SHARK-NIR, first results of the commissioning at LBT

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ABSTRACT

SHARK-NIR is an instrument which provides direct imaging, both coronagraphic and non-coronagraphic and with the possibility to perform dual-band imaging and low-resolution spectroscopy in Y, J and H bands, with the main scientific goal of detecting exoplanets, and characterizing already known planets, young stellar systems, jets and disks. SHARK-NIR takes advantage of the excellent performance of the Large Binocular Telescope AO systems, the wavefront sensors of which have been recently upgraded to SOUL. The latter is delivering a very good performance also at faint magnitude, opening to science otherwise difficult to be achieved, as for example AGN and QSO morphological studies. To fully exploit the just mentioned science cases, binocular observations will be performed using SHARK-NIR in combination with SHARK-VIS (operating in B, V, R and I bands) and LMIRCam of LBTI (operating from K to M bands), in a way to exploit coronagraphic observations in three different wavelengths. The instrument has passed the preliminary acceptance Europe in March 2022, being shipped immediately after at LBT, and re-integrated, installed and characterized daytime in three pre-commissioning run at the telescoped. SHARK-NIR had a very successful first light in January this year, and we will report of the results obtained in the three commissioning runs performed in the first half of 2023.

Keywords: LBT, XAO, Pyramid WFS, Coronagraphy, Planet finding

1. INTRODUCTION

SHARK (System for coronagraphy with High order Adaptive optics from R to K band) [1] is an instrument proposed for the LBT[2] in the framework of the "2014 Call for Proposals for Instrument Upgrades and New Instruments". It is composed by two channels: SHARK-VIS[3], working from 0.5µm to 1µm, and SHARK-NIR[4], working in the near infrared bands, from 0.96µm to 1.7µm. These two instruments (which are, essentially, two coronagraphic cameras) will take advantage of the extreme AO correction provided by LBT. The AO Wave Front Sensors (WFS) of LBT has been recently upgraded from FLAO (First Light Adaptive Optics[5]) to SOUL (**S**ingle Conjugated Adaptive **O**ptics **U**pgrade for **L**BT[6]), based on the pyramid WFS[7] and using the Adaptive Secondary Mirror (ASM) corrector[8]. The SOUL systems are equipped with CCD characterized by a Read Out Noise which is nearly 0, thus allowing to use very faint target stars for the wavefront reconstruction. Furthermore, the Pyramid WFS has a demonstrated gain in sensitivity compared to other WFSs ([10], [11], [12], [13], [14]), giving in this way the possibility to achieve, with SOUL, high SR (of the order of 70%) at moderately faint magnitude (R~13 or even occasionally fainter, depending on the observing conditions[6]).

Such performance may give to SHARK-NIR unique opportunities in the coronagraphic instrument scenario:

- opening the field of high-contrast AO coronagraphic imaging to stars much fainter than required by other coronagraphic instruments, thus allowing deep search for planets around suitable targets such as, for example, M dwarfs in nearby young associations and solar type stars in nearby star-forming regions (Taurus-Auriga at 140 pc)
- in the extragalactic field, the sample of AGN and of Quasars to be explored increases from a few tenths to a few hundreds, increasing quite a lot the number of targets of this type that can be observed and studied

Another unique feature consists in the fact that the spectral coverage of the two SHARKS, used in combination with LMIRcam of LBTI[15],[16], will go from V to M band, giving to LBT the unique capability to make contemporary coronagraphic observations with the three instruments, a unique scenario for coronagraphy in the framework of the modern planet finders (see [17], [18], [19] and [20]).

This paper will report about the SHARK-NIR recent activities, going from the instrument shipping (June 2023) to the currently undergoing commissioning phase.

2. INSTRUMENT DESCRIPTION

SHARK-NIR is installed at the entrance left focus of LBTI (LBT Interferometer), as it is shown in Figure 1. A motorized deployable arm allows to insert a dichroic just before the entrance window of LBTI, to feed SHARK-NIR with the NIR light. SHARK-NIR is a camera for direct imaging coronagraphy and spectroscopy, using the corrected wavefront provided by the LBT Adaptive Secondary Mirror (ASM), operated through one of the existing LBTI AO WFS. Nevertheless, SHARK-NIR is also equipped with an internal DM (ALPAO 97-15), positioned on the first instrument pupil plane, which is used for two purposes:

- The local correction of the Non-Common Path Aberrations (NCPA), measured directly on the scientific camera using the Phase Diversity (PD) technique
- The correction of undesired PSF movements during a scientific exposure (using the DM as a tip-tilt corrector), essentially due to the residual jitter. Such correction requires a dedicated T-T sensor (based on the First Light C-RED2 camera), which has been placed after the first pupil plane, where a beam splitter positioned into the collimated beam picks-up few percent of the light (10%) and sends it to the sensor. Also, a Wave Front Computer (WFC, which is realized by Microgate) allows the fast T-T correction achieved with the DM, which maintains at the same time the proper shape for the NCPA local compensation.

Figure 1: the two SHARK channels installed at the LBTI entrance foci

To achieve the required extreme performance, optics machined to a state of the art technology and polished to nanometric level of roughness, properly aligned and installed on very robust mounts have been used inside HARK-NIR. Also, the whole instrument mechanics has to be very stiff and designed to minimize the effects of flexures.
An Atmospheric Dispersion Corrector (ADC) has been implemented to maintain the performance as good as possible at every observing altitude, and the whole instrument is mounted on a mechanical bearing to accomplish the science cases that need to perform the field de-rotation.
A NIR camera, based on an Teledyne H2RG detector, cooled at about 80°K to minimize the thermal background, will provide a FoV of the order of 18”x18” operating in Y, J and H bands, with a plate scale foreseeing a bit more than two pixels on the diffraction limit PSF at 0.96µm.

A few coronagraphic techniques are implemented into the instrument, with the purpose to match as much as possible the different requirements of the different science cases (in terms of contrast and Inner Working Angle - IWA):

- Gaussian Lyot, which requires a gaussian stop into the 1st focal plane and a pupil stop on the 2nd pupil plane
- Shaped Pupil, which requires an apodizing mask into the 1st pupil plane and an occulting mask into the 1st focal plane
- Four Quadrant, which requires a “knife edge” like mask into the 1st focal plane and a pupil stop on the 2nd pupil plane

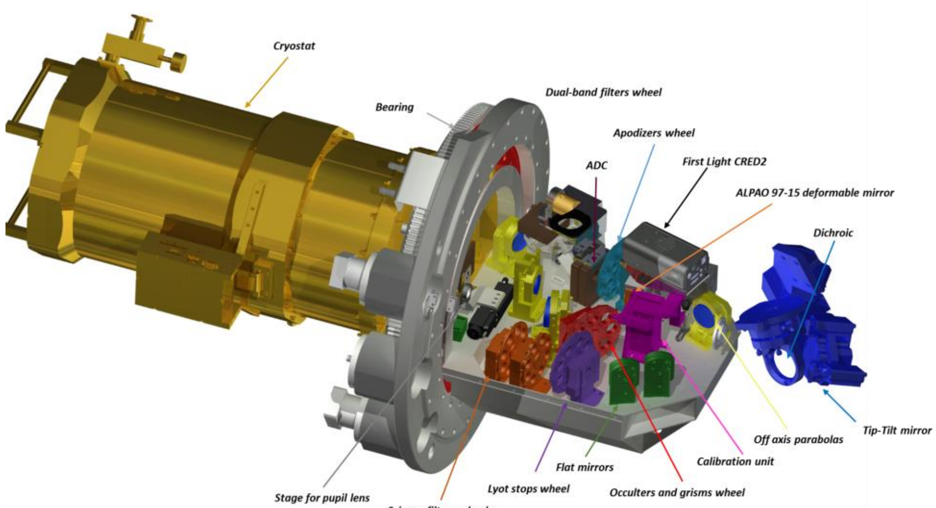

Figure 2: the opto-mechanical concept of the SHARK-NIR optical bench

A filter wheel, positioned between the DM and the beam splitter feeding the T-T sensor, placed at 50mm from the pupil plane, is carrying the Shaped Pupil apodizing masks. These masks are normally placed exactly into the pupil plane, which is occupied by the DM in our design. We did evaluate the impact of having the masks slightly displaced with respect to the pupil plane, and the effect is basically negligible with the considered coronagraphic techniques if the masks are designed to take this fact into account.
The opto-mechanical design of SHARK-NIR is shown in Figure 2, where all the main components are highlighted.

3. PRE-COMMISSIONING ACTIVITIES

SHARK-NIR has successfully passed the Preliminary Acceptance Europe in April 2022, and it has been shipped to LBT in June 2022. The pre-commissioning activities started immediately after its arrival at the telescope, and they are briefly described in the following sections.

Figure 3: the shipping phase

3.1 Pre-commissioning run 1: instrument reinstallation and testing in the LBT laboratory area

It has been carried out just after the instrument arrival, lasting about 3 weeks from about June 20 to about July 10 2022, and the main purpose of this run has been the instrument re-installation and test in the LBT high-bay laboratory, where a clean tent allowed to perform the activities in a clean environment. The main activities carried on have been:

- Box opening and instrument/equipment inspection
- Installation of SHARK-NIR bench in the clean tent, on a stand positioned close to an optical bench, hosting a testing setup prepared on purpose
- Installation of the scientific camera to the SHARK-NIR bench
- Installation of the electronic and of the instrument workstations
- Extensive test of the instrument software
- Functional test of the instrument and of the scientific camera
- Accurate cleaning of the instrument opto-mechanical components
- Accurate shimming of the scientific camera to position it confocal with the coronagraphic focal plane
- Optical test to verify the coronagraphic masks centering accuracy

- NCPA measurement and correction using the internal DM to optimize the instrument optical quality (less than 20nm rms of overall wavefront residual have been achieved)
- Box storage

All the activities performed has been successful and the instrument has been left parked in the electronic lab fully operative and connected to the network, in a way to perform remote testing from Europe.

Figure 4: some photos of the activities performed during the pre-commissioning run 1

3.2 Pre-commissioning run 2: instrument installation and alignment to the LBT

This run has been carried out in September/October 2022, it lasted 3 weeks, and it was aimed to install SHARK-NIR to the telescope and to properly align it, using LBT light sources allowing to materialize the internal focal and pupil plane. During this run, we mostly used the ARGOS source light, which is delivering a good optical quality PSF but can be used just at Zenith.

The main activities performed during this run have been:

- Preparation of all the handling tools necessary for the installation at the telescope
- Cable chain installation on the instrument
- Cables routing inside the cable chain and extensive functional test
- Installation of the instrument at the telescope
- Installation of the deployable arm
- Installation of the electronics at the telescope and cable routing and connection
- Functional test of all the instrument functionalities
- Instrument alignment to the LBT and co-centering with the LBTI infrared camera, LMIRCam
- NCPA measurement and correction using the internal DM to optimize the instrument optical quality (less than 20nm rms of overall wavefront residual have been achieved)

- Handling tools storage

Also in this case, all the activities foreseen have been successfully performed, and the instrument has been left installed, aligned and fully connected to the LBT network for remote testing activities.

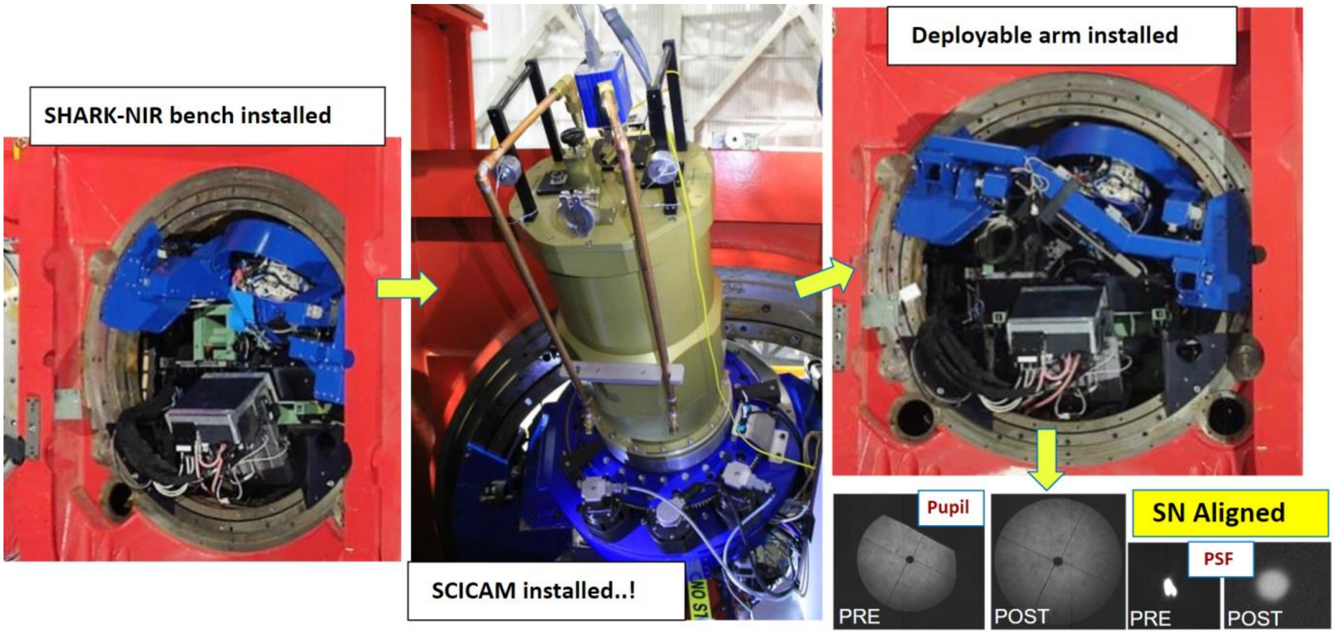

Figure 5: some highlights of the activities performed during pre-commissioning run 3

3.3 Pre-commissioning run 3: daytime testing

This run has been carried out in November 2022, it lasted 2 weeks, and the main purpose was to perform day-time test of SHARK-NIR using the light sources provided by the telescope and introducing, whenever needed, the turbulence through the adaptive secondary mirror (0.5" and 1" seeing could be simulated).

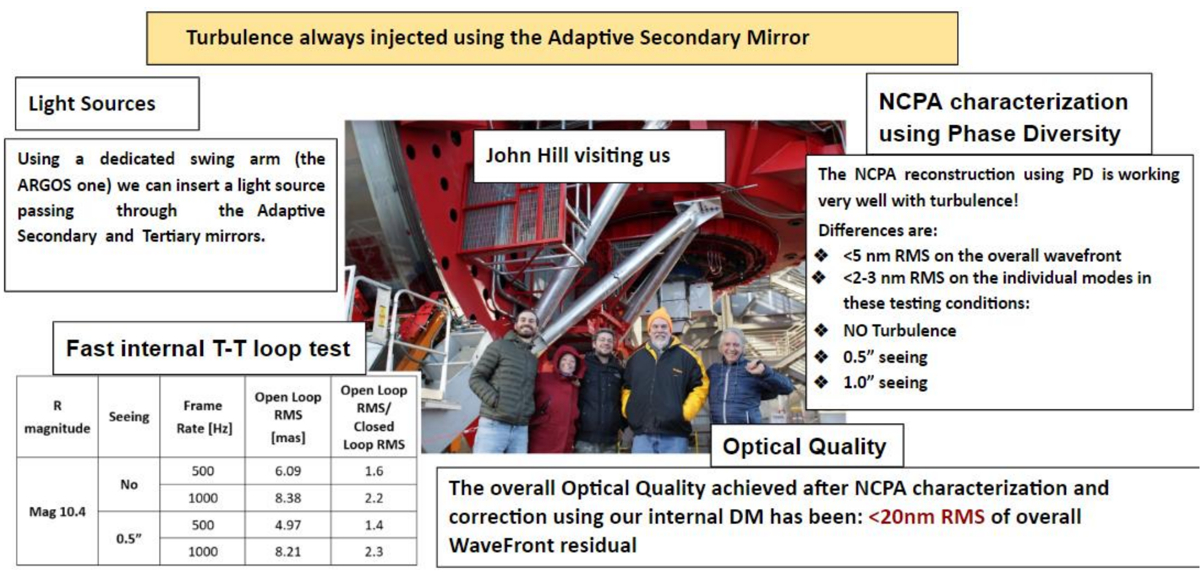

Figure 6: highlights of the pre commissioning run 3

The main activities performed have been:

- Fast internal tip-tilt loop test and characterization with and without turbulence, obtaining results pretty much similar to the ones obtained during the characterization in Europe
- NCPA characterization using the Phase Diversity with and without turbulence, at different bearing angles; the PD show to be very accurate in characterizing the NCPA also with the simulated turbulence of 0.5” and 1”, showing maximum differences <5nm on the overall wavefront in the various testing conditions (<2-3 nm on the individual modes reconstructed)
- Extensive test of the instrument control SW

The best achieved optical quality have been less than 20nm rms of overall wavefront residual.

4. COMMISSIONING ACTIVITIES

In 2023 the instrument commissioning has been carried on, through 3 commissioning runs performed between January and May, for a total of 14 nights. The instrument first light happened on January 6, and in the following sections we report the main activities which have been carried on during the commissioning. A fourth commissioning run is foreseen at the beginning of October 2023.

4.1 Commissioning Run 1

This run has been carried out in January 2023 and it lasted 6 nights. The main purpose was to commission the direct imaging mode and to debug/test the main instrument and software functionalities. The main activities performed have been:

- Monocular and Binocular telescope presets
- Phase Diversity test
- ADC optimization and test
- Field derotation test
- SCICAM test
- Internal Tip-Tilt loop test
- Sky Background test
- Throughput assessment
- Plate scale assessment
- Templates needed for Gaussian Lyot mask centering debugging and optimization
- Contrast with Gaussian Lyot mask test

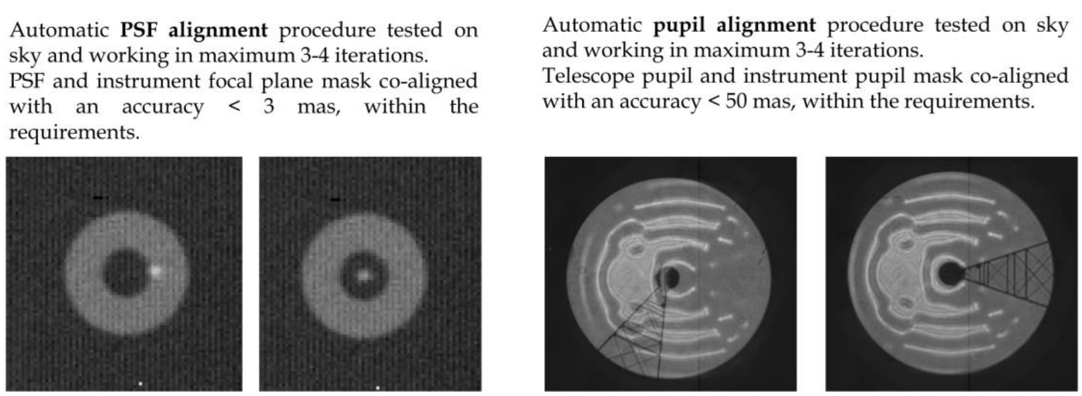

Figure 7: test of the templates to center the focal and pupil plane masks

We had 70% of open dome, with just one night of decent seeing of about 1”. Nevertheless, the run has been quite successful, and we could perform most of the foreseen activities.

4.2 Commissioning Run 2

This run has happened form March 6 to 8 (3 nights), and had the purpose to commission the coronagraphic observing mode. Here we highlight the main activities carried on:

- SCICAM read-out modes test
- Low frequency Tip-Tilt correction test
- Refinement of the field derotation law
- Further ADC optimization and test
- ASM Fourier mode implementation test
- Contrast with Shaped Pupil simmetric mask test
- Test with the Gaussian Lyot mask

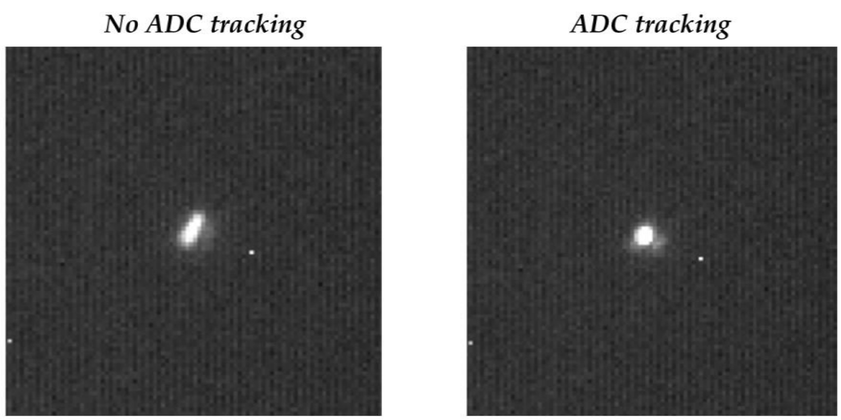

Figure 8: the ADC tracking test; after some refinement, we could achieve a PSF residual ellipticity <1.1 at an elevation of 45° and considering the full wavelength range (from Y to H band) of SHARK-NIR

We had just 40% of open dome, with just few hours with about 1” seeing, and thus we could test just 2 coronagraphic masks for a very limited amount of time: the Gaussian Lyot one and the symmetric Shaped Pupil one. Both of them have been showing a behavior pretty much in agreement with the simulated performance in similar observing conditions.

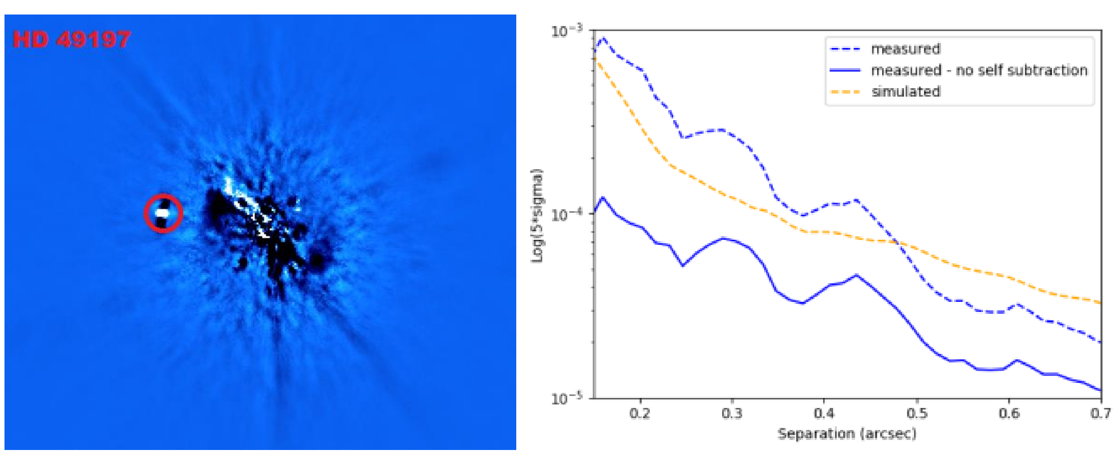

Figure 9: the coronagraphic test with the Gaussian Lyot mask on HD 49197

In Figure 8 we report the final result concerning the ADC fine tuning and test, while in Figure 9 we show the performance achieved with the Gaussian Lyot mask on HD 49197 (M_V: 7.8 M_H: 6.1), which is quite a famous and simple target, with a brown dwarf companion about 8 magnitudes fainter than the main star. The result is obtained using the SHARK-NIR data reduction pipeline, applying the ADI technique, combining 73 images with an exposure time of 29.95s each, for a total exposure time of 36.4 minutes. The seeing was ranging from 1” to 1.2”. The total rotation of the FOV during the observation was 11.6 degrees. As you can see, although the seeing was far from being optimal, and the rotation during the scientific exposure very small wrt what is normally required by the ADI technique, on the right image of Figure 9 we show that the measured contrast if not far from the simulated one in similar conditions.

4.3 Commissioning Run 3

This run has happened form May 2 to 5 (4 nights), and had the purpose to check the coronagraphic observing mode not previously tested, such as the asymmetric Shaped Pupil, the Four Quadrant Phase Mask (FQPM). Additionally, some residual ADC test and the Dual Band Imaging commissioning was foreseen. The weather hasn’t been fantastic, we had 45% of open dome but mostly with strong wind and bad seeing.

Anyhow, this is what we have achieved during such run:

- Astrometric calibration and distortion map determination acquiring data on a globular cluster (M13)
- Plate scale measurement
- Performed observations with the symmetric Shaped Pupil mask
- Performed observations with one of the 2 asimmetric Shaped Pupil mask (SP2a)
- Performed a test on the application of a Fourier mode on the Adaptive Secondary mirror

In Figure 10 here below you can see a summary of the test performed applying the Fourier mode to the Adaptive Secondary Mirror, with the purpose to create some spots to be used as reference of the star position in the field.

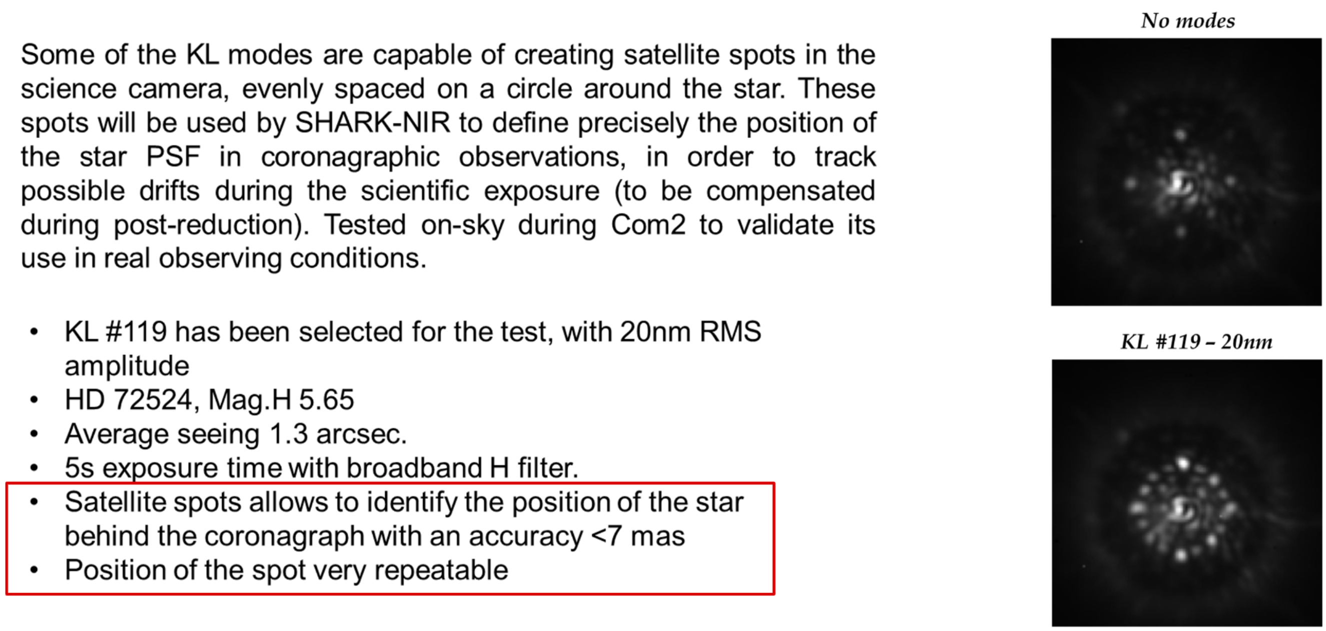

Figure 10: the Fourier mode test result

The mode has been applied several times to check the repeatability of the generated spots and the position of the star wrt the generated spot has also been measured, and both test gave a result of the order of few mas of accuracy.

Dual band imaging mode and FQPM could not be tested due to the lack of time.

5. CONCLUSIONS

As already mentioned, the last commissioning run will be performed in October 2023 and it will last 3 nights. The purpose of the 4th commissioning run will be the commissioning of the spectroscopic mode and of the dual band imaging mode.

Even though we lost almost 50% of the time due to bad weather, we could carry on most of the activities foreseen for the commissioning phase. The main functionalities of the instrument have been tested, the communication with the Telescope Control System and with the Adaptive Optics system is working properly and most of the observing modes have been tested and have been proven to work. Extensive activities of software debugging and procedures optimization has been performed, and all the templates for the various pupil and focal plane masks orientation and centering have been fine-tuned and are working within expectation, at least for the Gaussian and for the symmetric Shape Pupil techniques. Although we had really few hours of decent seeing, ranging from 0.9” to 1.2”, the very preliminary coronagraphic results that we obtained seem to be in good agreement with simulations performed in similar observing conditions, both in term of discovery area and in term of contrast.

The science verification period will start just after the 4th commissioning run, with 6 nights assigned at the end of October 2023, where binocular observations will be carried on with LBTI/LMIRCam and/or LBTI/ALES and we have good indications that the instrument is ready for science. Before the end of the year, there will probably be the possibility to make binocular observations also with SHARK-VIS, which is also undergoing the commissioning phase in fall 2023, and will be ready soon to go for science too.

6. ACKNOWLEDGEMENTS

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Eventually, we emphasize that observations have benefited from the use of ALTA Center (alta.arcetri.inaf.it) forecasts performed with the Astro-Meso-Nh model. Initialization data of the ALTA automatic forecast system come from the General Circulation Model (HRES) of the European Centre for Medium Range Weather Forecasts.

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