HIGH-ORDER CORONAGRAPHIC PHASE DIVERSITY: DEMONSTRATION OF COFFEE ON SPHERE

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Abstract. The final performance of current and future instruments dedicated to exoplanet detection and characterization (such as SPHERE on the VLT, GPI on Gemini South or future instruments on the E-ELT) is limited by long-lived intensity residuals in the scientific image plane, which are due to uncorrected quasi-static optical aberrations upstream of the coronagraph. In order to measure and compensate for these aberrations, we have proposed a dedicated focal-plane sensor called COFFEE (for COronagraphic Focal-plane wave-Front Estimation for Exoplanet detection), which consists in an extension of conventional phase diversity to a coronagraphic system: aberrations both upstream and downstream of the coronagraph are estimated using two coronagraphic focal-plane images, recorded from the scientific camera itself. In this communication, we present COFFEE's improvements for estimation and compensation of aberrations upstream of the coronagraph as well as experimental results. The phase estimation is now performed on a pixel-wise map, which, used with a dedicated regularization metric, allows COFFEE to estimate very high order aberrations. Besides, COFFEE has been modified so that it can be used with any coronagraphic focal plane mask (such as an Apodized Lyot Coronagraph or a Four Quadrant Phase Mask). Such improvements allow us to estimate and compensate for quasi-static aberrations with nanometric precision, leading to an optimization of the contrast on the scientific detector. Lastly, we use COFFEE to measure and correct the wavefront on the SPHERE (Spectro-Polarimetric High-contrast Exoplanet Research) instrument during its integration phase: COFFEE's estimation is used to compensate for the quasi-static aberrations upstream of the coronagraph, leading to a contrast improvement on the scientific camera.

1 Introduction

The observation of an extremely faint object such as an exoplanet very close to its parent star requires the use of an extreme adaptive optics (XAO) system coupled with a high-contrast imaging technique such as coronagraphy. The current generation of instruments dedicated to exoplanets direct imaging (SPHERE on the VLT [1], GPI on Gemini North [2]) aim at detecting massive gaseous planets 10^6 to 10^7 times fainter than their host star.

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The ultimate limitation of a high-contrast imaging instrument lies in its quasi-static non-common path aberrations (NCPA): these aberrations, uncorrected by the AO loop, create speckles on the detector plane [3], limiting the achievable contrast. Besides, these long-lived speckles can easily be mistaken for a planet. Thus, in order to reach the instrument ultimate performance, these aberrations upstream of the coronagraph must be estimated and compensated for.

Several techniques dedicated to this goal have been proposed. Closed loop methods, which assume small aberrations[4,5], estimate the electric field in the detector plane using at least three images. The technique proposed by Baudoz *et al.*[6] relies on a modification of the imaging system, but requires only one image.

The focal plane wave-front sensor we have proposed [7], called COFFEE (for COronagraphic Focal-plane wave-Front Estimation for Exoplanet detection), requires only two focal-plane images to estimate the aberrations upstream of the coronagraph without any modification of the coronagraphic imaging system or assuming small aberrations. We have adapted COFFEE to make it able to estimate high-order aberrations for any coronagraphic device[8]. Such improvements are recalled in Section 2. Section 3 present the experimental validation of COFFEE on the SPHERE instrument. In particular, we demonstrate the ability to optimize the contrast on the detector plane using COFFEE's estimation to compensate for the aberrations upstream of the coronagraph. Section 4 concludes the paper.

2 High-order coronagraphic phase diversity

COFFEE's used to be limited by both aliasing and the model error[9]. The former was due to the use of a Zernike basis and prevent COFFEE from estimating high order aberrations. Moreover, the estimation of these high order aberrations is mandatory to optimize the contrast in the detector far from the optical axis. The latter was originating in the image formation model used by COFFEE. The estimations were indeed performed using a perfect coronagraph model, and thus limited by a model error. In practice, COFFEE's use was limited to the apodized Roddier & Roddier coronagraph.

In order to get rid of these two limitation, we have developed a new version of COFFEE, which is able to estimate for high-order aberrations[8]. Section 2.1 recall the modification of the maximum *a posteriori* (MAP) approach on which COFFEE is based, which includes a modification of the basis used for the aberration estimation, now composed of pupil indicator functions (pixels). Besides, a modification of the image formation model, described in Section 2.2, allows COFFEE to work with any coronagraphic device.

2.1 Criterion expression

We consider a coronagraphic imaging system made of four successive planes denoted by A (circular entrance pupil of diameter D_u), B (coronagraphic focal plane), C (Lyot Stop), and D (detector plane). The optical aberrations are considered as static and introduced in pupil planes A and C. The coronagraphic device is composed of a focal plane mask located in plane B and a Lyot Stop in plane C. No particular assumption is made on the pupil shape or intensity, which can be calibrated using data recorded from the instrument. COFFEE requires only two images i_c^{foc} and i_c^{div} recorded on the detector (plane D) that, as in phase diversity, differ from a known aberration ϕ_{div}, to estimate aberrations both upstream (ϕ_u) and downstream (ϕ_d) of the coronagraph.

Considering the calibration of the instrument with an unresolved object, we use the following imaging model:

$$\begin{aligned} \boldsymbol{i}_c^{\text{foc}} &= \alpha_{\text{foc}} \boldsymbol{h}_{\text{det}} \star \boldsymbol{h}_c(\boldsymbol{\phi}_u, \boldsymbol{\phi}_d) + \boldsymbol{n}_{\text{foc}} + \beta_{\text{foc}} \\ \boldsymbol{i}_c^{\text{div}} &= \alpha_{\text{div}} \boldsymbol{h}_{\text{det}} \star \boldsymbol{h}_c(\boldsymbol{\phi}_u + \boldsymbol{\phi}_{\text{div}}, \boldsymbol{\phi}_d) + \boldsymbol{n}_{\text{div}} + \beta_{\text{div}} \end{aligned} \tag{2.1}$$

where α_p is the incoming flux (p is for "foc" or "div"), $\boldsymbol{h}_c$ the coronagraphic "point spread function" (PSF) of the instrument (which is the response of a coronagraphic imaging system to a point source), h_{det} the known detector PSF, $\boldsymbol{n}_{\text{foc}}$ and $\boldsymbol{n}_{\text{div}}$ are the measurement noises and comprise both detector and photon noises, β_p is a unknown uniform background (offset), and $\star$ denotes the discrete convolution operation.

COFFEE is based on a maximum *a posteriori* (MAP) approach: it estimates the aberrations $\boldsymbol{\phi}_u$ and $\boldsymbol{\phi}_d$ as well as the fluxes $\alpha = [\alpha_{\text{foc}}, \alpha_{\text{div}}]$, and the backgrounds $\beta = [\beta_{\text{foc}}, \beta_{\text{div}}]$ that minimize the neg-log-likelihood of the data, penalized by regularization terms $\mathcal{R}(\boldsymbol{\phi}_u)$ and $\mathcal{R}(\boldsymbol{\phi}_d)$ designed to enforce smoothness of the sought phases:

$$(\hat{\alpha}, \hat{\beta}, \hat{\boldsymbol{\phi}}_u, \hat{\boldsymbol{\phi}}_d) = \underset{\alpha, \beta, \boldsymbol{\phi}_u, \boldsymbol{\phi}_d}{\arg\min} [J(\alpha, \beta, \boldsymbol{\phi}_u, \boldsymbol{\phi}_d)] \tag{2.2}$$

where

$$\begin{aligned} J(\alpha, \beta, \boldsymbol{\phi}_u, \boldsymbol{\phi}_d) = \frac{1}{2} &\left\| \frac{\boldsymbol{i}_c^{\text{foc}} - (\alpha_{\text{foc}} \boldsymbol{h}_{\text{det}} \star \boldsymbol{h}_c(\boldsymbol{\phi}_u, \boldsymbol{\phi}_d) + \beta_{\text{foc}})}{\boldsymbol{\sigma}_n^{\text{foc}}} \right\|^2 \\ &+ \frac{1}{2} \left\| \frac{\boldsymbol{i}_c^{\text{div}} - (\alpha_{\text{div}} \boldsymbol{h}_{\text{det}} \star \boldsymbol{h}_c(\boldsymbol{\phi}_u + \boldsymbol{\phi}_{\text{div}}, \boldsymbol{\phi}_d) + \beta_{\text{div}})}{\boldsymbol{\sigma}_n^{\text{div}}} \right\|^2 \\ &+ \mathcal{R}(\boldsymbol{\phi}_u) + \mathcal{R}(\boldsymbol{\phi}_d) \end{aligned} \tag{2.3}$$

where $\|x\|^2$ denotes the sum of squared pixel values of map x, $\boldsymbol{\sigma}_n^{\text{foc}}$, and $\boldsymbol{\sigma}_n^{\text{div}}$ are the noise standard deviation maps of each image. The corresponding variance can be computed as a sum of the photon and detector noise variance. The former can be estimated as the image itself thresholded to positive values, and the latter can be calibrated prior to the estimation.

Both aberrations $\boldsymbol{\phi}_u$ and $\boldsymbol{\phi}_d$ are expanded on a basis $\{\boldsymbol{b}_k\}$. As described in Paul *et al.* [8], the use of a pixel indicator basis ($\boldsymbol{\phi} = \sum_k p_k \boldsymbol{b}_k$) allows the estimation of high order aberrations. Besides, the use of such a basis strongly reduce the aliasing error. Since a pixel basis leads to a large number of unknowns, it is mandatory to perform the criterion minimization with an adapted regularization metric in order to reduce the noise sensitivity. This regularization metric is based on the available *a priori* knowledge on the quasi-static aberrations, assumed to be endowed with a power spectral density (PSD) S_{ϕ_k} (where k stands for u (upstream) or d (downstream)) which decreases as $1/\nu^2$ (with ν the spatial frequency). Such an assumption corresponds to a classical assumption for mirror fabrication errors. The regularization metric $\mathcal{R}(\boldsymbol{\phi}_k)$ can thus be expressed as[8]:

$$\mathcal{R}(\phi_k) = \frac{1}{2\sigma^2_{\nabla\phi_k}} \|\nabla \phi_k(r)\|^2 . \tag{2.4}$$

The minimization of metric $J(\alpha, \beta, \phi_u, \phi_d)$ of Eq. (2.3) is performed by means of a limited memory variable metric (BFGS) method [10,11], which is a fast quasi-Newton type minimization method. It uses gradients $\frac{\partial J}{\partial \phi_u}$, $\frac{\partial J}{\partial \phi_d}$, $\frac{\partial J}{\partial \alpha}$ and $\frac{\partial J}{\partial \beta}$ to estimate ϕ_u, ϕ_d, α and β.
In a previous paper[8], we established that a suitable diversity phase ϕ_{div} for COFFEE was a mix of defocus and astigmatism: $\phi_{\text{div}} = a_4^{\text{div}} Z_4 + a_5^{\text{div}} Z_5$ with $a_4^{\text{div}} = a_5^{\text{div}} = 0.8$ rad RMS, introduced upstream of the coronagraph.

2.2 Coronagraphic image formation model

To perform the minimization of criterion J in Eq. (2.3), the image formation model used by COFFEE (Equation (2.1)) requires the expression of a coronagraphic PSF h_c. Let r be the pupil plane position vector and γ the focal plane position vector. the entrance pupil function P_u is such that:

$$P_u(r) = \Pi\left(\frac{2r}{D_u}\right)\Phi(r), \tag{2.5}$$

with Π the disk of unit radius, D_u the entrance pupil diameter, and Φ a known apodization function. The electric field in the entrance pupil can be written as:

$$\Psi_A(r) = P_u(r)e^{j\phi_u(r)}. \tag{2.6}$$

The electric field in the detector plane Ψ_D is obtained by propagating Ψ_A through each plane of the coronagraphic imaging system: the signal is first focused on the coronagraphic focal plane mask $\mathcal{M}$; then, the electric field is propagated trough the Lyot Stop pupil $P_d(r)$ ($P_d(r) = \Pi\left(2r/D_d\right)$ with D_d the Lyot Stop pupil diameter). The electric field in the detector plane Ψ_D can thus be written as:

$$\Psi_d(\gamma) = \mathcal{F}^{-1}\left\{\mathcal{F}\left[\mathcal{F}^{-1}\left(\Psi_A(r)\right)\mathcal{M}\right]P_d(r)e^{j\phi_d(r)}\right\}, \tag{2.7}$$

where $\mathcal{F}^{-1}$ is the inverse Fourier transform operation. For the sake of simplicity, spatial variables r and u will be omitted in the following.

The coronagraphic PSF h_c is the square modulus of Ψ_D:

$$h_c = \left|\mathcal{F}^{-1}\left\{\mathcal{F}\left[\mathcal{F}^{-1}\left(\Psi_A\right)\mathcal{M}\right]P_d e^{j\phi_d}\right\}\right|^2 \tag{2.8}$$

In Equation (2.8), $\mathcal{M}$ can easily be adapted to represent any coronagraphic device, allowing COFFEE to be used with any high contrast imaging instrument. It is noteworthy mentioning that in the case of a Lyot-style coronagraph, the coronagraphic PSF h_c (Eq. (2.8)) is computed using the method developed by R. Soummer et al. [12] that allow an accurate numerical representation of such coronagraphs by properly sampling the coronagraphic focal plane mask which can hardly be done using the common Fast Fourier Transform (FFT) algorithm, since it would require to manipulate very large arrays.

3 Application to the SPHERE instrument

COFFEE has been applied to the SPHERE instrument during its final integration phase in Grenoble. In Section 3.1, we briefly describe the experimental setup of the bench. Section 3.2 present the result of the estimation of an aberration introduced upstream of the coronagraph using the deformable mirror (DM). Lastly, in Section 3.3, COFFEE's estimation is used to compensate for the aberrations upstream of the coronagraph in a closed-loop process.

3.1 Experimental setup

The SPHERE system[1], is designed for the direct imaging of young giant extra-solar planets from the ground. This instrument includes en extreme adaptive optics (XAO) system, SAXO[13],

image size	$60 \times 60\ \lambda/D$ (200×200 pixels, oversampling factor 1.69)
Light spectrum	Monochromatic, wavelength $\lambda = 1589$ nm
Entrance pupil	diameter D_u, no central obstruction, apodizer in the pupil
Lyot stop pupil	diameter $D_d = 0.96D_u$, central obstruction (15%)
Coronagraph	Apodized Lyot Coronagraph (ALC), focal plane mask angular diameter $d = 4.52\lambda/D$
Detector noise	$\sigma_{e^-} = 15$ e$^-$
Integration time	0.6 s
Number of image averaged for COFFEE's estimation	100

Table 1. Parameters of the experimental validation of COFFEE on the SPHERE system

for the atmospheric turbulence compensation. The main limitation of this instrument lies in the non-common path quasi-static aberrations (named hereafter NCPA). To compensate for these aberrations, SPHERE's baseline relies on a differential estimation performed with phase diversity[14], a focal plane wave-front sensor that works with classical imaging (no coronagraph). Aberrations are measured downstream of the coronagraph (ϕ_d) and from the system entrance to the IRDIS detector (ϕ_{IRDIS}). Aberrations upstream of the coronagraph ϕ_u are then computed as the difference between these two measurement: $\phi_u = \phi_{IRDIS} - \phi_d$. We note that this wave-front sensor is unable to estimate high-order aberrations.

Using the high-order version of COFFEE presented in this paper instead of classical phase diversity to compensate for SPHERE's NCPA would allow to estimate and compensate for high-order aberrations, leading to a contrast optimization far from the optical axis. Besides, since COFFEE is now able to work with any coronagraphic focal plane mask, one measurement will be enough to estimate the aberrations upstream of the coronagraph, instead of the two measurements required by the current baseline.

The coronagraphic images used by COFFEE are recorded from the near infrared detector IRDIS[15]. Table 1 gather the parameters used for COFFEE experimental validation: In order to record the diversity image, the diversity phase is introduced upstream of the coronagraph by modifying the reference slopes of the XAO loop, using a method similar to the one described by Paul *et al.*[9].

3.2 NCPA measurement

In this section, we introduce a calibrated aberration upstream of the coronagraph using the AO loop, creating a defocus aberration in the DM pupil plane. This aberration is then estimated by COFFEE, using two focal plane coronagraphic images (focused and diversified).

Figure 1 shows the result of the defocus estimation. One can easily see the defocus aberration pattern in the estimation performed by COFFEE (Figure 1, middle). As for the simulation, the accuracy of the estimation performed by COFFEE leads to a good match between the experimental image (Figure 1, left) and the image computed using COFFEE's estimation (Figure 1, right).

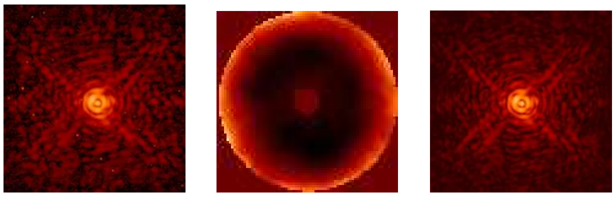

Fig. 1. Estimation of a defocus with COFFEE. From left to right: experimental image recorded from IRDIS, defocus aberration estimated by COFFEE, image computed by COFFEE from the estimated aberration.

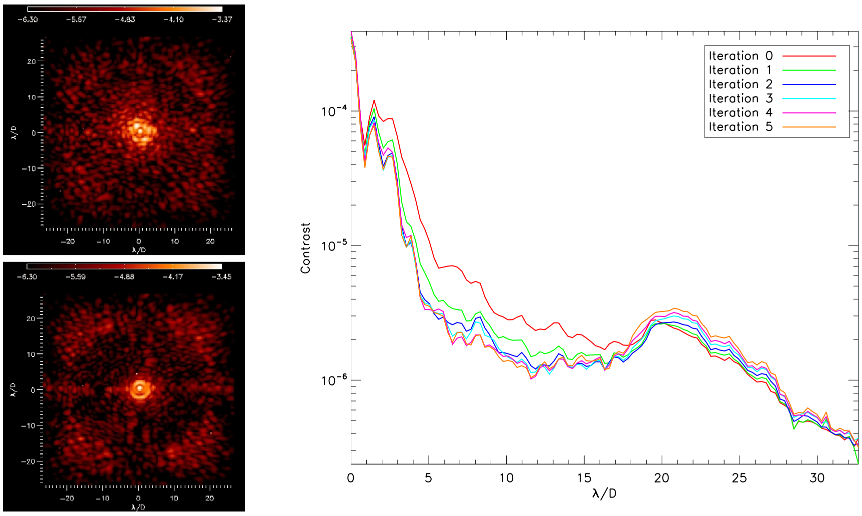

Fig. 2. SPHERE NCPA upstream of the coronagraph compensation using COFFEE ($g = 0.5$). Left: coronagraphic images recorded from IRDIS before compensation (top) and after 5 iterations of the PCL (bottom). Logarithmic scale for both images. Right: average raw contrast profiles for each iteration (iteration 0: before compensation).

3.3 Closed-loop process

Lastly, COFFEE's ability to compensate for the aberrations upstream of the coronagraph is demonstrated on the SPHERE instrument. To perform such an operation, we use a method named hereafter the Pseudo-Closed Loop (PCL) process[9,16]. This iterative process, which aims at modifying the reference slopes of SAXO (whose thorough description has been performed by C. Petit *et al.*[17]), is described below: for the PCL iteration i:

1. acquisition of the focused $\boldsymbol{i}_{\text{foc}}$ and diverse $\boldsymbol{i}_{\text{div}}$ images;
2. estimation of the aberration $\hat{\boldsymbol{\phi}}_u^i$ upstream of the coronagraph;
3. computation of the corresponding reference slopes correction $\delta \boldsymbol{s}_i = g \boldsymbol{\mathcal{M}} \hat{\boldsymbol{\phi}}_u^i$, where g is the PCL gain. $\boldsymbol{\mathcal{M}}$ is a matrix which represent the linear transformation that allows to compute slopes from a given aberration. This matrix can easily be computed from the XAO loop matrices.
4. the AO loop is closed on the modified reference slopes.

The computation time required for one PCL iteration is typically 6 minutes, allowing us to compensate for quasi-static aberrations upstream of the coronagraph.

Figure 2 present the results obtained after 5 iterations of the PCL. On this figure, one can see that the compensation of the aberrations upstream of the coronagraph allows to remove speckles

in the coronagraphic images (figure 2, left) in the whole detector plane area controlled by the AO loop. The average raw contrasts are computed from the coronagraphic images. Their plot (figure 2, right) clearly shows a contrast improvement in the focal plane when the number of iterations increases. As it has been said previously, classical phase diversity (which is the current SPHERE baseline) is unable to estimate high-order frequencies. Concretely, using phase diversity estimation, it is possible to optimize the contrast in the detector plane up to $8\lambda/D$. As one can clearly see on figure 2, the estimation performed by COFFEE, which includes high-order aberrations, allows to deal with speckles up to $18\lambda/D$.
On Figure 2 (right), one can notice that beyond $18\lambda/D$, the incoming energy on the detector is increasing. This behavior seems to originate in the DM central actuators, which are not controlled the same way than the others actuators, since they will be located under the telescope central obstruction. This increasing of high-order speckles does no longer appear when there is a central obscuration in the entrance pupil.

4 Conclusion

In this paper, an extended version of our coronagraphic phase diversity, nicknamed COFFEE, has been presented. The use of a regularized pixel basis in the estimation (Section 2) allows COFFEE to estimate high order aberrations with nanometric precision. This high-order version of COFFEE has been successfully validated on the SPHERE instrument during its final integration phase (Section 3): in this paper, we demonstrated the ability of COFFEE to estimate aberrations on SPHERE in Section 3.2, and Section 3.3 described the closed loop process, where COFFEE's estimation is used to improve the contrast on the detector.

Further developments of COFFEE will include a joint estimation of the amplitude aberrations, mandatory to reach a very high contrast level, such as the one required for the detection of earth-like planets. Besides, COFFEE can be extended to work on ground-based, long exposure images with residual turbulence induced aberrations. Another perspective lies in the optimization of the computation time required by COFFEE to estimate the aberrations. Such developments will eventually allow COFFEE to work on-line, during the scientific exposure.

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