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SHARK-NIR, the coronagraphic camera for LBT in the AIV phase at INAF-Padova

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ABSTRACT

Exo-Planets search and characterization has been the science case driving the SHARK-NIR design, which is one of the two coronagraphic instruments proposed for the Large Binocular Telescope. In fact, together with SHARK-VIS (working in the visible domain), it will offer the possibility to do binocular observations combining direct imaging, coronagraphic imaging and coronagraphic low resolution spectroscopy in a wide wavelength domain, going from 0.5μm to 1.7μm. Additionally, the contemporary usage of LMIRCam, the coronagraphic LBTI NIR camera, working from K to L band, will extend even more the covered wavelength range. The instrument has been designed with two intermediate pupil planes and three focal planes, in order to give the possibility to implement a certain number of coronagraphic techniques, with the purpose to select a few of them matching as much as possible the requirements of the different science cases in terms of contrast at various distances from the star and in term of required field of view.

SHARK-NIR has been approved by the LBT board in June 2017, and the procurement phase started just after. We report here about the project status, which is currently at the beginning of the AIV phase at INAF-Padova, and should last about one year.

Even if exo-planets is the main science case, the SOUL upgrade of the LBT AO will increase the instrument performance in the faint end regime, allowing to do galactic (jets and disks) and extra-galactic (AGN and QSO) science on a relatively wide sample of targets, normally not reachable in other similar facilities.

Keywords: Coronagraphy, eXtreme Adaptive Optics, Large Binocular Telescope

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1. INTRODUCTION

SHARK (System for coronagraphy with High order Adaptive optics from R to K band) [1] is a second generation instrument for the LBT[2]. It is composed by two channels, covering different and partially overlapping wavelength ranges: SHARK-VIS[3] will work from 0.5µm to 1µm, while SHARK-NIR[4] is dedicated to near infrared bands, Y, J and H, operating from 0.96µm to 1.7µm. Both channels have been approved for construction to be later installed one for each LBT arm. SHARK will exploit, in its binocular fashion, unique challenging science ranging from exoplanet search and characterization to star forming regions with simultaneous spectral coverage from R to H band, taking advantage of the excellent performances of the LBT AO[5] systems, based on the Pyramid Wave Front Sensor[6] (PWFS) and on the Adaptive Secondary Mirrors[7].

The spectral coverage will become even larger when used in combination with LMIRcam of LBTI[8], which will be upgraded soon to work in K band, and will thus offer coronagraphic direct imaging from K to M band. In this scenario, LBT will have the possibility to make contemporary coronagraphic observations with three instruments in a wavelength range going from V to M band.

It has also to be underlined that LBT is improving the AO systems with the SOUL upgrade (see [10]), which will consist of:

- upgrading the ASM speed to 2KHz and improving the controller in order to increase the number of possible corrected modes from the current 400 to about 600
- using a new detector with nearly 0 Read out Noise (RoN), the OCAM 2 camera from first light

SOUL should thus be able to improve the performance, above all in the faint end regime, by gaining between 1 and 2 magnitude, increasing a lot the sample of possible exo-planetary systems to be exploited, and allowing to make also extra-galactic science by characterizing for example the morphology of faint targets such as AGN and QUASARS.

This paper describes the SHARK-NIR instrument, which has been approved for construction in July 2017, with a final design different from the one proposed at the Conceptual Design Review, modified to perform both fast internal tip-tilt correction to minimize the residual jitter and to locally correct Non Common Path Aberrations (NCPA), to let the pyramid work in optimal conditions.

2. SHARK-NIR FINAL DESIGN

The SHARK-NIR project underwent the FDR in January 19 2017. The result has been very positive, with the final recommendation of the FDR panel to proceed as soon as possible to the fabrication stage. Nevertheless, the panel also identified a few reason of concerns. The main technical concerns are summarized in the following:

- The panel indicates to evaluate the possibility to have a local fast Tip-Tilt (T-T) correction, that will require also a dedicated fast T-T sensor, to possibly address jitter larger than the one considered in the FDR error budget; this would also allow to improve the coronagraphic performance, allowing to reach smaller inner working angles
- The panel asked to investigate what the effect on the AO performance may be when removing the NCPA with the Adaptive Secondary Mirror (ASM); in fact, if the NCPA to be removed are not negligible, their removal with the ASM will degrade the PSF quality on the pyramid, fact that may impact the AO performance

The panel was strongly suggesting to address this issues in a delta-study, that the SHARK-NIR team performed immediately after the review and that lasted about three months.

The result of this investigation has been that both a larger residual jitter and the NCPA can affect significantly the system performance, with a performance loss in term of contrast that can approach in both cases half a magnitude.

We thus proposed a design considering to have a local DM introduced to compensate for the NCPA. The DM substitutes the slow frequency TT corrector foreseen for the FDR design, and it is placed in the intermediate pupil plane position. The selected DM is the ALPAO DM 97-15, characterized by 97 magnetic actuators and a pupil size of 13.5mm, well suited to correct the intermediate SHARK-NIR re-imaged pupil and to compensate for low order NCPA.

We also proposed to have an internal fast TT loop to minimize the residual jitter. The TT corrector is the same DM used to compensate for the NCPA, which can allow a 1.65KHz bandwidth with a TT stroke of +/- 30µm, corresponding to a tilting angle of the DM of +/- 7.5 arcminutes. Of course, a fast and sensitive camera (in Y, J and H band) is required to accomplish the TT evaluation, necessary to drive the ALPAO DM 97-15. We made an evaluation of commercial quad-cell InGaAs detectors but their very poor sensitivity and high noise would have limit the TT sensing only to very bright stars (Mv 2-3). A suitable camera to be used for this purpose is the First Light C RED-2, which is equipped with a 640 x 512 InGaAs sensor operating in the SWIR (Short Wave Infrared), from 0.9 to 1.7 µm, with a very good Quantum Efficiency over 70% in the whole band. This camera would allow to perform TT sensing down to magnitude 12-13, keeping the centroid error below 3 mas rms, still taking only 5% of light off the scientific camera through a beam splitter (no changes with respect to the FDR design).

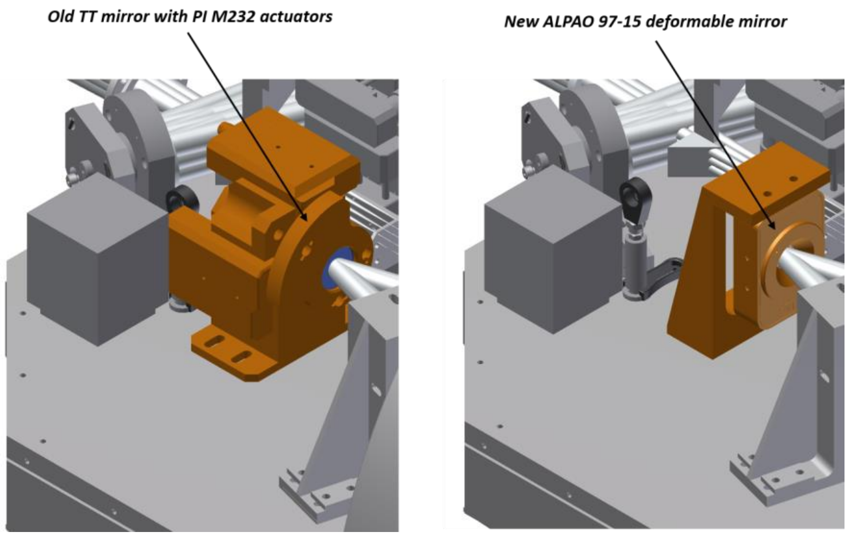

Figure 1: on the left side, the FDR low frequency TT corrector; on the right side, the DM 97-15

Of course, such a fast internal loop needs a Wave Front Computer (WFC) performing the real time computation, the NCPA subtraction and controlling the fast TT loop, that will be provided by microgate, and which is based on a BCU board such as the ones used to control all the AO loops at LBT. The WFC will have the possibility also to store the NCPA map to be applied to the DM 97-15 for their removal.

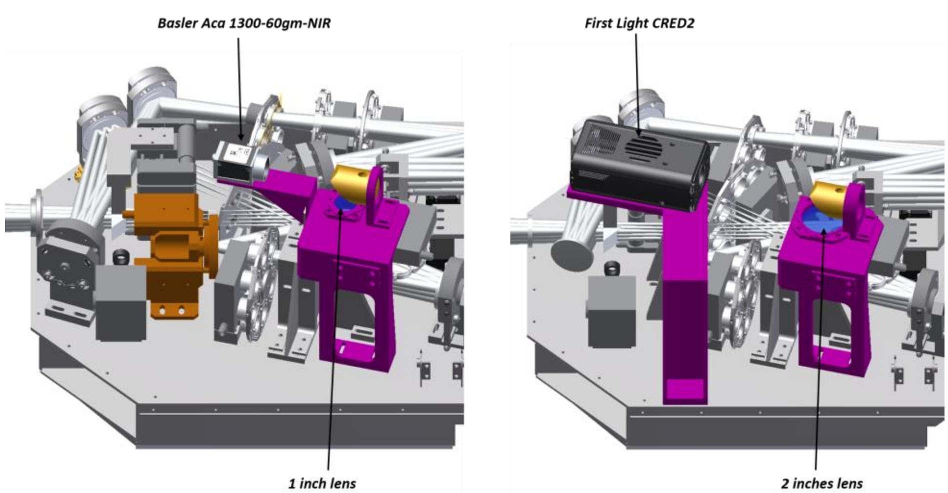

Figure 2: on the left the TT Sensor area (and its supporting structure in violet color) with the Basler Ace camera presented at the FDR; on the right, the same area with the fast TT camera CRED-2, supported with a structure separated from the one holding the last lens, which has a focal length 50mm longer than the FDR one.

As it is shown in Figure 1 and in Figure 2, the impact on the opto-mechanical design of the instrument has been minimal, and the both the panel and the board approved the modifications, giving the final green light for construction in July 2017.

3. THE SCIENTIFIC CASE

The direct detection of extra solar planets is one of the most exciting goals, as already mentioned in the previous sections. Indeed, the resolution achievable with a 10-m class telescope allows to access, in the NIR domain, gaseous giant planets of Jupiter size or bigger, and still it is a very challenging task to be achieved, due to the very high contrast and vicinity to the hosting star required. There are several scientific goals to be possibly exploited in the exo-planet science case, ranging from the direct detection of unknown giant planets, to the follow up of known planets (through spectroscopic and photometric characterization), which requires of course the implementation of a spectroscopic mode with modest spectral resolution, which is currently foreseen in SHARK-NIR through a long slit positioned into the intermediate focal plane.

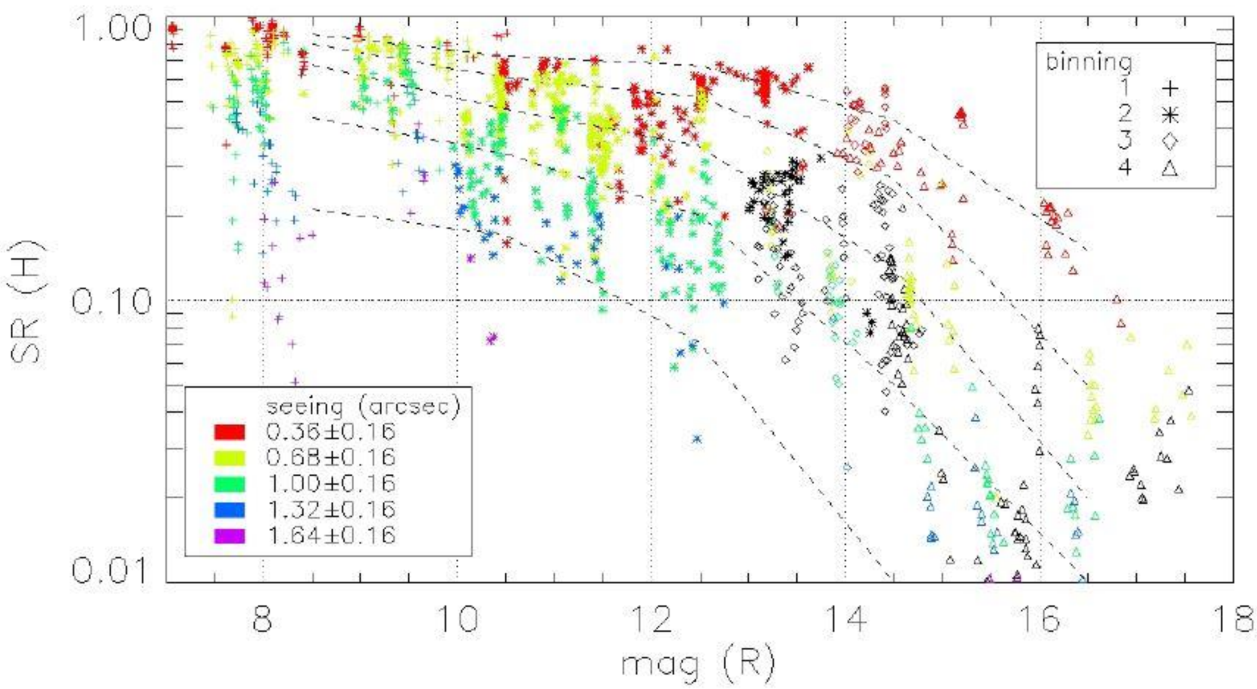

Figure 3: a summary of the FLAO performance obtained in H band with different observing conditions

The science to be exploited with SHARK-NIR is definitely not only limited to the exo-planet case. The study of proto-planetary disks is fundamental to comprehend the formation of our own solar system as well as of extra-solar planetary systems. To understand how matter aggregates to form the building blocks of planetary bodies, there is the need to investigate not only the evolution of the disk itself, but also the role of jets in shaping its structure. This requires observing the system at high angular resolution as close as possible to the parent star, occulting its light to enhance the area where the interplay between the accretion and ejection of matter dominates the dynamics.

Other very interesting and challenging topics can be found in the extragalactic science, where the capabilities of SHARK-NIR in terms of spatial resolution and contrast enhancement may be applied to study the AGN-host relations as well as Dumped Ly-α systems (DLAs), to constrain the Black Hole feeding mechanism and to trace, in bright quasars, molecular outflows powerful enough to clean the inner kilo-parsec and quench the star formation.

There is anyhow an important feature of the LBT AO which, exploited in the proper way, may give to SHARK-NIR the possibility to explore unique coronagraphic science. The Pyramid WFS has a demonstrated gain in sensitivity compared to other WFS commonly used, such as SH (see [9] [11], [12], [13], [14] and [15]). This fact gives to the LBT AO systems the capability of achieving high Strehl Ratio (of the order of 70%) at moderately faint magnitude (R~12 or even occasionally fainter, depending on the observing conditions), as it is shown in the impressive collection of FLAO results reported in Figure 3.

This excellent performance will be further enhanced with the implementation of the AO upgrade SOUL, as it is shown in Figure 4 where, depending on the CCD choice, the capability of achieving Strehl as high as 70% can be pushed to star as faint as magnitude 13.5, and it has to be emphasized that these curves have been computed not in excellent seeing conditions (0.8”).

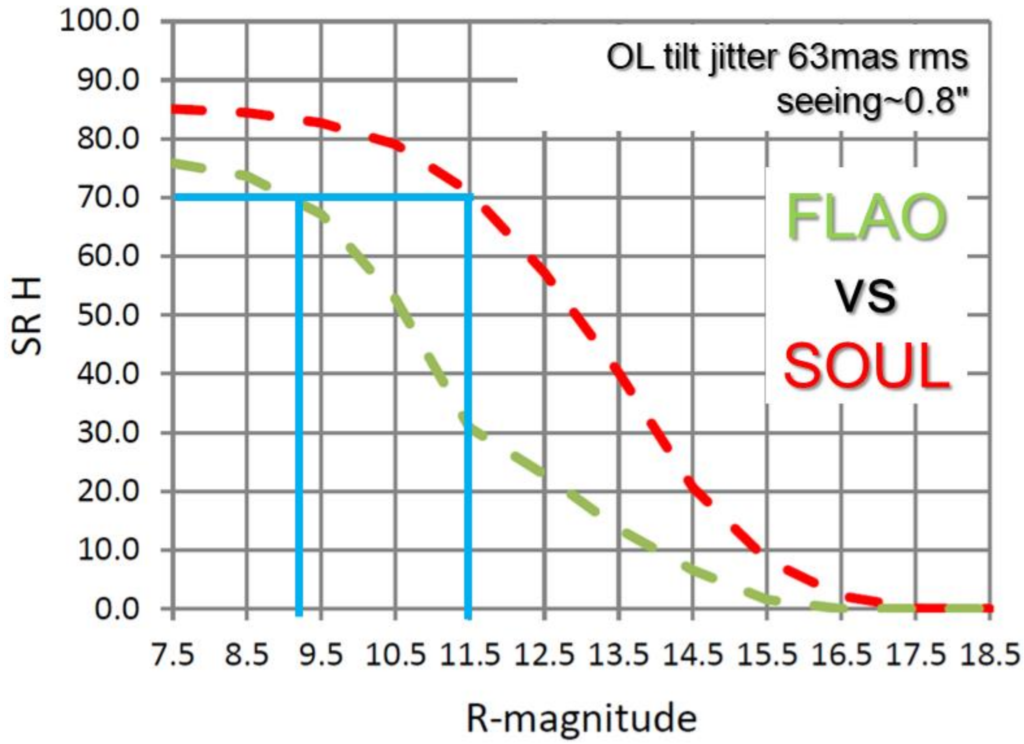

Figure 4: the SOUL improvement in the LBT AO performance (the current is in green line), computed with a seeing of 0.8”. The SOUL camera is the OCAM2K camera from First Light Imaging.

This performance will open the field of high-contrast AO coronagraphic imaging to stars much fainter than feasible using other coronagraphic instruments, allowing deep search for planets around targets like, e.g., M dwarfs in nearby young associations and solar type stars in nearby star-forming regions (Taurus-Auriga at 140 pc). Also in the extragalactic field, the sample of AGN and, above all, of Quasars to be explored will go from a few tenths to a few hundreds, changing the perspective of the science to be achieved.

This is definitely the characteristic which may give to SHARK-NIR unique opportunities in the coronagraphic instrument scenario.

4. SHARK-NIR INSTRUMENT DESCRIPTION

The basic idea of SHARK-NIR is a camera for direct imaging coronagraphy and spectroscopy, using the corrected wavefront provided by the LBT ASM, operated through one the existing AO WFS.

A very suitable position for the installation of SHARK-NIR is at the entrance of LBTI (see Figure 5), very close to the WFS that is dedicated to LBTI itself, which should be used to sense and drive the ASM, providing the corrected wavefront to SHARK-NIR. A dichroics, deployable in front of the entrance window of LBTI, shall pick-up and re-direct the wavelength range between 0.96 and 1.7 microns toward SHARK-NIR, letting the VIS light to go to the WFS.

Being SHARK-NIR also a coronagraphic instrument, the camera has to be designed to accomplish an extreme performance, ideally not to decrease the correction provided by the AO system. In fact, all the coronagraphic techniques that may be implemented need a SR as high as possible to provide very good contrast. This require optics machined to a state of the art technology and polished to nanometric level of roughness, properly aligned and installed on very robust mounts. The whole instrument mechanics has to be very stiff and designed to minimize the effect of the flexures.

Additionally, to maintain the performance as good as possible at every observing altitude, it is necessary to implement an ADC to compensate for the atmospheric dispersion.

Some of the foreseen science cases need to perform the field de-rotation, to accomplish which the whole instrument has to be mounted on a mechanical bearing.

A NIR camera, based on an HAWAII II detector, cooled at about 80°K to minimize the thermal background, will provide a FoV of the order of 15”x15”, with a plate scale foreseeing two pixels on the diffraction limit PSF at 0.96µm.

A few subsystems have been introduced in the instrument design with the purpose of optimizing the instrument performance, as already mentioned in Sec. 2.

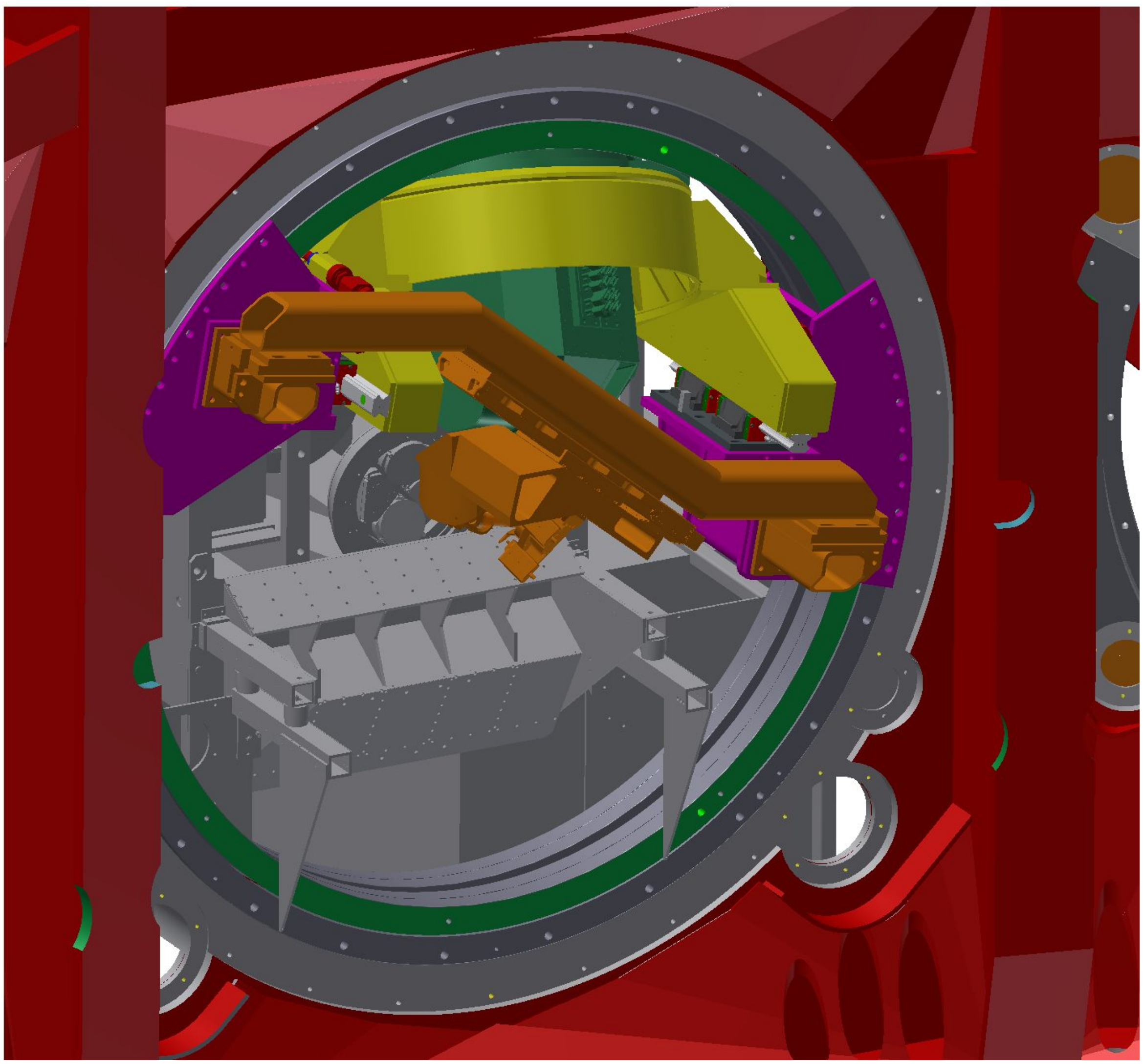

Figure 5: the SHARK-NIR instrument positioned at the entrance of LBTI and connected to the telescope structure

For the NCPA minimization, a local DM has been introduced into the first pupil plane, allowing a local removal of the aberrations. The same DM, used in T-T fashion, may be used to correct undesired PSF movements during a scientific exposure. The latter correction requires a dedicated T-T sensor, which has been placed after the first pupil plane, into the collimated beam (a beam splitter will pick-up 5% of the light to be sent to the sensor).

Three intermediate coronagraphis planes (two pupil planes and one focal plane) are available in the current design, permitting to consider coronagraphic techniques which require apodizing masks, such as the Apodized Pupil Lyot Coronagraph (APLC), which has been implemented both in SPHERE[16] , GPI[17] and SCExAO[18]. Between the DM and the beam splitter feeding the T-T sensor, a filter wheel positioned at 50mm from the pupil plane carries the apodizing masks. These kinds of masks are normally placed exactly into the pupil plane, which is occupied by the DM in our design. We have carefully evaluated the impact of having the masks slightly displaced with respect to the pupil plane, and it turned out that the effect is basically negligible if the masks are designed to take this fact into account.

As we mentioned at the beginning of this section, SHARK-NIR has essentially three observing modes, described in the following sections.

4.1 Direct Imaging Mode

In this observing mode, SHARK will provide an unobstructed FoV of 18"x18", with a correction which is nominally nearly perfect over the full 18" diameter (SR>99.5% at 1μm). Even considering very relaxed tolerances for the alignment of the optical elements (±200μm for the off-axis parabola decenter, ±3' for their tilt), the final performance is very good (SR>97.5% at 1μm over the full 18" diameter).

Even with the ADC inserted (which is deployable, to have the best possible optical quality when observing at small zenithal angles), the optical performance remains very good, ensuring for example an on-axis SR >98%, while at the detector corner (at the edge of the field diagonal) it decreases to ~94%, for a zenithal distance of 50°.

The total throughput of the instrument without the ADC into the field is about 55%, while inserting the ADC it is about 50%.

Field rotation can be compensated through the mechanical bearing, which will accomplish a tracking precision of about (λ/D)/20 at 1μm and perform a maximum rotation of 190°.

The scientific filters available for the direct imaging mode are 14, distributed in the two filter wheels positioned in the collimated beam after the 2nd pupil plane.

4.2 Coronagraphic Mode

The current design of SHARK-NIR foresees two intermediate pupil and one focal plane, with the purpose of implementing a large variety of coronagraphic techniques, including the ones that require the pupil apodization, such as the APLC or the Shaped Pupil (SP). We have carefully evaluated which techniques may be worth of being implemented, considering both the characteristics of the most diffused coronagraph and considering the LBT AO situation and the results of extensive simulations, and we have selected 4 techniques, which are:

- 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 Phase Mask (FQPM), which requires a four quadrant mask into the 1st focal plane and a pupil stop into the 2nd pupil plane
- Vortex (still under evaluation), which require a Vortex mask into the 1st focal plane and a pupil stop into the 2nd pupil plane

All these techniques have the purpose to dim (ideally cancel) the light of the central star, in a way to enhance the contrast in the vicinity of the star itself, allowing to detect much fainter companions (exo-planets case for example) or to explore the morphology of the object under study (Jets/Disks case and AGN/QSO case). They are characterized by different operating distances from the central star (IWA), and by different contrast that can be reached at a certain distance, by different throughput and by different FoVs.

Ideally, we would like to implement a few techniques in a way to fulfill as much as possible the different needs of the different science cases (in term of contrast and IWA), and to provide a useful tool to select the proper technique for each kind of scientific target.

This observing mode will provide the possibility to observe both using the field derotation (through a bearing) and to observe in ADI mode. The ADI mode foresee to let the field rotate, during the observation, to distinguish the planet (which will rotate with the field) with respect to the Quasi Static Speckles, supposing that the latter will move of a very small amount during the observing time. To exploit the science cases which need the field derotation, it will be possible to use only center-symmetric masks (such as the ones of classical Lyot and Gaussian Lyot), since otherwise the apodizing masks (which are normally design to take into account also the secondary spiders) would also have to be rotated, adding a considerable complexity to the instrument.

The coronagraphic FoV, as already mentioned, will depend on the coronagraphic techniques selected, and will range from about 12λ/D for the Shaped Pupil, to the full camera FoV of 18”x18” for the Lyot and FQPM cases. The IWA is also depending on the technique, and will go from 1-2λ/D (FQPM and SP) to 4-5 λ/D (Gaussian Lyot).

The total throughput of the instrument depends upon the coronagraphic technique and the presence of the ADC, and is of the order of 25% with the standard Lyot technique, decreasing to ~10% with the SP coronagraph.

The optical quality of the FoV is greater than 99% and also in this case, the ADC may be inserted into the beam to compensate for the atmospheric dispersion.

In this observing mode, 14 scientific filters can be selected for the observations.

4.3 Spectroscopic Mode

A long-slit spectroscopic (LSS) coronagraphic mode will be implemented in SHARK, with two different resolutions: a low-resolution mode (R~ 100), in order to target faint targets, and a medium-resolution mode (R~700) to get spectral information of the faint objects around the bright targets.

In fact, in the focal plane wheel (the ones carrying the occulting masks defining the coronagraphic IWA), a few positions will be dedicated to long slits, while one mask providing the low spectral resolution of R~ 100 (obtained through a dispersing prism), and another mask providing the medium spectral resolution of R~ 700 (obtained through a GRISM) will be accommodated in the pupil plane wheel. The implementation of two orthogonal focal plane slits is recommended to properly orient the mask on the object of interest (a known planet, for example), considering that we have a max bearing rotation of 185° and to ensure a minimum residual derotation of 90° for the observation without changing to the perpendicular slit.

The total throughput with the Prism is of the order of 25%, while with the GRISM is about 15%.

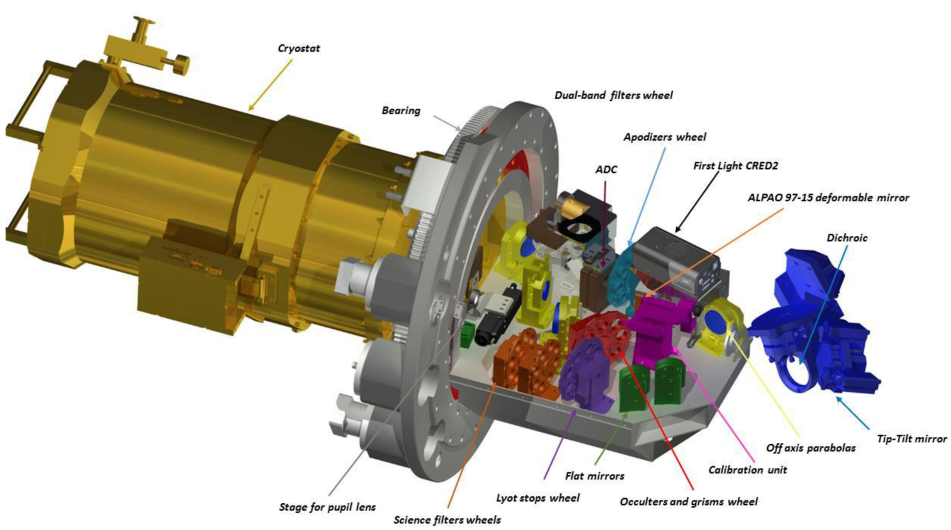

Figure 6: a view of the opto-mechanics of the SHARK-NIR optical bench and NIR camera

The camera (shown in the 3-D view of Figure 6, and provided by Steward Observatory) is Cryogenic, and will be using an HAWAII II detector. The LN2 tank shall ensure a hold time of about 28 hours.

5. INSTRUMENT STATUS

SHARK-NIR is in the Assembly, Integration and Verification (AIV) phase. All the main optical components have been received and individually tested, and we are starting the integration of the various sub-systems onto the optical bench.

Concerning the test at component and sub-systems level, the current situation is:

- the motor control electronics (delivered by MPIA) has been extensively tested together with the motorized axis and the Instrument Control Software, and the acceleration, deceleration and speed parameters of each stage are being optimized these days
- each individual motor has been tested to check the main characteristics, such as unidirectional and bidirectional repeatability and positioning repeatability on the limit switches
- the mounts of the optics have been functionally tested to check the specified adjusting ranges
- each delivered optical component has been interferometrically tested, both individually and after being integrated in their mounts, to discover possible stresses caused the mounts themselves; for all the optical components tested till now, the optical quality is in specification and remains the same after installing them in their mounts
- functional test have been performed on the C-RED 2 camera and on the ALPAO DM 97-15, and an optical bench to test the fast tip-tilt loop and the NCPA proper correction has been assembled, integrated, tested and shipped to Microgate for the final integration with the RTC and to perform extensive test (see Figure 7).

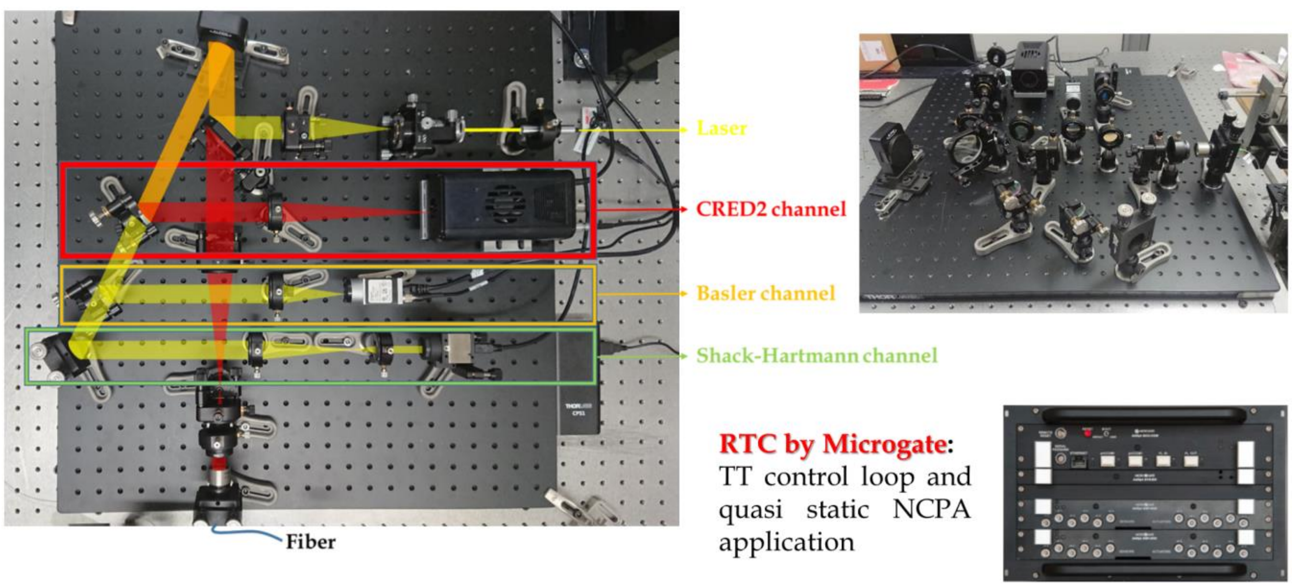

Figure 7: the optical bench delivered to Microgate for the test of the fast internal TT loop and of the correct application of the NCPA: a channel with a commercial camera can detect the quality of the TT correction, while a channel with a commercial Shack-Hartmann can check if the shape of the DM is kept stable during the TT loop and to which level of accuracy is maintained.

As it is shown in Figure 8, also the assembly of the main opto-mechanical components on the SHARK-NIR bench has started, and the alignment of the optical bench is starting these days.

Figure 8: the SHARK-NIR bench mounted on the bearing and with the a few mounts installed

6. CONCLUSIONS

The new design of the instrument, which is now considering to have internal NCPA compensation and a fast tip-tilt loop for the minimization of the residual Jitter, should enhance the coronagraphic performance of SHARK-NIR, also considering the presence, in the current instrument configuration, of techniques (such as the FQPM) which requires high accuracy in the mask centering and very good stability during the exposure. The instrument capability to reach its science goals is for sure improved with the proposed instrument upgrades, since the pyramid wavefront sensor will operate always at its maximum sensitivity and the residual jitter will be reduced down to very small values.

The synergy between SHARK-NIR, SHARK-VIS channel and LMIRcam will allow LBT to make contemporary binocular coronagraphic observations in three different wavelengths, giving unique opportunities to exploit at best the very challenging exo-planet case.

The high sensitivity of the AO system in the faint end regime, which will be further increased by SOUL, will give to LBT a huge advantage with respect to any other similar system operating nowadays, opening to science never explored before in coronagraphic direct imaging. In fact, this magnitude gain will increase a lot the sample of possible exo-planetary systems to be exploited, and will allow to make also extra-galactic science by characterizing for example the morphology of faint targets such as AGN and QUASARS.

The instrument is now in the AIV phase, which should be concluded in July 2019, in a way that SHARK-NIR will be installed at LBT in fall 2019, ready to be on operating on sky in early 2020.

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