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Study of the LIFT focal-plane wavefront sensor for GALACSI NFM

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ABSTRACT

The infrared low order sensor (IRLOS) upgrade project was recently launched to increase the sky coverage of GALACSI narrow-field mode (NFM).^{1,2} While the baseline is to perform low-order wavefront sensing with a 2x2 Shack-Hartmann wavefront sensor (SHWFS) operating in the J+H band, a full-pupil mode was proposed to address the faintest end of the magnitude range by concentrating the photons from the full aperture in a single point spread function (PSF). In this context, we have investigated the wavefront sensing approach called the linearized focal-plane technique (LIFT). It enables the retrieval of low-order modes such as tip/tilt, defocus, astigmatism (and possibly more) from a single focal-plane PSF of a very faint natural guide star (NGS) target. LIFT is a phase diversity technique based on introducing a known amount of astigmatism into the optical path. The morphological change induced by the astigmatic shift allows encoding information about the phase aberrations into the PSF morphology.

In this work, we discuss the linearity and flux sensitivity of the method and present experimental on-sky results obtained at the VLT. We discuss the applicability of this method in realistic conditions and the limitations that this method can face while operated on-sky.

Keywords: Adaptive optics, Atmospheric turbulence, Wavefront sensors, Point spread functions, PSF reconstruction, Phase diversity, LIFT, Telescopes

1. INTRODUCTION

1.1 General context

The unitary telescope number 4 (UT4) at the VLT utilizes the adaptive optics facility (AOF), which includes a deformable secondary mirror (DSM)³ and 4 laser guide stars (4LGSs).⁴ In practice, a separate adaptive optics (AO) module called GALACSI provides wavefront sensing and additional AO correction. It works in wide-field mode (WFM) and narrow-field mode (NFM) that provide GLAO and LTAO types of correction, respectively.⁵ These two regimes are enabled by 4LGSs associated with 4 corresponding Shack-Hartmann wavefront sensors (SHWFSs). However, they are insensitive to low-order modes such as tip/tilt. In addition, the altitudinal drift of the sodium layer introduces a quasi-static bias to defocus. Therefore, LGSs are used to provide the measurements for the so-called high-order loop (HO), while lower orders (LO) are sensed by the infrared low-order wavefront Sensor (IRLOS).^{5,6} It includes 2x2 SHWFS that measures tip/tilt (TT), defocus, and astigmatism using NGS. Only TT is controlled at a fast rate. Focus and astigmatism are measured for slow truth sensing purposes.

Thus, finding a suitable NGS close to an object of interest is crucial to providing a good correction. Consequently, more accessible NGSs provide more sky coverage. The way to extend the number of available NGSs is to increase the patrol field and/or to sense fainter targets (Fig. 1). With this intention, the IRLOS upgrade

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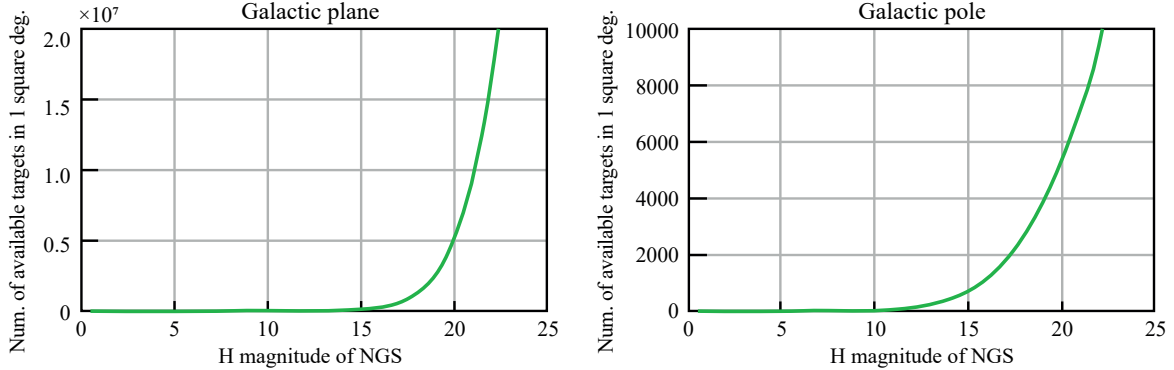


Figure 1. Sky coverage as a function of the NGS H-magnitude. The sky coverage is defined as the number of stars available as NGS. With more NGSs available, the probability of having a suitable NGS nearby the scientific object increases.

project was implemented in 2021.^{1,2} The goal of this project was to expand the limiting magnitude of IRLOS up to $J_{mag} = 17$, meaning a +2 magnitudes increase compared to the previously accessible $J_{mag} < 15$.⁷ The upgrade included the replacement of the previous generation detector, as well as the introduction of the new full-pupil mode. The idea behind this mode was to remove the 2x2 lenslet and use a single PSF full-pupil of an NGS to extract the information about the low-order modes. In this case, the utilization of the whole pupil increases the sensitivity by a factor of 16. Part of the gain comes from increasing the amount of collected flux in the aperture (factor of 4), and the other part comes from shrinking the diffraction-limited PSF (another factor of 4). This is only possible because GALACSI NFM provides high performance (Strehl ratio) in the near-infrared where IRLOS operates (J+H).

It was proposed to use a focal plane WFSing technique called LIFT⁸ to enable the wavefront reconstruction from a single PSF. The initial idea was to use LIFT as a truth sensor to sense the defocus, astigmatism, and possibly a few other low-order modes at a slow pace. LIFT was also supposed to operate in the low-flux conditions and work with targets up to $J_{mag} = 17$.

LIFT is the phase-diversity technique which is based on inserting a known amount of astigmatism into the optical path as phase diversity. This resolves the sign ambiguity of even modes.^{8,9} LIFT uses as input a single focal-plane PSF with the astigmatic diversity applied and outputs the estimated values for the desired modal coefficients. The choice of modal basis can be arbitrary. In this work, we consider Zernike modes.

LIFT utilizes per-pixel variance to weight the pixels depending on the intensity. E.g., in the electron noise limited case (i.e., in the low-flux regime), the regions that are closer to the PSF core are prioritized. This makes LIFT robust while working with noisy data observed in faint conditions. On the hardware side, LIFT is implemented by inserting a cylindrical lens into the optical path of IRLOS. The lens was placed into the filter wheel so that IRLOS could switch between a 2x2 lenslet for SH WFS and a cylindrical lens for LIFT. But this design also implies that a cylindrical lens cannot be used together with a spectral filter, meaning that the acquired LIFTed PSFs are strongly polychromatic across the full J and H spectral bands.

2. VERIFICATION

This work aims to study the capabilities and limitations of LIFT within the framework of GALACSI NFM. It is first done in simulated conditions that mimic the on-sky performance of AOF. Next, the method was verified experimentally on the test bench and later on sky. The result will be discussed in the following section.

2.1 Simulations

LIFT performs in closed-loop conditions with a good correction case.¹⁰ Nevertheless, with the level of correction in NFM, the RMS of the residual wavefront can typically reach 150 [nm] at the good seeing case of about 0.6 [arcsec].⁷ In addition, LIFT must work with strongly polychromatic PSFs. Similar challenging conditions were simulated to characterize LIFT and study its linearity and sensitivity properties.

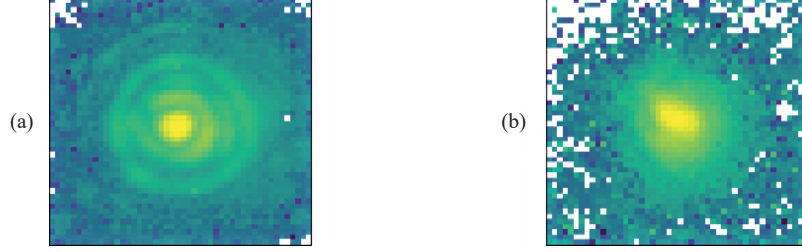


Figure 2. Example of the monochromatic IRLOS PSF (a) acquired with a spectral filter ($1.6 \mu m$) and polychromatic (J+H) PSF (b). One might see that in the polychromatic case, most of the features of the PSF are blurred out.

2.1.1 Linearity

Exploring the linearity ranges for several reconstructed modes helps to understand the scale of aberrations that can be sensed. For this sake, the pure aberration is introduced and then reconstructed. In this case, only defocus is considered.

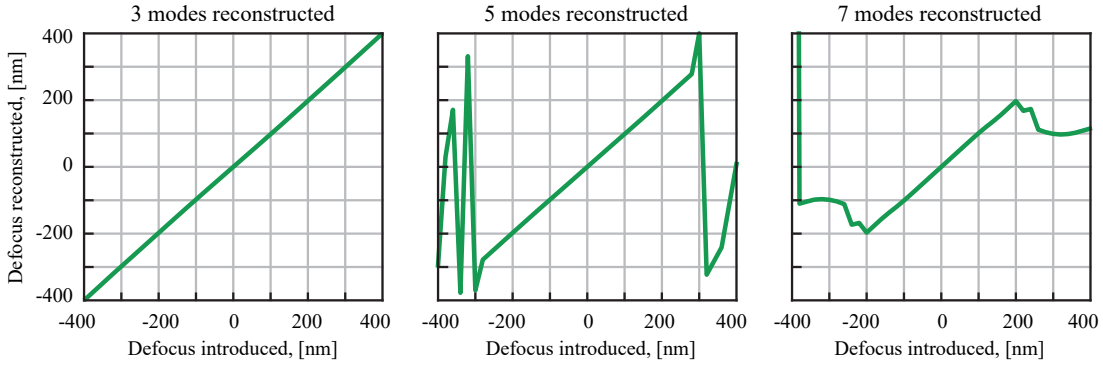


Figure 3. Linearity ranges for defocus aberration. Linearity scans are performed by inserting a known amount of defocus to the modeled PSFs and then reconstructing with LIFT. It can be seen that the range of defocus linearity decreases with more modes introduced into the reconstruction. This trend is also true for other modes besides the defocus. The reason for this is the cross-coupling of modes with similar morphological features during the estimation.

Figure 3 clearly shows that the amount of sensed defocus is insufficient for the open-loop measurements. It also demonstrates that LIFT cannot be used for bootstrapping of defocus prior to observations.

2.1.2 Sensitivity

These tests were performed to determine the limiting magnitude of LIFT and to see the evolution of reconstruction accuracy with the increasing target magnitude and decreasing flux. Simulated exposure is 1 second per PSF. In these simulations, the average RMS of residual optical path difference (OPD) is set to 120 [nm] . 10 modes were introduced additionally to the residual phase screens to synthesize random sets of non-common path aberrations (NCPAs) with a maximal OPD per mode of 50 [nm] . The maximal value of inserted defocus was set to 200 [nm] . 200 random PSFs were generated and reconstructed for each magnitude value to collect the statistics.

On Figure 4a, LIFT shows inferior reconstruction accuracy in the low-flux regime ($J_{mag} > 16$) if more modes are included in the estimations, while reconstructing only 3 modes (tip/tilt and defocus) leads to better results in this regime. However, few first orders are insufficient to describe the shape of a PSF, affected by higher order aberrations. This introduces the model error and reduces the quality of reconstruction in the high-flux regime ($J_{mag} \leq 16$) (Fig. 4b). For this reason, the number of reconstructed modes should be set depending on the flux level.

Unfortunately, in the end, it was decided not to use the full-pupil mode as the upgraded detector, improved alignment, and SW tuning enabled IRLOS to sense targets of $J_{mag} = 19$ with the existing 2×2 SH WFS,

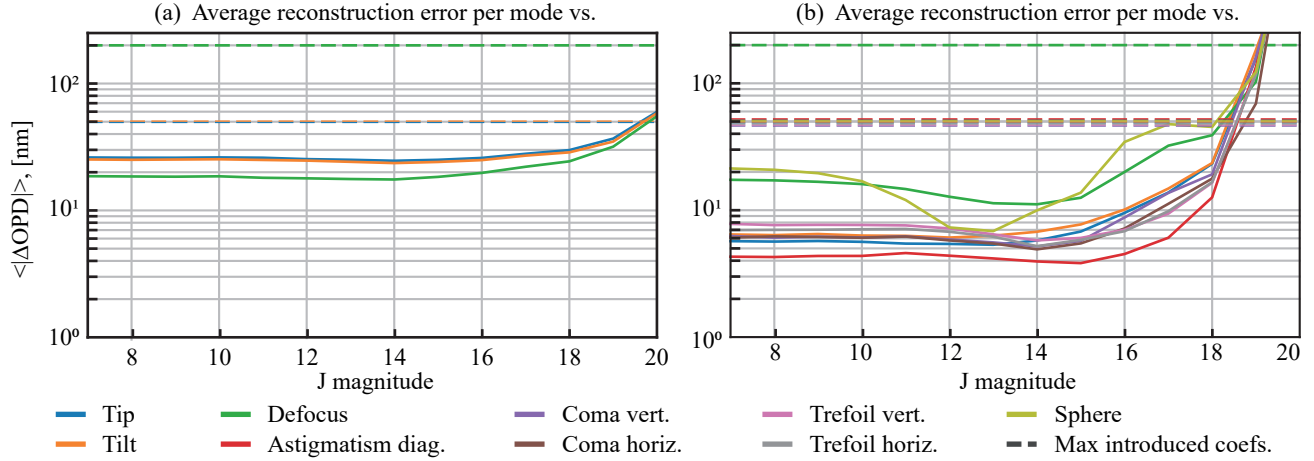


Figure 4. Each curve shows the average absolute difference between the simulated and reconstructed modal coefficients. (a) Only the first 3 modes are reconstructed. (b) 9 modes were reconstructed. The diversity mode (oblique astigmatism) is excluded from the estimation. One can see that reconstructing fewer modes leads to superior accuracy in the low-flux regime while introducing more modes in the high-flux regime provides a more accurate representation of the PSF shape.

which was +2 magnitudes more than the initial goal of limiting $J_{mag} = 17$. Moreover, the full-pupil mode demonstrated to be difficult to operate robustly. Indeed, the optical design provides a narrow depth of focus and a tiny field of view that complicates the acquisition of faint targets. Even though LIFT demonstrated the ability to perform WFSing for extremely faint targets, the idea of using LIFT as a LO WFS was therefore deprioritized. Nevertheless, the experimental verification of the method still was conducted.

2.2 Experimental verification

The experimental verification of LIFT was first performed in the lab on the optical setup that was designed in a similar fashion to the real IRLS (Fig. 5).

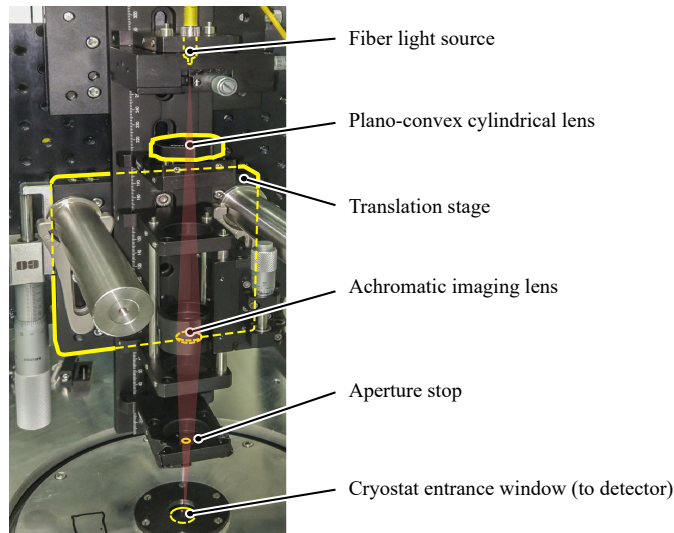


Figure 5. The experimental setup was used to produce the defocus scans. Different known values of defocus were achieved by shifting the whole setup relative to the plane of the detector using the translation stage. An halogen lamp with the central $\lambda \approx 1650$ [nm] was used as the light source. The detector used in these experiments was later installed on the VLT.

These experiments were conducted in the absence of wavefront residuals. Orders higher than defocus were not inserted. The defocus ramp was introduced by gradually shifting the setup relative to the focal plane of the detector (Fig. 6). The detector used for these tests is the one that was later installed at the telescope during the upgrade procedure.

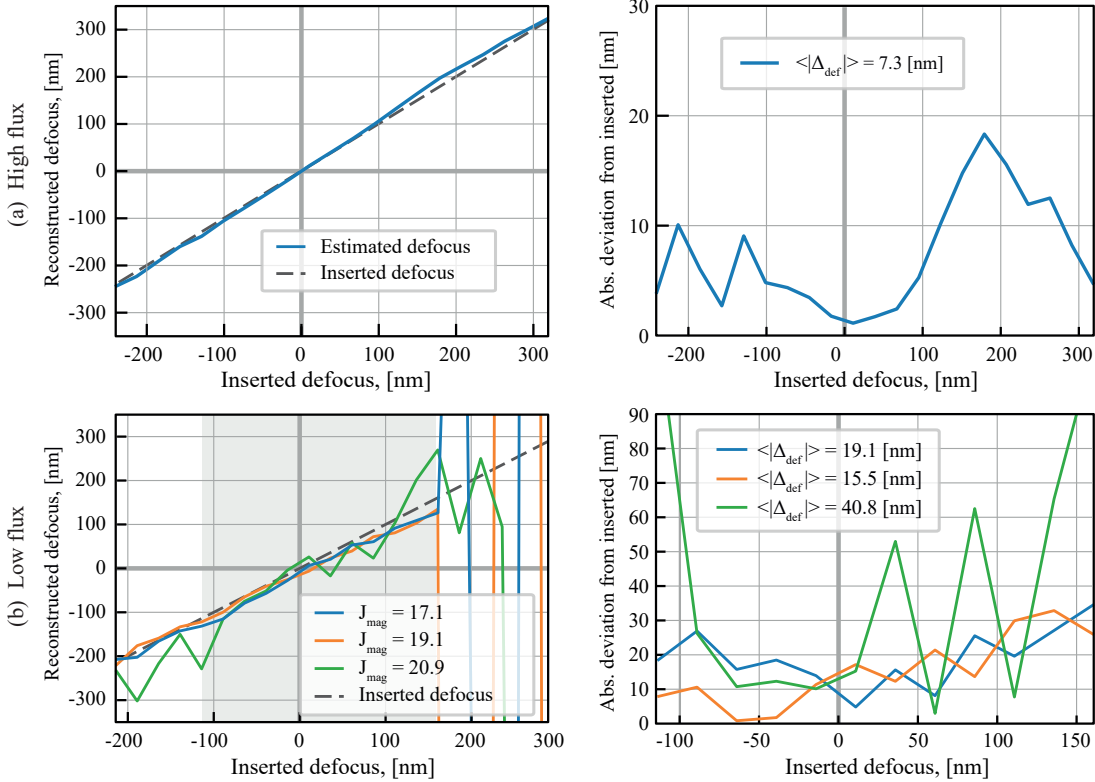


Figure 6. Defocus scans were performed on the experimental setup for high-flux (a) and low-flux (b) conditions. Left column shows the estimated defocus, right column shows the absolute deviation from the value of the inserted defocus. Only 3 modes (tip/tilt and defocus) were included in reconstruction in all cases. Results for $J_{\text{mag}} = 17.1$ show worse precision as they were obtained with the less accurately calibrated dark field maps.

Figure 6 shows that in the low-flux regime, the reconstruction is noisy. Nonetheless, these results demonstrate the capability of LIFT to perform under faint conditions on real hardware. The high-flux scans have shown almost perfect reconstructions with the linearity range values corresponding to the simulations (Sec.2.1.1). However, these rather simplistic tests did not fully represent the complexity of the realistic on-sky conditions. Therefore, the next crucial step was to validate LIFT on the sky.

2.3 On-sky verification

In these tests, only high flux targets were considered ($J_{\text{mag}} = 9 - 13$). Only 4 experiments were performed during these tests (3 presented in this work). Like in the lab, the defocus ramp here was introduced by shifting the focusing stage of MUSE. Since bright targets were used, the first 10 Zernike modes were reconstructed except the diversity mode. The idea was to try reconstructing NCPAs (i.e., the first 9-10 Zernike modes) alongside the inserted defocus. Ideally, NCPAs should have remained constant during these scans since only defocus was introduced. However, reconstructed coefficients demonstrated variability along the scan (Fig. 8). In addition, the average values of NCPAs coefficients varied from sample to sample. It might mean that NCPAs depended on the pointing of the telescope as all scans were acquired for different targets.

Worth noticing that to achieve these results the object shape assumption was used (Fig. 8) even though this is rigorously and strictly incorrect since we observe unresolved targets towards the faint end. The reason is

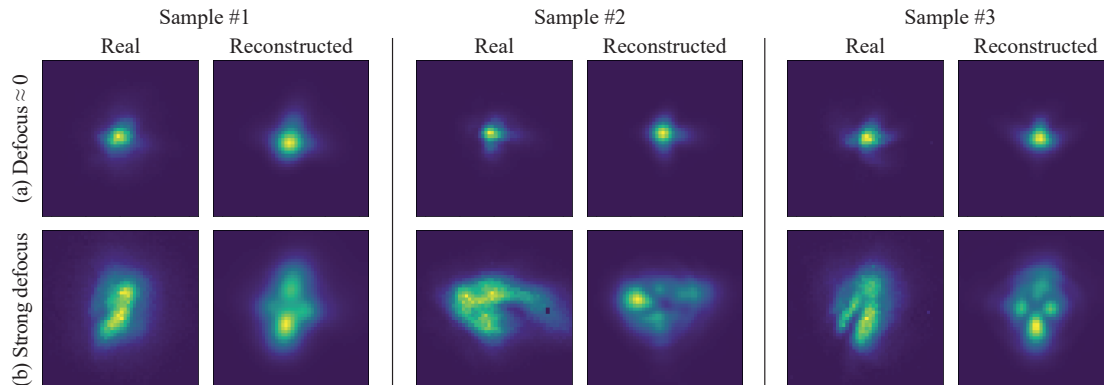


Figure 7. (a) Example reconstruction for 3 experiments on the sky with near zero defocus. Each experiment consists of a defocus ramp obtained for a separate target. With strong defocus, on-sky PSFs reveal their complex structure, which the PSF model inside LIFT cannot represent accurately.

that in realistic conditions, the PSF shape is mostly defined by aberrations. So, the unmodelled aberrations are taken into account as a “fake” object. Assuming the point source and neglecting the object led to the inferior reconstruction quality (Fig. 8b). Since LIFT is the focal plane-based technique, the reconstruction accuracy strongly depends on the PSF model in use.

The object must be calibrated or set by hand before reconstruction. Alternatively, it can be jointly estimated with the modal coefficients. The first case can be cumbersome and sometimes impractical during the on-sky observations, and the joint estimation can lead to the cross-coupling between the object and aberrations since both may have an identical effect on the PSF morphology.

3. CHANGE OF STRATEGY

As mentioned in Section 2.1.2, the full-pupil mode was deprioritized, and the existing 2x2 SH solution remained. Thus, LIFT will not be used as LO WFS for now. Therefore, the possible applications of LIFT were rethought. In the end, the paradigm was shifted from LO WFSing toward the more general PSF reconstruction (PSF-R). It means that the problem is no longer viewed solely as an estimation of modal coefficients. The new vision is to fit a more advanced physics-based multi-parameter PSF model that can recreate the complexity of IRLS PSFs (Fig. 7). On-sky tests revealed that having such a model is instrumental for providing accurate reconstructions in the future.

3.1 Complex PSF

As mentioned earlier, in on-sky tests, all complex effects were roughly approximated by convolving PSF with the 2D gaussian object. However, one can try to isolate the distinct contributors.

3.1.1 AO residuals

As said before, GALACSI NFM provides the correction with the typical residual wavefront RMS of 150 [nm] at 0.6 [arcsec] seeing. The residuals redistribute photons outside the PSF core and distort high-spatial morphological features associated with the high order modes.

3.1.2 Jitter

Such effects as the wind shake might blur long exposures PSF. As mentioned in Section 2.1.2, LIFT is supposed to work with 1-2 seconds exposure images. Within this time, shaking of the telescope structure caused by low wind may introduce jitter and additional blurriness to PSFs.

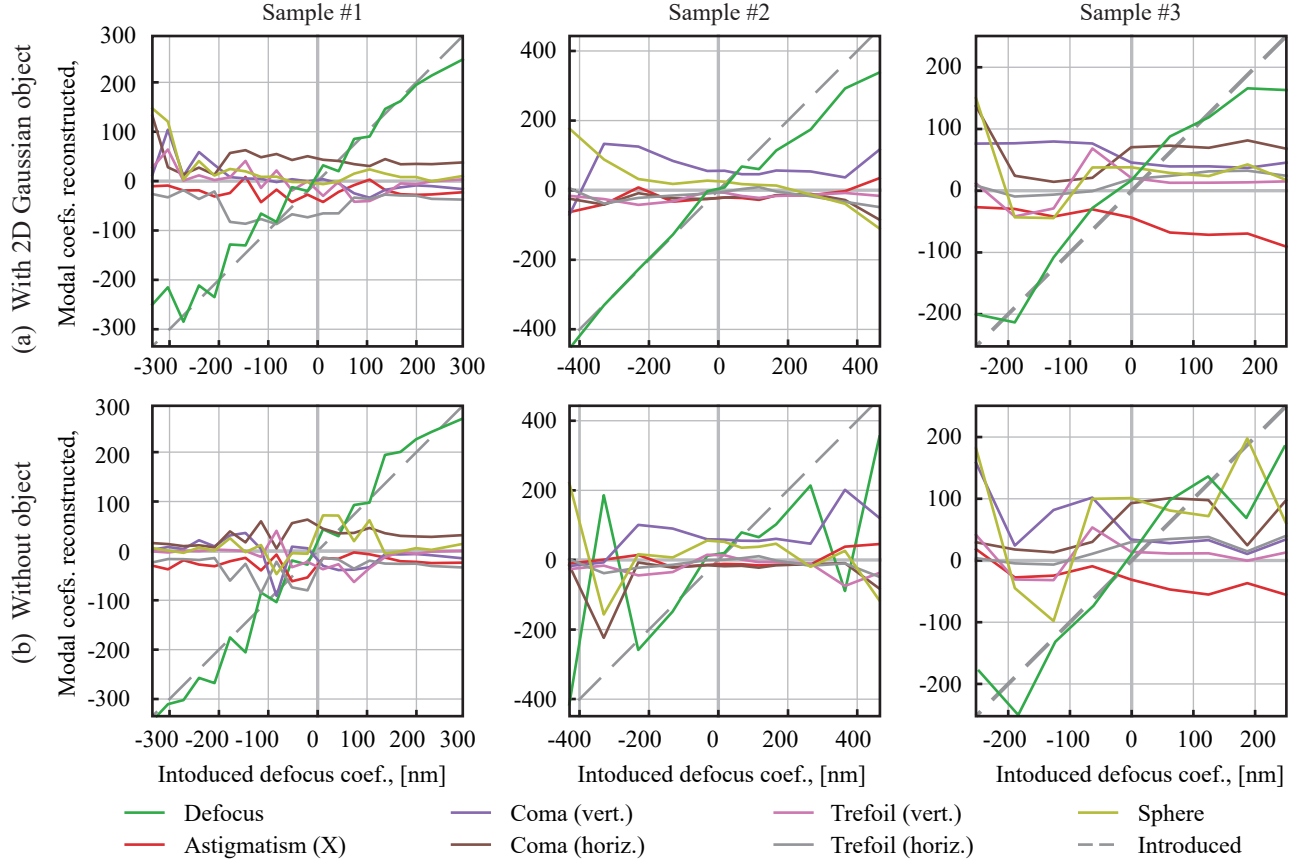


Figure 8. (a) Reconstructed modal coefficients for 3 defocus scans acquired on-sky. The known amount of defocus was introduced by adjusting the MUSE focusing stage. 2D Gaussian function was used as the assumption for the shape of the object. (b) Same reconstruction performed without assuming the object shape. The quality of the estimation is degraded in this case.

3.1.3 Atmospheric refraction

Since there is no spectral filter, the uncompensated atmospheric dispersion can introduce severe distortion for a target low above the horizon.

3.1.4 NCPAs

Before the full-pupil mode was introduced, NCPAs present in IRLS had never been calibrated and therefore remained unknown. When LIFT was first tested, it became apparent that NCPAs significantly contribute to the error budget and greatly influence the structure of PSF. Moreover, as mentioned before, these NCPAs seem to vary from target to target and possibly depend on the pointing and the field rotation. The situation is aggravated by the fact that there is no way to select a specific narrow band to study monochromatic LIFTed PSFs, so the observed NCPAs can also be strongly chromatic.

Unfortunately, the currently collected four on-sky datasets are too scarce to provide enough information to disentangle all mentioned contributors effectively. More data must be collected before it becomes possible to approach this problem in terms of PSF-R.

4. CONCLUSION AND PROSPECTS

LIFT is a crude and simple model. Nevertheless, it demonstrated its ability to operate in real-life scenarios and successfully estimate defocus on the sky. However, LIFT experiences difficulties when PSF is polychromatic and not well corrected. It also suffers from uncalibrated and possibly chromatic NCPAs inside IRLS.

The full-pupil mode is no longer used and LIFT is not supposed to operate as LO WFS in low-flux conditions anymore. Thus, the attention was shifted towards turning LIFT into a multi-parameter physics-based PSF model that would fit additional parameters together with the modal coefficients. For this sake, more advanced PSF models are currently being explored.¹¹ It also allows to go beyond IRLOS and opens up horizons for finding applications with other AO systems, including ones on ELT.

Acquiring more technical data during the observations is crucial to fulfilling this goal. Unfortunately, due to the low priority of the full-pupil mode and scarcity of technical time on VLT UT4, it is challenging to collect more data samples of LIFTed PSFs. This situation might change in the future. A broader database of IRLOS PSFs would not only facilitate building more accurate models but also broaden the perspectives for applying the machine learning approaches to this task.

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