The way to XAO: a system to correct NCP and TT aberrations tested in lab for SHARK-NIR

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ABSTRACT

SHARK-NIR is the coronagraphic camera for direct imaging and spectroscopy designed for LBT, currently in its AIV phase. Exo-planets are the main scientific targets of the instrument as well as galactic jets and disks. Exploiting SOUL, the upgraded LBT AO system, will push the sensitivity in the faint end regime, allowing observations of extragalactic AGNs and QSOs.
LTB AO system feeds SHARK-NIR with an already corrected wavefront, which enters the instrument channel when reflected by a dichroic: the transmitted light goes to the wavefront sensor. The AO correction residuals are of the order of 50 *nm*, moreover, there is a contribution (~100 *nm*) called Non Common Path Aberrations (NCPA), mainly due to manufacturing and alignment issues, and to flexures and temperature variations affecting the optical elements, from the dichroic along the instrument.
To reach very high contrast with direct imaging, the coronagraphs need a smaller wavefront residual (not exceeding 40 *nm*), and a reduced residual jitter: from ~15 *mas* to 3-5 *mas*. The current configuration foresees an internal Deformable Mirror (DM) to compensate both NCPA and residual tip-tilt. The strategy consists in evaluating the NCPA before each observation, adequately adapting the DM, finally closing the tip-tilt loop in real time, maintaining the NCPA shape.
We set up a test-bench to measure the DM performance, applying a realistic NCPA shape and then closing the Tip-Tilt loop using the technical camera foreseen for the instrument. Tip-Tilt corrections are retrieved by centroid analysis comparing the *rms* of a *time history* introduced in the system, i.e. a typical Tip-Tilt residual over a certain amount of time, when closing the loop. We check the DM shape using a Shack-Hartmann sensor. In this paper, we report the results for different simulated magnitudes, *time history* amplitudes and loop frequencies, choosing these parameters according to SHARK-NIR science cases.

Keywords: Astronomical Instrumentation, Coronagraph, Assembly Integration and Test, Adaptive Optics, Non Common Path Aberration, Large Binocular Telescope

1. INTRODUCTION

The Large Binocular Telescope[1] (LBT) is equipped with an adaptive optics system, the First Light Adaptive Optics[2] (FLAO), able to provide a corrected wavefront with Strehl Ratio higher than 0.8 in H band. Moreover, the foreseen upgrade to this system, Single conjugate adaptive Optics Upgrade for LBT [3] (SOUL), besides providing an additional 1-2 magnitude gain in the faint end, will be able to control up to 600 modes (from the current 400) working at 2KHz. The choice for a coronagraph as a second-generation instrument for LBT comes from the opportunity to exploit the already corrected wavefront of the secondary adaptive mirror[4], and goes along with the intrinsic high angular resolution of the telescope. SHARK (System for coronagraphy with High order Adaptive optics from R to K band)-NIR[4][5] is a

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coronagraphic camera for LBT that will be located in the proximity of the Large Binocular Telescope Interferometer[6] (LBTI) and will share with it a dichroic that send the visible light toward the FLAO and the NIR light to SHARK-NIR itself. It is clear that LBT AO system cannot correct the aberrations from the dichroic to the scientific detector of SHARK-NIR. These aberrations, which arise within the instrument, are the Non Common Path Aberration (NCPA). NCPA are expected to have a typical amount of about 110 nm rms of the wavefront[7], but should be reduce to about 40 nm rms in order to reach the required coronagraphic contrast of 10^{-5}-10^{-6} [8][9]. Moreover, the SHARK-NIR coronographs need a residual jitter of the order of 3-5 mas, while the telescope delivers a PSF affected by a Tip-Tilt (TT) distribution that can reach 15 mas amplitude (FLAO commissioning report). The inner AO channel of SHARK-NIR is designed in order to correct the residual telescope TT in closed loop, while correcting an amount of NCPA measured before the observation[11]. The combination of FLAO and internal SHARK-NIR AO will push observations in the eXtreme Adaptive Optics regime.

At the time of writing, SHARK-NIR is in its European Assembly, Integration and Verification phase at the National Institute of Astrophysics (INAF), in the Padova Astronomical Observatory laboratory[12][13][14]. Before the actual integration, a component and sub-system characterization phase is in progress.

In this paper, we report the results of the performance of the SHARK-NIR AO channel (highlighted in Figure 1 on the opto-mechanical design of the instrument) as tested in laboratory on a dedicated test bench, shown in Figure 2 and Figure 3 described in Section 2. In particular, we tested the performance of the system in closing the TT loop, and its capability to maintain the NCPA correction during the TT-loop.

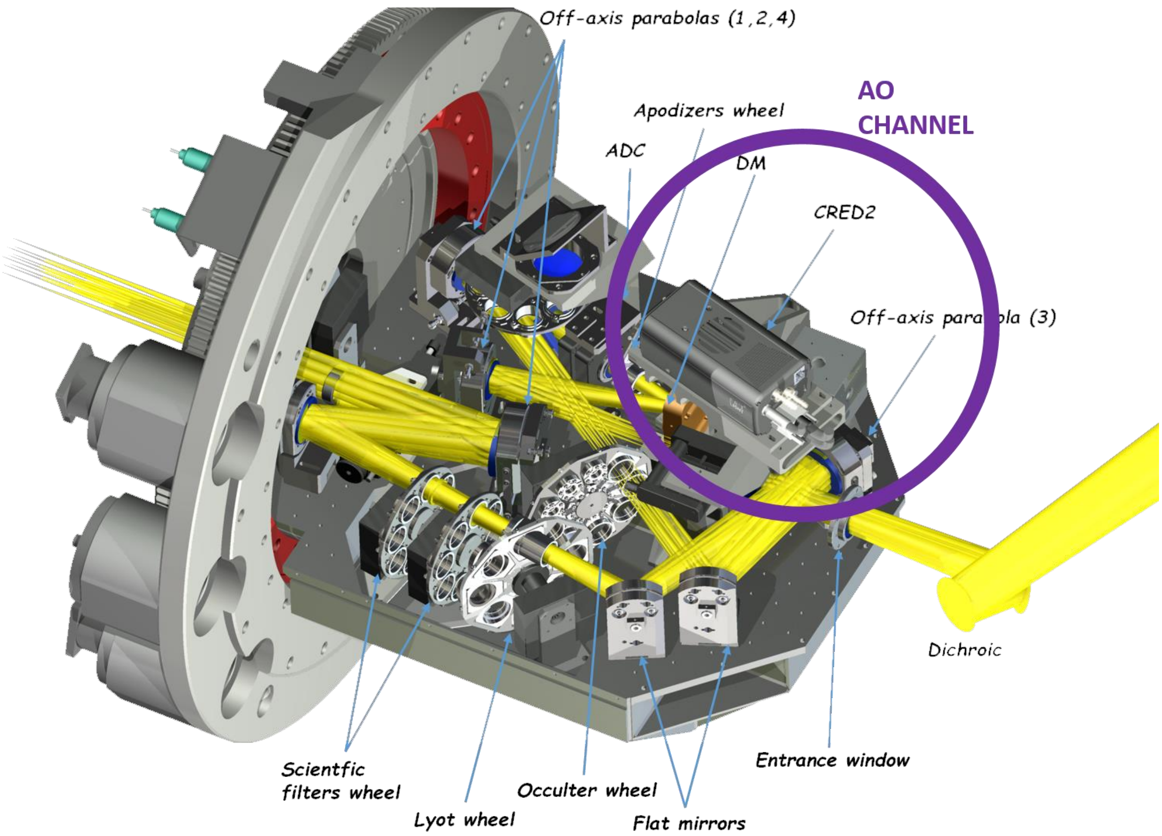

Figure 1. SHARK-NIR mechanical design with the AO channel highlighted.

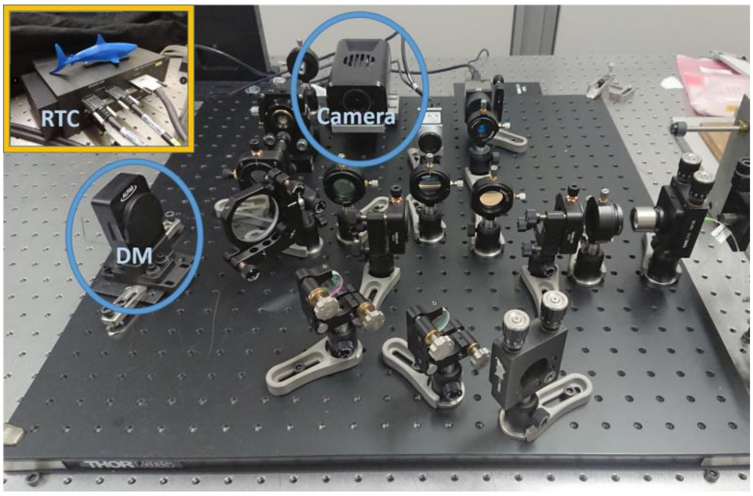

Figure 2. The test bench dedicated to the SHARK-NIR AO channel characterization.

2. TEST BENCH

We build a laboratory test bench in order to characterize the performance of the SHARK-NIR AO system, testing its capability to close a TT loop and to correct a given NCPA shape during the TT-loop itself. Figure 3 is a picture of the bench, where the actual element of SHARK-NIR AO are mounted: an ALPAO 97-15 Deformable mirror, a FirstLight CRED2 camera, and a Microgate Real Time Computer (RTC). As depicted, there are three channels: we use the CRED2 channel for the TT loop; the Shack-Hartmann channel allows evaluating the NCPA correction during the TT-loop; we used the Basler channel to check the stability of the system. The CRED2 channel is illuminated by a fiber fed by a broadband lamp, while the Shack-Hartmann receives the light by a red laser diode. We calibrated the luminosity of the lamp in order to simulate the desired R-magnitude for the test.

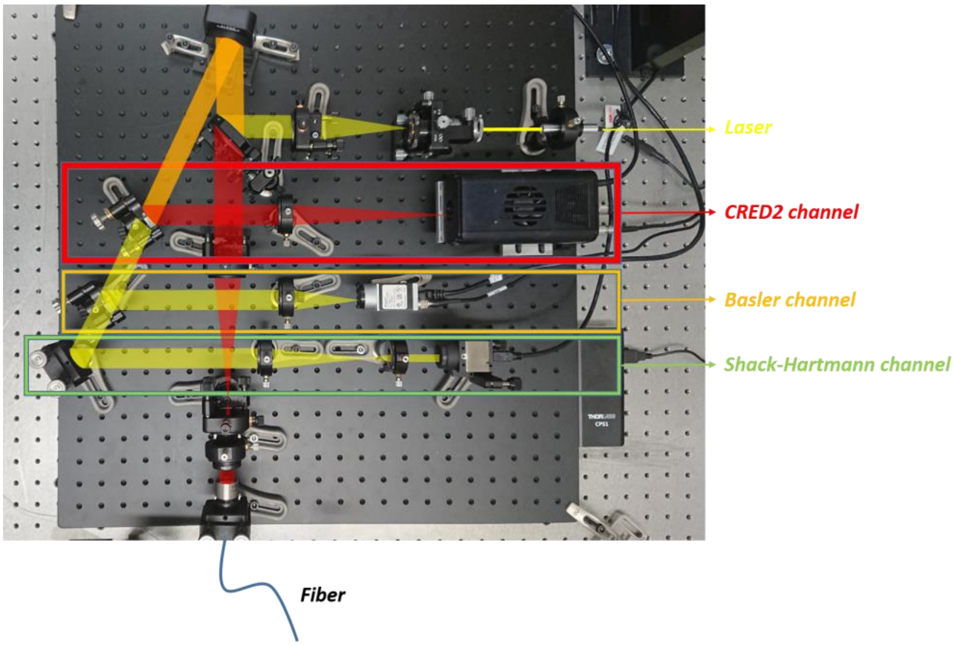

Figure 3. The test bench dedicated to the SHARK-NIR AO channel characterization with the different channels highlighted: in red the actual AO-channel for the Tip Tilt loop, in green the Shack-Hartmann channel to test the NCPA correction, and in yellow a service channel.

3. TIP-TILP LOOP

When testing the TT loop, we use a software provided along with the RTC. This software is able to inject a TT time history by poking the TT mode to the DM. The TT time history used comes from the SHARK-VIS Forerunner experiment[10] and can be re-sized in amplitude. We decide to inject time histories with rms amplitude of 5, 10, and 15 mas, considering 15 mas an upper and unlucky limit for the LBT AO correction. Of course, the software has implemented an algorithm to correct the TT. This algorithm consists in analyzing the images taken by the detector that contains the image of the star (the focused image of the fiber in the laboratory case). First it removes a dark offset; than it constraints to zero all the pixels with values below a certain chosen threshold; finally it calculates the center of gravity (weighted by the pixels flux) of the image and pokes a TT mode command to the DM in order to target a chosen position for the PSF on the detector.

For the three input time histories and for the three R magnitudes considered (8, 9, 10), we run the software to close the loop at two different rates: 500 Hz and 1KHz. The duration of the test, both in open and in closed loop is three seconds: during the loops, we collect all the images taken by the detector, resulting in about 1500 frames at 500 Hz and 3000 at 1 KHz. We analyze the distribution of the centroids in post-processing using a cross correlation algorithm, since we found it more robust (note that this algorithm is slower with respect to the one implemented in the RTC, and cannot be used within our hardware at those frame rates). A typical distribution of the centroids in the loops is Gaussian as depicted in Figure 4, where there is the comparison between a typical centroid distribution without (green) and with (red) applied correction: left panel refers to a regime where the correction works, while in the right panel the boundary parameters do not allow to close the loop. The scale for on the detector is 21 mas / px matching the actual scale of the nominal design.

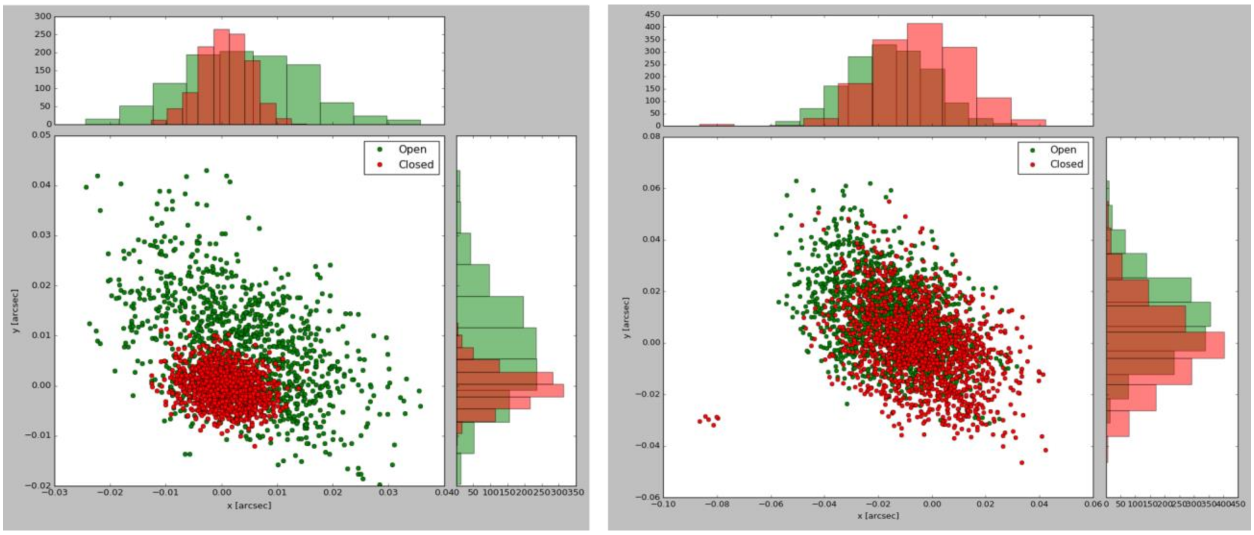

Figure 4. Two examples of comparison between the distributions of centroids without (green) and with (red) the TT correction applied. The correction worked on the example of left panel, not in the right one.

In Table 1, we report the results for all the combinations of time-history, magnitude and speed of the loop (all the results are in mas).

Table 1. The rms of the distribution of the centroids (unit [mas]) for different magnitudes, frame rates and input time histories.

R magnitude	Input time history / Frame Rate [Hz]	15 mas	10 mas	5 mas	No input time-history
Mag 8	500	5.7	4.6	2.1	0.9
	1000	3.2	1.5	1.2	0.4
Mag 9	500	5.9	4.1	1.3	1.6
	1000	3.3	3.2	2.9	2.4
Mag 10	500	6.8	4.3	2.8	1.4
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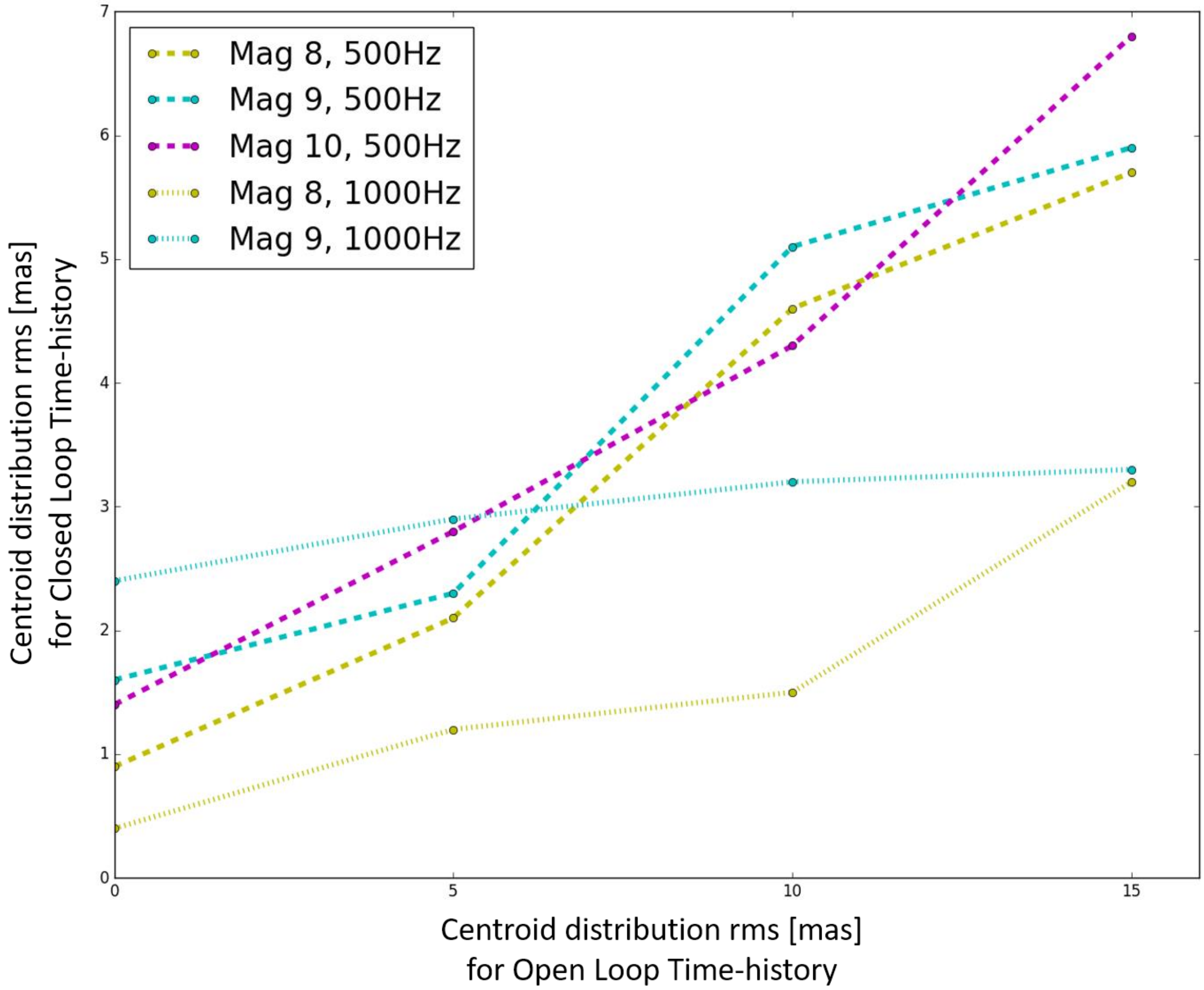

Figure 5. On x-axis the input time-history amplitude; on y-axis the distribution of the centroids when the loop is closed, for different magnitudes and detector frame rates.

4. NCPA CORRECTION

The baseline strategy for the evaluation of the NCPA for SHARK-NIR consists in using the Phase Diversity algorithm[15][16] on the re-imaged pupil images made by a deployable lens on the scientific detector, before the observation. The DM is accordingly deformed in order to correct these aberrations, and then the TT loop can begin. We test the capability of the DM to maintain the proper correction shape during the TT loop. We apply to the DM a typical NCPA correction shape, of the order of 110 nm, up to the 30th Zernike's mode. Then, we start a three seconds open loop followed by a three seconds closed loop. During the loops, we measure the value of the Zernike's coefficients by using the Shack-Hartmann channel, illuminated by the laser source. We compare these results with the capability to maintain the flat shape during the loops. In Table 2, we report the Shack-Hartmann output convention up to the ninth mode.

Table 2. The convention for the Zernike's mode in the output of the SH-wavefront sensor used for the experiment. These modes # correspond to the number in the x-axes of Figure 6, Figure 7, Figure 8, and Figure 9.

Mode #	Mode Name	Mode #	Mode Name
0	Piston	5	Astigmatism
1	Tip	6	Trefoil
2	Tilt	7	Coma
3	Astigmatism	8	Coma
4	Power	9	Trefoil

Also in this case, we consider 5, 10 and 15 mas amplitudes for the input time-history, and the 500 and 1000 Hz frame rate; the magnitude in the CRED2 channel is always R=8. During the loops, each mode displays fluctuations: for each of them, we report the standard deviations of their distributions (Figure 6 for 500 Hz test, and Figure 7 for 1 KHz test) and the peak-to-valley (PtV) deviations (Table 3 for 500 Hz test and Table 4 for 1 KHz test). We can see that the modes showing higher amplitudes in their distributions are the low order ones. It is clear that, for the open loop results, there is a dependence on the amplitude of the time history.

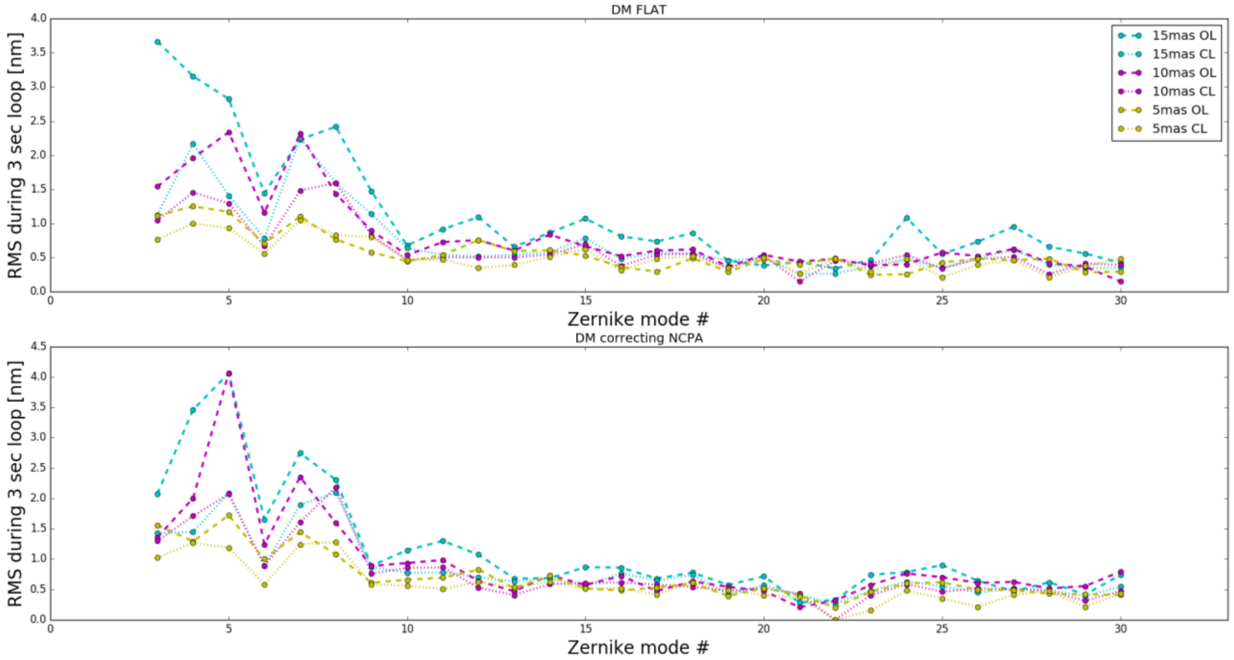

Figure 6. For the 500 Hz test, the standard deviation of the distributions of each mode up to the 30th during a 3 seconds test. Upper panel: the DM is in its flattened configuration; bottom panel: the DM has a typical NCPA correction shape.

Table 3. For the 500 Hz test, the maximum fluctuation registered during a 3 seconds test and the related mode.

FLAT	**OL [nm]**	**CL [nm]**	**NCPA**	**OL [nm]**	**CL [nm]**
5 mas	6	6	**5 mas**	11	7
10 mas	10	8	**10 mas**	15	13
15 mas	27	13	**15 mas**	19	10

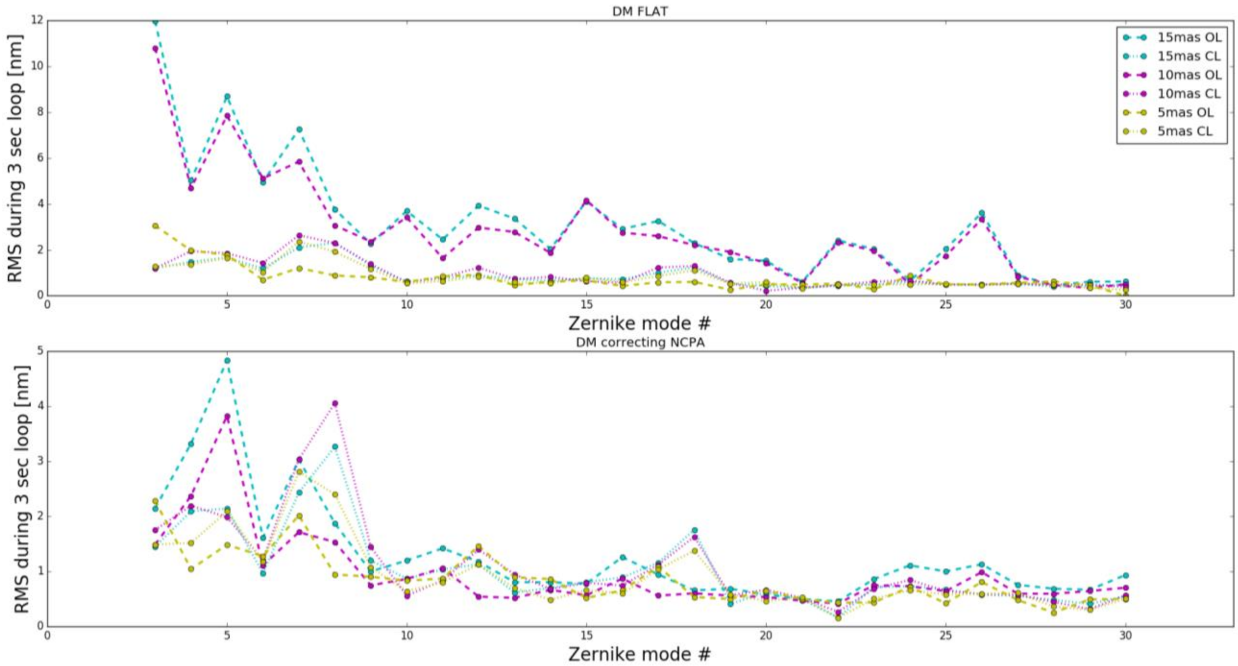

Figure 7. For the 1 KHz test, the standard deviations of the distributions of each mode up to the 30th during a 3 seconds test. Upper panel: the DM is in its flattened configuration; bottom panel: the DM has a typical NCPA correction shape.

Table 4. For the 1 KHz test, the maximum fluctuation registered during a 3 seconds test and the related mode.

FLAT	OL [nm]	CL [nm]	NCPA	OL [nm]	CL [nm]
5 mas	23	16	**5 mas**	16	10
10 mas	56	13	**10 mas**	20	23
15 mas	69	10	**15 mas**	25	15

In the following plots (Figure 8, Figure 9), we report the difference between the average value of the modes in open loop and the average value of the modes in closed loop as a function of the mode number. Also in this case, we check three input time histories and we close the loop at 500 and 1000 Hz and at R=8. The points are distributed around the zero value: this means that, on average, the same correction is applied for different amplitudes of the TT modes. The fact that the maximum discrepancies between open and closed loop appear at 1 KHz framerate can be related to the higher capability to close the loop at 1 KHz wrt 500 Hz: this results in a bigger discrepancy between open and closed loop TT amplitude (Figure 5).

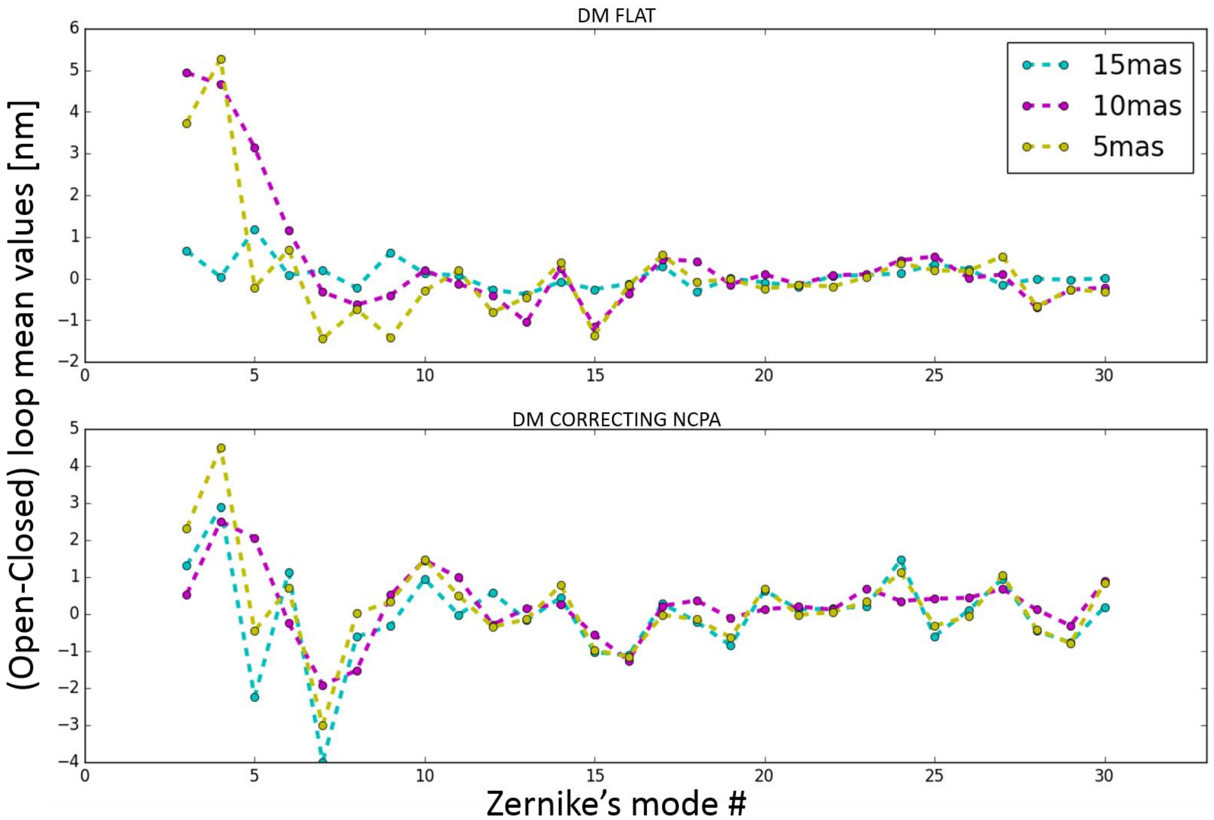

Figure 8. For the 500 Hz test, the difference between the average open-loop modes values and the average closed-loop mode values. In the upper panel, the results for the flat mirror and in the bottom panel for the DM with typical NCPA correction shape.

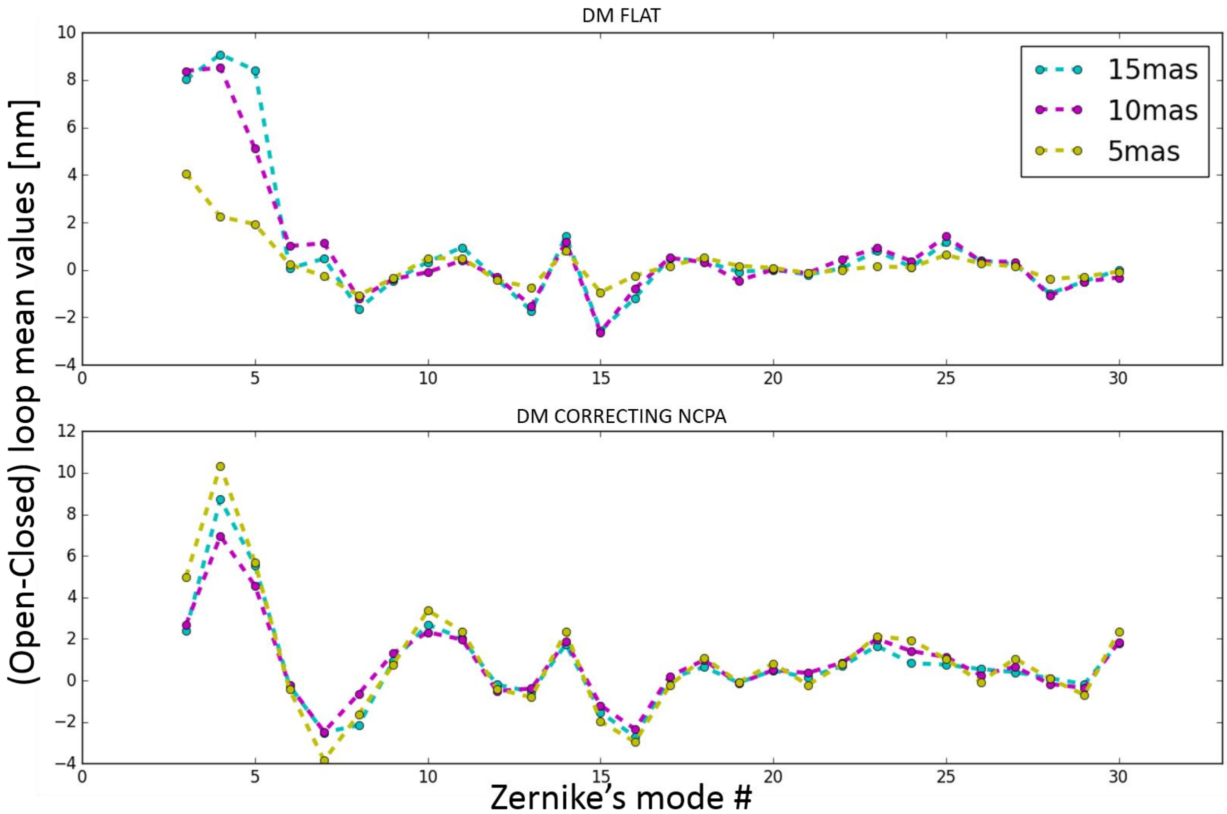

Figure 9. For the 1 KHz test, the difference between the average open-loop modes values and the average closed-loop mode values. In the upper panel, the results for the flat mirror and in the bottom panel for the DM with typical NCPA correction shape.

5. SUMMARY AND CONCLUSIONS

We tested the performance of the SHARK-NIR AO-channel in INAF-Padova laboratory. We tested the capability of the system to close a Tip Tilt loop, starting from different input TT amplitudes and simulated magnitudes. When we close the loop, the gain in the centroid distribution wrt the input amplitude is between 2.1 and 2.5 working at 500 Hz, and between 3 and 5 working at 1000Hz, almost independent by the magnitude. Then, we test the capability of the mirror in maintain a typical NCPA correction during a TT loop. The standard deviation of the distribution of each mode during the loop does not exceed 4 nm in close loop. Given the requirement, we consider the performance of the AO-channel successful. We are working in order to extend the magnitude faint end to R=11 or higher, focusing on the algorithms for centroid calculation and on the reduction of detector noise.

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