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Spatial filtering applied to the pyramid WFS: simulations and preliminary results

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ABSTRACT

In this paper we discuss the potentiality of the spatial filtering approach for the case of a pupil plane wavefront sensor like the pyramid sensor. Filtering is realized by selectively blocking the light just before the pyramid prism. Several schemes can be followed to accomplish this: from a simple field stop that blocks high-order spatial frequencies in order to reduce the aliasing effect (an example is the so-called spatial filtered Shack-Hartmann) to more complicated frequency-selection schemes.

In this work we present the simulation environment that we developed to investigate different approaches in this sense aimed at understanding if any practical advantages in wavefront sensing can be effectively attained in particular regimes. We present some preliminary results obtained with end-to-end simulations. In particular, we qualitavely explored the simplest frequency-selection scheme consisting of a field stop just in front of the pyramid. We show that this can help mitigating the effect of contaminating high-order frequencies. Next steps will be in the direction of exploring different reference star brightness regimes in order to determine under which conditions spatial filtering can improve the quality of closed-loop correction. Moreover, different spatial filter sizes and shapes to control the frequencies conveyed to the wave-front sensor will be investigated.

Keywords: pyramid wavefront sensor, wavefront sensing, spatial filtering

1. INTRODUCTION

A wavefront sensor (WFS hereafter) is a key element to operate Adaptive Optics (hereafter AO) correction.[1,2] We recently entered[3,4] into the realm of the so-called eXtreme AO (or XAO), where Strehl ratio S>0.9 is routinely obtained, at least in the bright-end regime in the near infrared. It has been recognized that the pyramid WFS[5] is one of the possible key elements in future XAO systems,[2] both for its efficient use of the detector and for its inherent high sensitivity when used in closed loop.[6,7]

While several kinds of WFS concepts would probably achieve similar performances in the bright-end regime, the same does not necessarily hold true when going to faint targets or when observing at visible wavelengths. To improve the sensitivity in the faint-end regime, one could think of a WFS in which the signal is cleared out from the contribution of those spatial frequencies in the aberrated phase exceeding the highest one controllable by the AO system. These high frequencies introduce a spurious signal that pollutes the measurement because of poissonian fluctuations.

In a classical pyramid, the SNR in the reimaged pupil can be expresses as:

$$\frac{I_c}{\sqrt{I_c + I_0}}$$

where I_c is the illumination due to residuals of the modes handled by the AO system and I_0 is the background signal due to uncompensated high orders. If we assume to be at the knee of the Strehl vs. mag curve, these two signals must be of the same order of magnitude. With spatial filtering, this background signal is removed and the SNR becomes:

$$\frac{I_{SF}}{\sqrt{I_{SF}}}$$

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By making the two ratios equal, we obtain:

$$I_c = 2I_{SF}$$

This means that with spatial filtering we can obtain the same SNR in the pupil as a classical pyramid with half of the signal. This translates into a theorical gain in limiting magnitude of 0.75 mag.

From the optical point of view, several solutions have been proposed to turn a pyramid-like WFS into a new device that only senses the photons that are specific to a given range of spatial frequencies, namely the ones that mostly contribute to reach the ultimate performance.[8] The aim is increase the SNR in that range, under some conditions that has to be properly investigated. The aim of this paper is to investigate via numerical simulations such an approach applied to the pyramid WFS. Section 2 describes the simulation tool. In section 3 we investigate qualitatively the effect of high-order uncorrected frequencies on the WFS signal. Finally, in section 4 we propose a simple solution based on the introduction of a field stop just in front of the pyramid.

2. THE SIMULATION ENVIRONMENT

In order to investigate the impact of spatial filtering on the pyramid WFS, we developed a simulator in IDL language. The four pupils corresponding to each pyramid facet are generated with the phase-mask approach under the Fraunhofer approximation: the code takes the Fourier Transform (FT) of the complex amplitude in the entrance pupil, apply the pyramid phase mask and then applies the reverse transform. The simulator implements Matrix Fourier Transforms (MFT). With this approach, it is possible to independently set any desired sampling of pupil and focal planes.

Modelling the pyramid prism as a phase modifier allows to generate the pupils in only one step and to account for interference effects between them. The pupils spacing is properly tuned acting on the pyramid apex in order to easily register the pupil themselves and compute the sensor signal.

Pupil images are computed in normalized intensity units, but they can then converted into photon counts by specifying a magnitude for the target and the characteristics of a telescope. By doing so, noise sources like poissonian noise and read-out noise can be included. It is also possible to resample the reimaged pupils in order to simulate any desired number of subapertures. Figure 1 for example compares pupil images with 300, 40 and 20 subapertures obtained with the simulator.

Phase aberrations at the entrance pupil plane can be built one Fourier component at a time, by specifying period, amplitude and wave number for any of them one would like to include. Each component will produce a couple of speckles of λ/D size in the focal plane, whose brightness is determined by the amplitude of the mode. As it will be shown in the following, this approach has revealed useful for a preliminary investigation of the effect of spatial filtering.

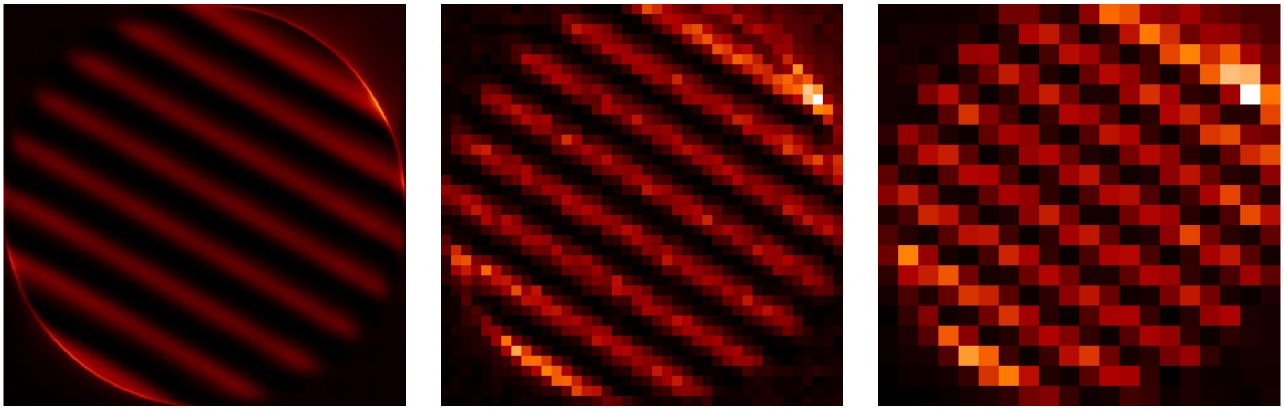

Figure 1. Pupil images with a different number of subapertures obtained with the pyramid simulator. From left to right: 300, 40 and 20 subapertures.

3. UNCORRECTED HIGH-ORDER FREQUENCIES

The basic idea behind spatial filtering is to remove from the re-imaged pupils the light coming from those high-order frequencies (HOF, hereafter) that cannot be sensed by the WFS. These high-orders could be either blocked or alternatively conveyed optically to a separate area of the detector.

To better understand how HOF can affect the pyramid signal, we performed the following experiment: let us suppose that we have a low-order aberration that we want to sense. This aberration is assumed to be composed of a single Fourier component of frequency equal to 8 cycles/pupil and amplitude equal to $\lambda/8$. We will call it the frequency of interest (FOI). The FOI generates pairs of symmetric speckles in the focal plane at distances from the center (the zero order) which are multiples of 8 λ/D (figure 2). A fringe pattern will then appear in the two reimaged pupils corresponding to the quadrants in which these speckles are located.

We introduce then an high-order aberration on top of the FOI. This aberration is composed of integer frequencies from 20 up to 100 cycles/pupil. Each of these spatial frequencies is repeated 100 times by randomly changing its orientation in order to populate homogeneously the focal plane with speckles (figure 2). We assume for the high-order aberration a constant amplitude per mode equal to $\lambda/8$, the same as the FOI. This choice is just for explorative purposes: we reserve for future developements the implementation of a more realistic spectrum for the high-order aberration like the Kolmogorov one, in which power rapidly decreases at high spatial frequencies.

Figure 3 shows the intensity in the reimaged pupil with and without HOF in the system. Pupil diameter is 300 pixels. In the two cases, two out of the four pupils generated by the pyramid are displayed: one carrying the FOI on the left and one without it on the right. It is clearly visible how HOF populate both pupils with spurious light. It is interesting to note that the contaminating light traces the FOI fringes, while it is almost uniformly distributed in the pupil without the FOI signal.

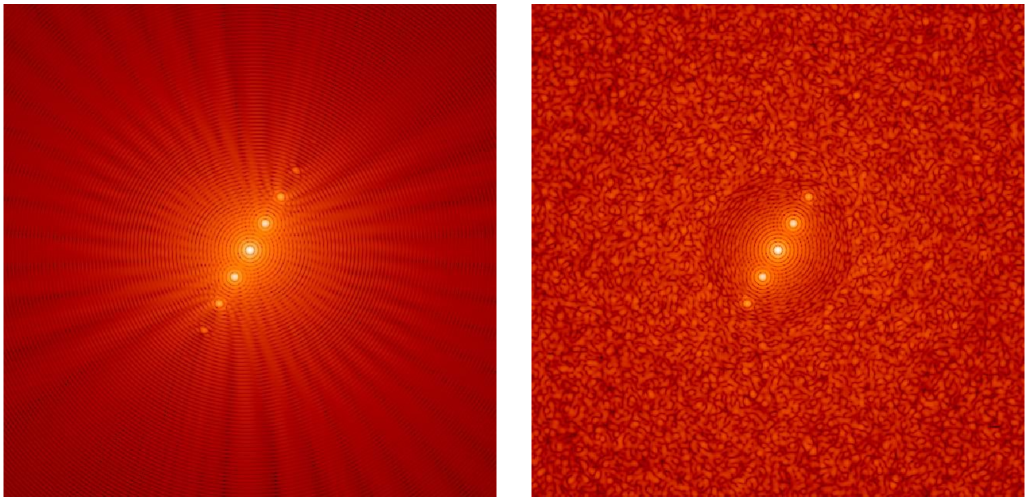

Figure 2. Focal plane intensity obtained introducing in the system a single Fourier component aberration of spatial frequency equal to 8 cycles/pupil (*left*) and then superimposing on it a high-order aberration of frequencies from 20 up to 100 cycles/pupil and of the same amplitude per mode (*right*).

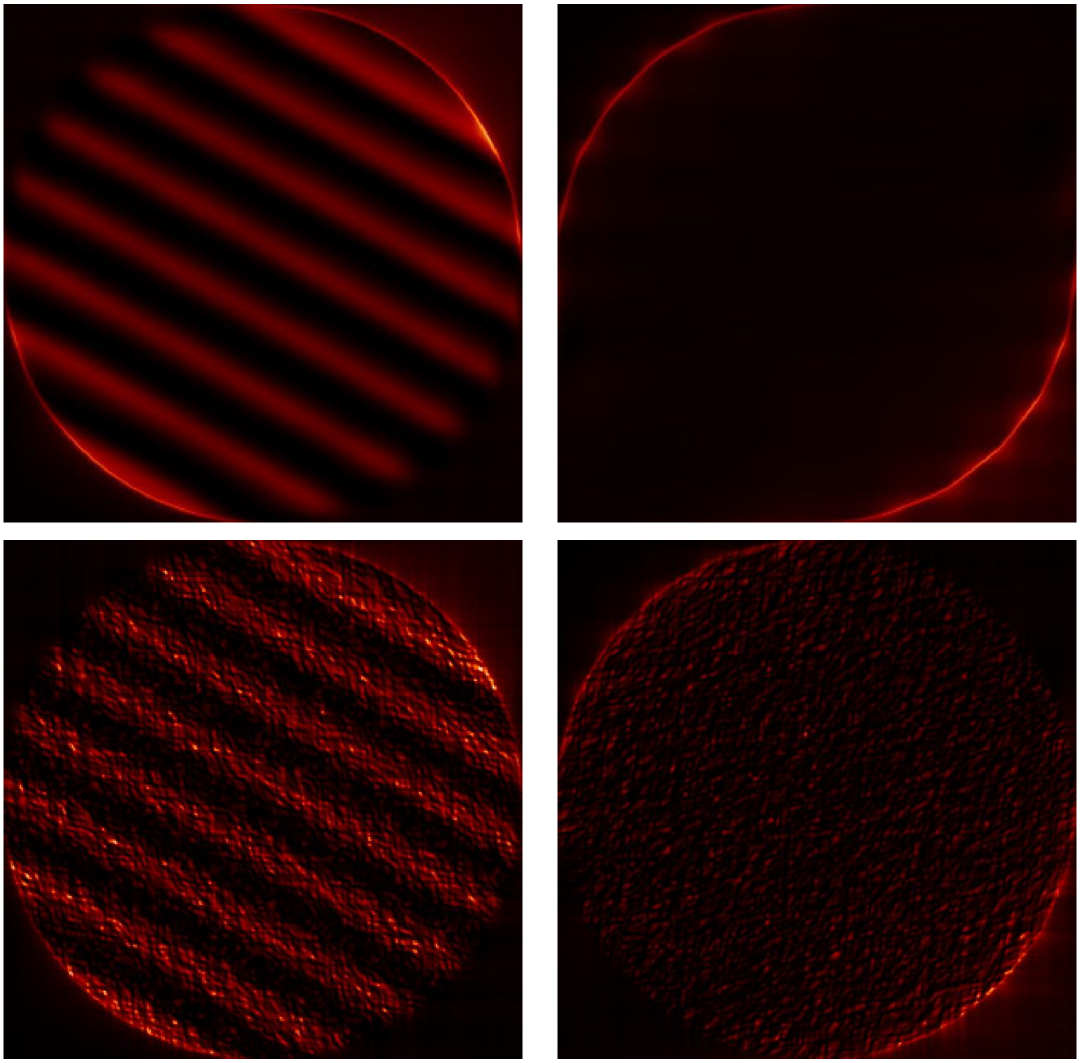

Figure 3. Images of two out of the four pupils generated by the pyramid in presence of the FOI alone (top line) and with the addition of the high-order aberration (bottom line). Pupils not containing the FOI are also shown in the two cases on the right.

4. FIELD STOP

The easiest spatial filtering scheme consists of introducing a circular field stop in the focal plane just in front of the pyramid. Such a stop will operate as a low-pass filter. However, no perfect removal of HOF light is of course possible because each high-order component actually covers the whole focal plane. In addition, the low-order mode that we want to recover is influenced by the presence of the stop because of diffraction effects. In order to investigate these effects, we pursue with the experiment set-up in section 3 by introducing a field stop of radius equal to $18\lambda/D$ to filter out HOF. Figure 4 shows the obtained pupil image compared to the nominal case of the FOI alone. In presence of the field stop, the light diffracted at the edge of the pupil disappears and a reduction in contrast of the fringes is visible. In order to quantify this effect, we plotted the intensity profiles extracted from the pupil images in the direction orthogonal to the fringes (figure 5). In presence of the field stop the noise due to HOF is eliminated, but the fringes are reduced in intensity by 15%.

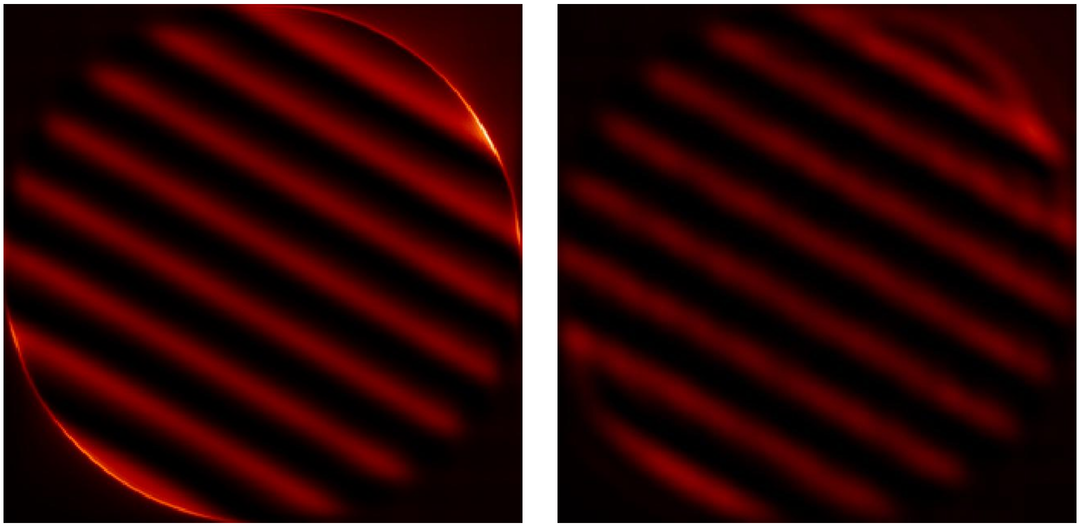

Figure 4. Pupil image in absence of HOF (*left*) compared to the same image in presence of HOF blocked by means of a field stop (*right*). The scale is the same in the two images.

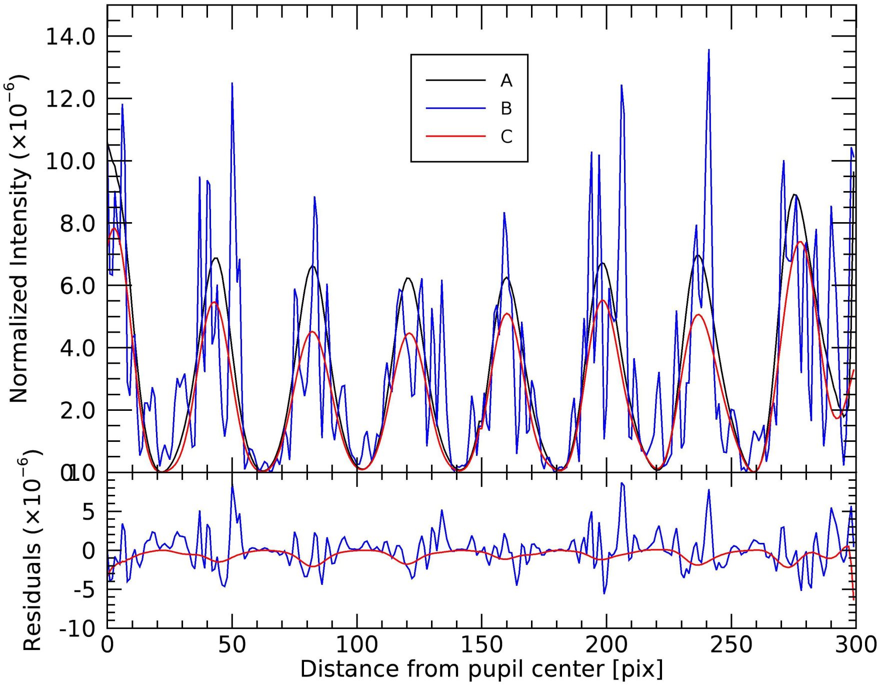

Figure 5. 1-D profiles of the fringes due to the low-order mode in absence of HOF (A), with HOF (B) and in presence of HOF masked with a field stop (C).

5. CONCLUSIONS

In this work we presented a preliminary qualitative analysis of the concept of spatial filtering applied to the pyramid WFS. For the purpose, we developed and validated a pyramid simulation tool in IDL language. We built a simple toy model to investigate the effect of contaminating high-order frequencies on a single Fourier component low-order aberration. We then investigated a simple frequency-selection scheme consisting of a field-stop just in front of the pyramid. We showed that in this way it is possible to retrieve the fringe pattern of the low-order aberration in the reimaged pupil with just a loss in fringe intensity of a 15%. Work is in progress to quantify in a more rigorous way the effect of spatial filtering by implementing wavefront reconstruction. Moreover, other frequency-selection schemes will be investigated together with different reference star brightness regimes in order to determine under which conditions spatial filtering can improve the quality of closed-loop correction.

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