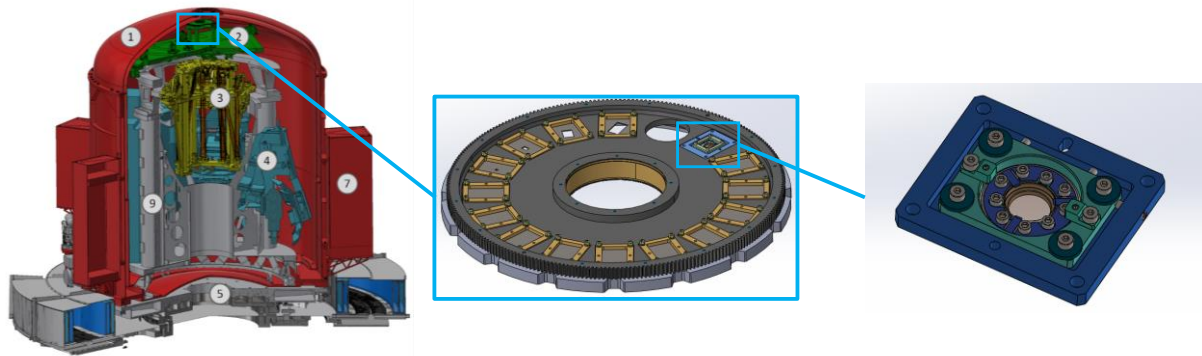


Figure 2-7: High-contrast FPM. Left: view of the HARMONI cryostat. The 3 FPM are integrated in the focal plane mask wheel (middle) at the entrance of the spectrograph. Right: mechanical support of one FPM.

2.5 Control electronics and control software

The HCM electronics includes six PI motorized stages, one camera for the ZELDA WFS and five PT100 temperature sensors. All are identified as “standard devices” for the ELT software environment.

The high-speed SWIR camera C-RED2 (from First Light Imaging) was selected for the ZELDA WFS. It is connected to an iPORT external frame grabber through its two camera link ports.

The motorized stages are distributed in the following subsystems:

- **The WFS mask positioner** composed of three axis translation stages M112.2DG aiming at compensating the differential motion between the HCM science channel and the WFS channel.
- **The ComCam selector** composed of one translation stage M112.2DG used to insert a lens in the WFS optical layout in order to convert the pupil imaging into field imaging.
- **The Apodizer assembly** based on one M403.1DG that adjusts the position of the apodizer and one M403.4DG that ensures the same adjustment but also selects the apodizer inserted in the beam.

To remotely control these devices, we will use modules from BECKHOFF, which are compliant with the ESO requirements applicable for all ELT instruments. The components planned to be used are:

- 1x CX2030 PLC
- 3x ES1098 (digital in.) for the limit switches
- 3x ES7342 for 6 PI motorized stages
- 2x EL3202 (analog inputs) to read temperatures from the PT100 sensors

The TwinCAT software from BECKHOFF is used to remotely control the PLC and its modules from a Windows workstation through the standard data exchange protocol OPC UA. This includes the list of the BECKHOFF modules controlled by the PLC, the linkage between the motorized stages and the limit-switch signals, the declaration of the variables exported through the OPC UA and the parameters for the motorized stages (speed, acceleration, gear-ratio, PID, etc).

Since OPC UA applications or libraries are usable by applications external to TwinCAT, we developed a basic custom application using the ELT FRAMEWORK Python libraries for the validation of the motorized stages. It allows to change operational state following ESO state machine, move motors and perform repeatability moving sequences.

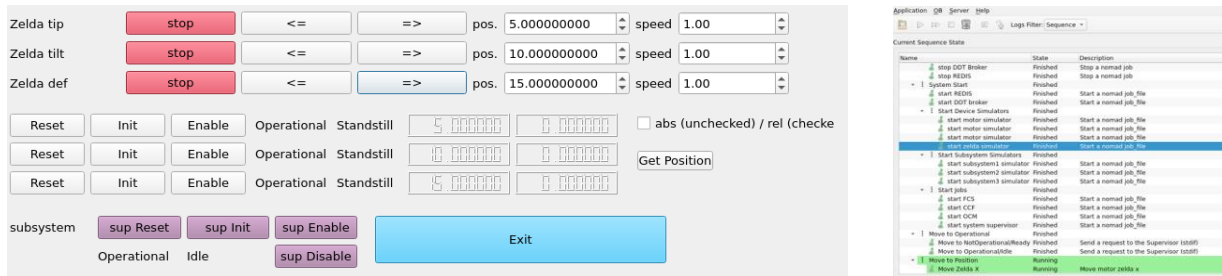


Figure 2-8: Left: custom control application using the ELT FRAMEWORK library. Right: ELT FRAMEWORK Sequencer initializing devices and simulators for the HCM bench

The ELT FRAMEWORK is the toolkit developed by ESO to help instrument developers to implement the control systems. It is mainly composed of:

- The *Function Control Framework* (FCF) includes a device manager for the control of a list of commonly used devices such as motors, lamps or sensors. The FCF also features graphical user interfaces and simulators that simplify the development of applications without real hardware.
- The *Sequencer* allows to write and execute sequence of commands defined within a Python script. Each sequence is composed of a set of blocking or non-blocking commands that can be executed sequentially or in parallel.
- The *Supervisor* is indented to provide state control and monitoring capabilities of all instruments' subsystems. It allows to set and visualize the operational state of the overall subsystem.

2.6 The HCM in operation mode

This section aims at describing the HCM in operation. It thus recalls first the operation conditions, and gives a typical sequence to start an observation.

Operation conditions:

- The HCM will be used with the 4mas platescale optics of the IFS
- The use of SCAO is mandatory to operate the HCM and reach a low WFE to be measured by the ZELDA
- The HCM science channel covers the end of the J band, the H, and K bands, and the H+K band
- The ZELDA channel covers the 1.15-1.2 μ m spectral range
- The HCM operates in pupil tracking mode

Planned calibration:

These calibrations will be done mainly with a dedicated AO calibration unit that embeds a 97-actuators deformable mirror [8]. This unit presents also several diffracted-limited sources, made of LED and single-mode fibers, to feed both the ZELDA channel and a part of the H band. This system allows the calibration of the NCPA at two levels, between the

SCAO and the ZELDA WFS, and more conveniently between the ZELDA and the IFS science detector. This will be done during daytime, by maximizing the Strehl Ratio by scanning the first 36th Zernike modes on the DM.

Preparation and observation sequence:

- Rotate the IFS to have the apodizer mask properly oriented relative to the telescope pupil
- Start the pupil tracking
- Switch the IFS in 4mas platescale
- Set the HCM in observation mode: HPO in the beam, apodizer selected
- Set the IFS focal plane mask wheel on the chosen HCM focal plan mask
- Close the SCAO loop
- Check the alignment of the star on the focal plane mask, and derive TT correction to be applied on M5 through a modification of the reference slopes of the WFS in SCAOS.
- Center the Zernike mask of the ZWFS
- Make a measurement of the Pupil position on the ZWFS camera
- Measure the WFE with the ZWFS, and split them into low-order, and high-order aberrations:
 - Low-order aberrations are used to modify the slopes of SCAOS Shack-Hartman WFS
 - High-order aberrations are used to modify the slopes of SCAOS Pyramid WFS
- Adjust the position of the apodizer according to the position measured on the ZWFS camera
- Start the exposure
- During the exposure:
 - Check the position of the star under the FPM
 - Accordingly, correct the TT to maintain a correct centering of the star under the FPM
 - Adjust the Zernike mask position to compensate for the differential chromatic shift between the science beam, and the WFS beam
 - The starlight flux is monitored under the FPM mask to avoid saturation

3. SYSTEM ANALYSIS

3.1 Global approach

A complete system analysis is given in [9], and we here give a short summary of this study. The performance of the HCM relies on several main parameters which are:

- The quasi-static aberrations, which must be lower than 25nm rms at the focal plan level to ensure a contrast of $\sim 10^{-5}$ (before data processing). This is the parameter that mainly drives the HCM performance.
- The residual diffracted light left out by the apodizers in the high-contrast region: the apodizers are designed to provide a 10^{-6} contrast, meaning that they are almost negligible in the error budget.
- The alignment between the telescope pupil and the apodizer must be controlled to avoid diffraction effects in the high-contrast image. In practice the apodizers are designed to be robust to misalignments up to 0.2% of the pupil diameter. Misalignments are anticipated to be less, and these effects are not considered in the error budget.

3.2 NCPA and WFE

The NCPA directly drive the specifications of the HCM components. Indeed, the wavefront aberrations created by the optical surfaces induce speckles in the focal plane. Figure 3-1 illustrates the optical paths from the common optics of the instrument to the SCAOS, the ZELDA WFS (ZWFS), and the FPM. Some surfaces are seen by the SCAO WFS (at $0.8\mu\text{m}$) and the HCM (at $1.2\mu\text{m}$), while some are not. To guarantee a maximum wavefront error of 25nm rms at the FPM level and then reach a contrast of $1e-5$ et 200mas (@ $2.2\mu\text{m}$), two regimes have to be considered:

- The low orders (LO) covering the first 36 Zernike modes (36Zm) corresponding to the frequency domain covered both by the DM of the low order loop of the SCAOS but also to the DM included in the AO calibration unit;
- The high orders (HO) covering the spatial frequency range up to $40\lambda/d$, minus the first 36Zm. This corresponds to a frequency domain that can be measured by the SCAO PWFS, and the ZWFS, and corrected by the M4.

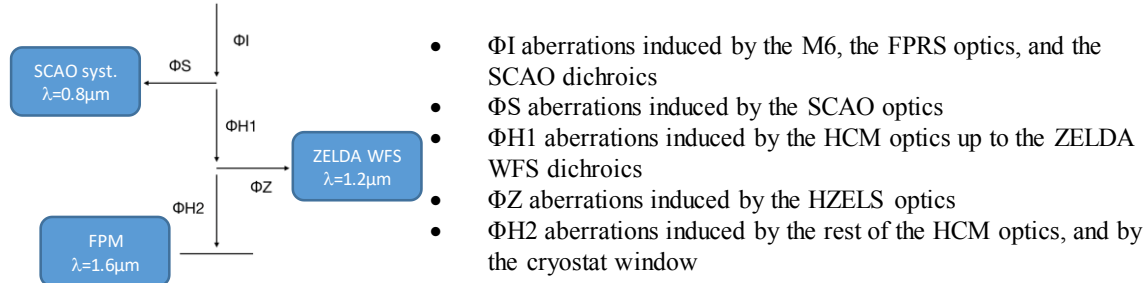


Figure 3-1: Schematic view of the wavefront aberrations induced by the optics from the FPRS down to the focal plane at the entrance of the cryostat in which the focal plane masks are located.

From that point, we used the PYTHON/PROPER package to simulate the full optical train to define WFE error budget for each optics contributing to the HCM. This gave the WFE budget for both contributions, the upstream beam to the ZELDA dichroic expressed as chromatic differential NCPA, and the effect downstream defined as common NCPA. Table 1 gives finally the mains contributors to the WFE budget.

| Contributor | WFE value (nm RMS) | Comments |
|---------------------------------------|--------------------|--|
| NCPA HO | 21 | See next section |
| Quasi static evolution during WFS dit | 10 | Based on optics in f^2 |
| ZELDA WFS precision | 5 | Requirement defined |
| Chromatism focus | 5 | Residual chromatism expected between both channels |
| Calibration residuals | 5 | Needs to be confirmed |
| Total | 25 | |

Table 1: Error budget on the WFE

3.3 Transmission

The expected transmission is given Table 2.

| SCIENCE | H band | K band | ZELDA WFS | [1.15-1.2μm] |
|--------------------------------|-------------|-------------|---------------------------|--------------|
| 4x Mirrors R% | 0.922 | 0.941 | 5x Mirrors R% | 0.88 |
| 10x AR coating (achromats+ADC) | 0.86 | 0.86 | 4x AR coating (achromats) | 0.89 |
| Glass Int. T% (Achromat + ADC) | 0.989 | 0.935 | Achromat Internal T% | 0.997 |
| WFS Dichroic | 0.946 | 0.944 | Dichroic refl coating | 0.96 |
| Apodizer (Coating, T%) | 0.96 | 0.958 | ZELDA mask | 0.94 |
| FPM Mask | 0.97 | 0.97 | Filter T% | 0.93 |
| Total | 0.69 | 0.66 | Total | 0.66 |

Table 2: Expected throughput of both HCM channels

4. MAIT ASPECTS

Some commercial components have already been identified and sometimes validated if required (WFS camera and translation stages for instance). For the most critical components, such as the apodizers, the Zernike mask and the focal plane masks, some prototypes have been produced to validate their feasibility and performance (see Figure 4-1). Another special case in the ZELDA WFS, for which a dedicated setup has been implemented to validate experimentally its operation in the HARMONI conditions, that is mostly with the dispersion residuals [10].

For the final product, although all the components will be produced in parallel, we plan to start the production of the optics first as the manufacturing delay is expected to be longer. Depending on the metrological tools that are required, the verification of the components will be done either by the sub-contractor or the HCM team at IPAG.

Once the components are delivered and tested, the integration will start in Grenoble. This integration, the alignment and the performance validation of the HCM rely on a dedicated AIT structure described in section 4.1.

During all these phases, dedicated software tools will be used to address non-conformity and validation processes. Note also that, to ensure the performances of the HCM, the cleanliness level of the integration rooms needs to be managed along the integration. Therefore, the integration and tests will be managed in an ISO7 both at IPAG and at the Laboratoire d'Astrophysique de Marseille (LAM).

Once aligned and validated at IPAG, the HCM will be shipped to LAM to first be installed on the NGSS structure and then integrated in the top-end assembly which gathers the upper parts of the HARMONI system, i.e., the FPRS, the CALUNIT, the LGSS, and the NGSS. The full integration of the top-end together with the IFS will be done only at ELT.

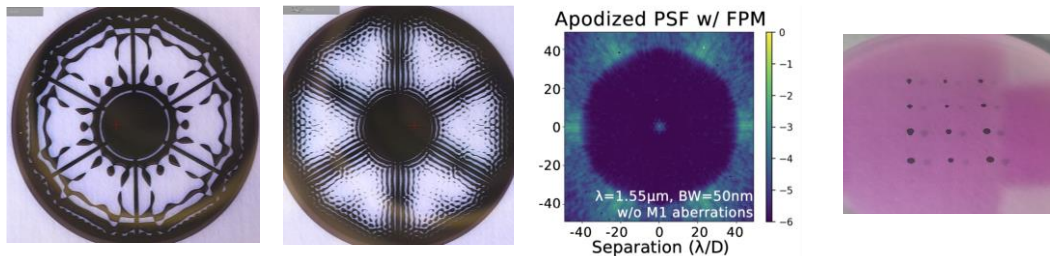


Figure 4-1: Picture of the prototypes produced to validate critical components. Left: Picture of two apodizer prototypes. Picture 3 is an experimental PSF obtained with one of these components. Right: picture of the several FPM deposited on the same substrate.

4.1 HCM AIT tool

This tool is required to fulfill several functions:

- Provide a telescope simulator
- Hold the HCM during its integration, its alignment and its validation in the laboratory
- Position the three sub-systems of the HCM in the same way they will be once in operation in HARMONI
- Provide a capability to image the FPM on a detector
- Provide required alignment tools or support

This tool is based on three main components which are:

The holding structure based on commercial aluminum rails is under design (see Figure 4-2). It will hold in place, for the integration at IPAG, the HPO, the HCM main bench, and the FPM in their final position to make the alignment, the validation and commissioning in Europe. It will also host the alignment or measurement tools required during the AIT phase, including the telescope simulator and the imaging system described below.

The telescope simulator aims at providing a replica of the beam as it leaves the FPRS. Figure 4-2 shows the HCM layout with the telescope simulator above. Its concept is based on the requirement to have two pupil planes, one to place a deformable mirror required to compensate the residual astigmatism of the SCAO and LTAO dichroics, but also to compensate the aberration of the simulator itself. A second pupil plane is required to place a mask of the ELT pupil. The simulator is therefore designed on two stages, the first one based on spherical mirrors (e_{fl}~585mm), and the second uses commercial achromats (e_{fl}=750mm). The source may be a single-mode fiber, but it could also be a multi-object fiber bundle composed of several single-mode fibers to mimic a star with planets at several positions around it.

An imaging system is required to make an image of the high-contrast PSF and the FPM to validate the contrast performance. Since the system relies on a SWIR C-RED2 camera, most of the tests will be managed in H band up to 1.7μm. Commercial achromatic lenses are used to make an image either of the focal plane mask, or of the pupil plane.

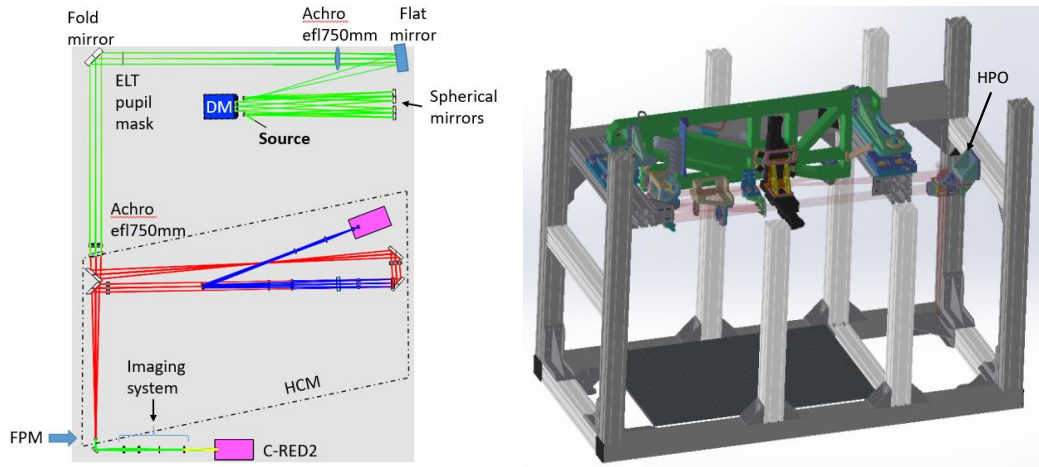


Figure 4-2: The HCM setup during the integration. Left: Side view of the optical design of the full system: telescope simulator + HCM+imaging system. Right: Structure under design that will hold and place the HCM components during AIT phase.

4.2 Alignment plan

AIT at IPAG

This part of the integration will be done in the integration hall at IPAG under a clean tent at ambient temperature. When the HCM will be inserted in the NGSS, however, it will operate at +2°C. We therefore also contemplate a validation of the alignment at 2°C.

The AIT tool is central to the alignment process of the HCM. We consider the following approach:

1. The AIT tool is integrated. The mechanical references for the HPO, HCB and FPM positioning will be measured with a 3D metrology tool to guarantee the nominal positions relative to each other's
2. In addition, some mechanical targets will be implemented in the AIT tool to materialize the vertical incoming beam coming from the HARMONI relay up to the entrance focal plane of the IFS where we place the FPM. This plane is our reference as it should be the same with or without the HPO in the beam
3. This first alignment allows to define some reference in the imaging system of the AIT tools in terms of image and pupil position on the detector
4. The HPO is pre-aligned using mostly the mechanical reference
5. The HCB is placed on the AIT tool, and then aligned independently according to the following steps:
 - a. Tools like a visible laser beam and an alignment telescope are mounted on the HCM bench
 - b. A narrow visible laser beam is propagated through each optics using reference mechanical targets defined in the design of the HCM bench
 - c. A single mode fiber placed at the intermediate focal plane, is used to make the collimation with the first achromat. This is done using a SWIR commercial WFS.
 - d. The pupil and image of the intermediate focal plane can be propagated in both the WFS channel and the science channel
6. The HPO is then mounted at its nominal mechanical position.
7. The M1 mirror of the HPO, is precisely adjusted to enter correctly the HC bench.
8. The M4, in the HPO, is adjusted so that the image is formed correctly on the reference images (see step 2 above), which means:
 - a. Adjust the tip-tilt of M4, to place the image and the pupil at right place (using ref of step 3)
 - b. Adjust the Z position of the second achromat to make the focus
 - c. Iterate between the system M2-M3-achromat1, to adjust the position of the pupil along Z
9. At this level the tests and validation can start

The system will be sent to LAM (on its AIT tool) once it has been validated at IPAG.

AIT at LAM

Our goal is here to replicate the alignment that will have been obtained on the AIT tool at IPAG, on the Internal structure of the NGSS. For that we plan to adjust only each sub-system relative to each other: the HPO and the HCM. No unitary component will be modified internally in the main bench or in the HPO.

The LAM team plans on its side to have an alignment tool above the NGSS structure. We will then use this tool to align the HPO and the HCM together. No performance verification is planned at this level.

Finally, the NGSS will be installed on the top-end in which the AO calibration and other dedicated tools will be used to check the operation and to validate the HCM in HARMONI. At this level, the NGSS will be in final conditions to validate the HCM at +2°C.

AIT in Canary Islands

The FPM being inserted in the IFS pre-optics, it needs to be integrated independently. A prototype is currently under design, to have, as soon as possible, a validation of the mounting of the FPM in the focal plane mask wheel. Once this step is validated, the final production will be just a replication of this prototype. Three FPM will be provided to Instituto de Astrofísica de Canarias (IAC) to be integrated with the pre-optics, and later in the spectrograph cryostat. The validation of the mount will be therefore done independently of the other HCM parts.

5. CONCLUSION

Although no high-contrast mode was initially developed in HARMONI, we showed that such a facility can be integrated, and the community is now convinced that this mode brings a critical capability that increases the scientific potential of the instrument. We defined a design which is compatible with the constraints required by the system. While few validations need to be done, no critical aspects has been raised and the module should be ready beginning of 2023 to start the Final Design Review process.

6. ACKNOWLEDGMENTS

This work benefited from the support of the University Grenoble Alpes (UGA) the Programme Investissement Avenir F-CELT (ANR-21-ESRE-0008), and the Commission Spécialisée Astronomie-Astrophysique (CSAA). Finally, the Grenoble team thanks the consortium for its support during this development.

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] Dohlen K. et. al., "HARMONI at ELT: Towards a final design for the Natural Guide Star Sensors system", this conference, 12187-50
- [3] Costille A. et al., "HARMONI at ELT: designing a laser guide star wavefront sensors for the ELT", This conference, 12185-172
- [4] Sauvage J.F. et al., "HARMONI at ELT: Wavefront control in SCAO mode", this conference, Paper 12185-47
- [5] Carlotti, A. et.al. "Optimal pupil apodizations of arbitrary apertures for high-contrast imaging," Optics Express , 2011, 19, 26796
- [6] N'Diaye M. et. El., "Calibration of quasi-static aberrations in exoplanet direct-imaging instruments with a Zernike phase-mask sensor", Astronomy and astrophysics, 2013, 555
- [7] N'Diaye M. et.al., "Lab results of the circular phase mask concepts for high-contrast imaging of exoplanets", SPIE, 2012, Vol. 8450, 84500N
- [8] Schwartz N., "HARMONI at ELT: Adaptive Optics Calibration Unit from design to prototyping", This conference, 12185-203
- [9] Carlotti A., "HARMONI at ELT: System analysis and performance estimation of the high-contrast module", This conference, Paper 12185-211
- [10] Adrien 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.