Towards on-sky coronagraphic wave-front sensing: Preliminary validation of coronagraphic phase diversity in the presence of residual turbulence

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ABSTRACT

In this proceeding, we present the first results of the in-lab experimental validation of COFFEE, the coronagraphic phase diversity, in the presence of adaptive-optics corrected turbulence residuals.

Keywords: phase diversity, high contrast imaging, inverse problems, instrumentation: adaptive optics, methods: data analysis, techniques: high angular resolution, techniques: image processing.

1. INTRODUCTION

Direct imaging of exoplanets is an important objective of contemporary astronomy. Two main difficulties must be solved in order to perform direct imaging of an exoplanet using a ground-based telescope. The first difficulty is the blurring of the images by atmospheric turbulence, which is preponderant over diffraction for telescope diameters of more than a few decimeters. This is addressed by the use of adaptive optics, which is the topic of this conference. The second difficulty is the extremely high contrast between the planet and its star, often of the order of (at least) 10^{-6}. This is addressed by the use of a coronagraph.

The ultimate limitation for imaging exoplanets comes from the quasi-static aberrations of the system. Indeed, any thermo-mechanical constraint, polishing anomaly, or generally any defect of the optical system results in a wave-front aberration. If they are not corrected by the adaptive optics system, these wave-front aberrations propagate in the optical system, and finally yield speckles in the focal plane of the detector. These speckles are of typical size λ/D, where λ is the wavelength of observation and D is the diameter of the entrance pupil of the telescope. Consequently, they can be easily mistaken for an exoplanet. In order to correct these aberrations, several methods have been developed. In this proceeding, we present an experimental in-lab validation of the extension of COFFEE, the coronagraphic diversity, to the estimation of phase defects through residual turbulence. A more developed and quantitative estimation is developed in a journal article.[1]

In section 2, we will recall the formalism of COFFEE. In section 3, we will recall the model for imaging in the presence of adaptive-optics-corrected turbulence developed in Ref. [2]. In section 4, we present the first results of the experimental validation itself.

2. PRINCIPLE OF CORONAGRAPHIC PHASE DIVERSITY (COFFEE)

As we explained in the introduction, any aberration on the optical path generates speckles in the scientific images if it is not corrected by the adaptive optics loop. Some aberrations, even if they are seen, are not corrected by the deformable mirror. For example, any aberration of spatial frequency superior to the cut-off of the deformable mirror is uncorrected. This explains that there is only a certain zone in the scientific image where we can hope to find exoplanets. Some aberrations, on the contrary, are unseen by the adaptive optics, for example the non-common path aberrations between the wave-front sensor and the science camera. Consequently, the scientific

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camera itself must be used as a wave-front sensor in order to measure those aberrations, which will be then corrected by the deformable mirror of the adaptive optics system.

COFFEE[3] is an extension of phase diversity to coronagraphic system, and thus relies only on few data: images acquired using the scientific camera, a precise optical model of the system, along when possible with information on the statistical properties of the unknown aberrations. COFFEE then decides which is the phase aberration that is the most consistent with its input. Consequently, one strength of COFFEE is that it does not need any modification of the system. In practice, COFFEE only needs a focal image and a diversity image in order to estimate the phase aberrations of the instrument. Let us explain this point, which is a classic feature of the phase diversity methods. Using only one image of the science camera as data is not enough, because any aberration of even order yields the same image as its opposite (for example, when presented with an out-of-focus image, one cannot tell whether the defocus is positive or negative). A second image generated by introducing a known aberrations, for example using the deformable mirror of the adaptive optics, will remove this ambigüity.

Formally, COFFEE is a maximum *a posteriori* method, relying on the Bayesian formulation of an inverse problem.[4] It consists in finding $\hat{\phi}$ that minimizes

$$J(\phi_u) = \sum_{(x,y)} \left\| \frac{\text{images}(x,y) - \text{model}[\phi_u](x,y)}{\sigma(x,y)} \right\|^2 + \mathcal{R}(\phi_u). \tag{1}$$

ϕ_u is the phase aberrations that generates speckles. In this equation, "images" is the set of experimental scientific images acquired by the scientific camera, "model" is a set of outputs of our model of the instrument, σ is the standard deviation of the measurement noise, and $\mathcal{R}$ is a regularization term which represents *a priori* information on ϕ_u.

3. LONG-EXPOSURE CORONAGRAPHIC IMAGING IN THE PRESENCE OF TURBULENCE

In practice, quasi-static aberrations evolve during the night, and are responsible for non-negligible levels of aberrations.[5,6] Moreover, on-sky quasi-static aberrations differ from aberrations measured using an internal source.[7] Consequently, calibration of phase aberrations must should be done on-sky several time per night. In order for COFFEE to do this, as we discussed in Sec. 2, and as is apparent from Eq. 1, we must have a good model of image formation. In this case, we need a precise model of coronagraphic imaging through turbulence. This is the reason why we have extended François Roddier's expression for long-exposure images in the presence of turbulence[8] to coronagraphic images in the presence of turbulence. Here, we recall the main characteristics of this expression.

Modeling light propagation using Fourier optics, the coronagraphic point spread function (in the absence of turbulence) is expressed as:

$$h_c\left(\alpha; \psi_u, \psi_d\right) = \left|\mathcal{F}^{-1}\left\{\psi_d \times \mathcal{F}\left[\mathcal{M} \times \mathcal{F}^{-1}\left(\psi_u\right)\right]\right\}(\alpha)\right|^2, \tag{2}$$

where α is the angular coordinate in the detector focal plane; $\psi_u = \exp(\mathrm{i}\phi_u)$ is the upstream aberration field (ϕ_u being the upstream phase aberration); $\psi_d = \exp(\mathrm{i}\phi_d)$ is the downstream aberration field; $\mathcal{M}$ is the coronagraphic focal plane mask in the presence of turbulence.

In the same manner, the coronagraphic point spread function in the presence of turbulence is the average

$$h_{lec}\left(\alpha; \psi_u, \psi_d\right) = \left\langle \left|\mathcal{F}^{-1}\left\{\psi_d \times \mathcal{F}\left[\mathcal{M} \times \mathcal{F}^{-1}\left(\psi_u \exp(\mathrm{i}\phi_t)\right)\right]\right\}(\alpha)\right|^2 \right\rangle_t, \tag{3}$$

where ϕ_t is the very short-lived atmospheric turbulence phase screen.

Extensive use of the Wiener-Khintchine theorem and assumption that turbulence is a stationary ergodic process, the following analytic expression holds (see Ref. [2] for proof and physical interpretation):

$$h_{lec}\left(\alpha; \psi_u, \psi_d\right) = \iint \exp\left[-\frac{1}{2} D_\phi(\alpha')\right] h_c\left(\alpha; \psi_u \exp(\mathrm{i}2\pi\alpha' \cdot \mathrm{Id}), \psi_d\right)\, \mathrm{d}\alpha', \tag{4}$$

where D_ϕ is the phase structure function of the (potentially adaptive-optics corrected) atmospheric turbulence.

This formula is computationally efficient, which allowed us to integrate it into COFFEE.

4. FIRST EXPERIMENTAL RESULTS

Now that we have a model for coronagraphic imaging through turbulence to use in our Eq. 1, we wish to validate it experimentally. For that, we used the Marseille imaging testbed for high contrast imaging (MITHIC) at the laboratoire d'astrophysique de Marseille. MITHIC is a coronagraphic system equipped with a spatial light modulator in the upstream pupil plane, which allows to create upstream phase aberrations with a very high spatial resolution. The downside of this solution is that the incoming light needs to be polarized. MITHIC is also equipped with a module of rotating phase screens which simulate the residual atmospheric turbulence of SPHERE on the European very large telescope (VLT).

We proceed in three steps for our preliminary validation. The first step is to impose a flat on the spatial light modulator. The resulting images in the focal plane of the detector are presented on Fig. 1. Note that the structure of this image is very similar to AO-corrected coronagraphic images obtained on SPHERE.[9]

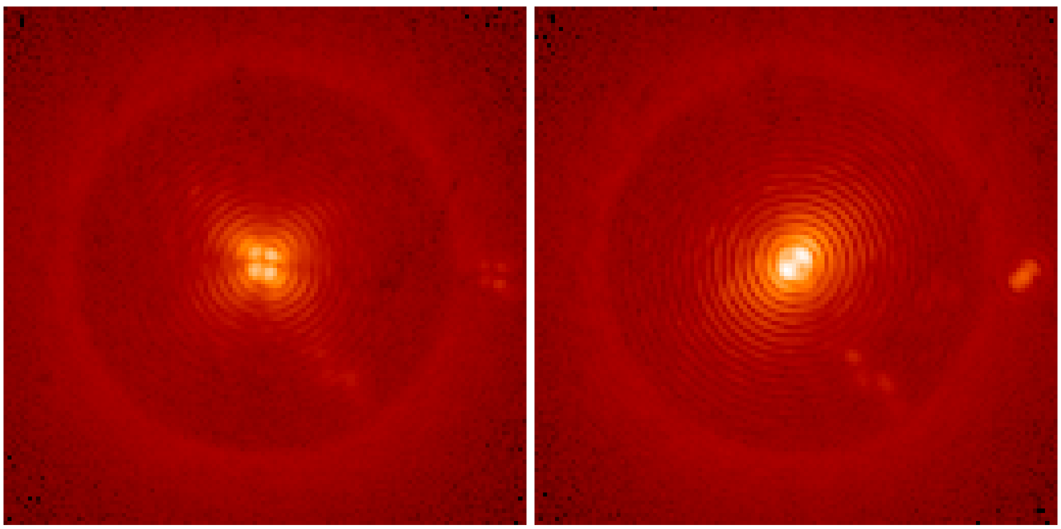

Figure 1. Focal (left) and diversity (right) images obtained with a flat on the spatial light modulator

The second step is to impose a distinctive phase aberration on the spatial light modulator. We chose a high-order aberration with an F-shape, which is shown on Fig. 2.

The resulting images in the focal plane of the detector are presented on Fig. 3.

The third and last step is to perform COFFEE reconstructions on the images presented on Fig. 1 on the one hand, and on those presented on Fig. 3 on the other hand. The result is presented on Fig. 4.

This first result shows qualitatively that COFFEE is able to reconstruct phase aberrations in the presence of residuals of adaptive-optics corrected turbulence.

5. CONCLUSION

In this proceeding, we have shown experimentally that it is possible to use COFFEE, the coronagraphic phase diversity, to measure quasi-static aberration in the presence of residual turbulence. More quantitative results are in progress. The next step is to validate the technique on-sky.

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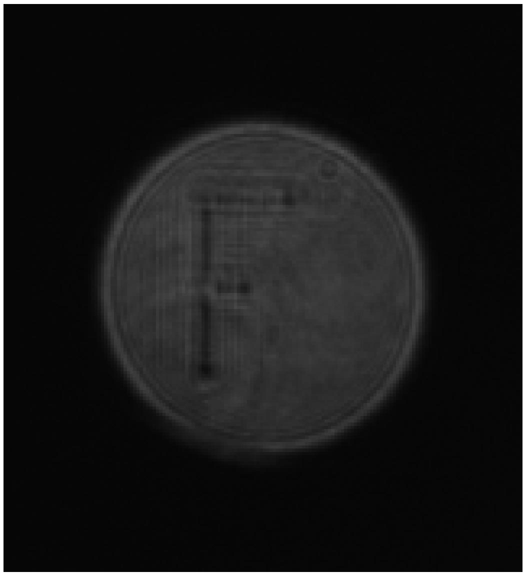

Figure 2. Phase imposed on the upstream pupil thanks to the spatial light modulator (pupil imaging on an auxiliary path)

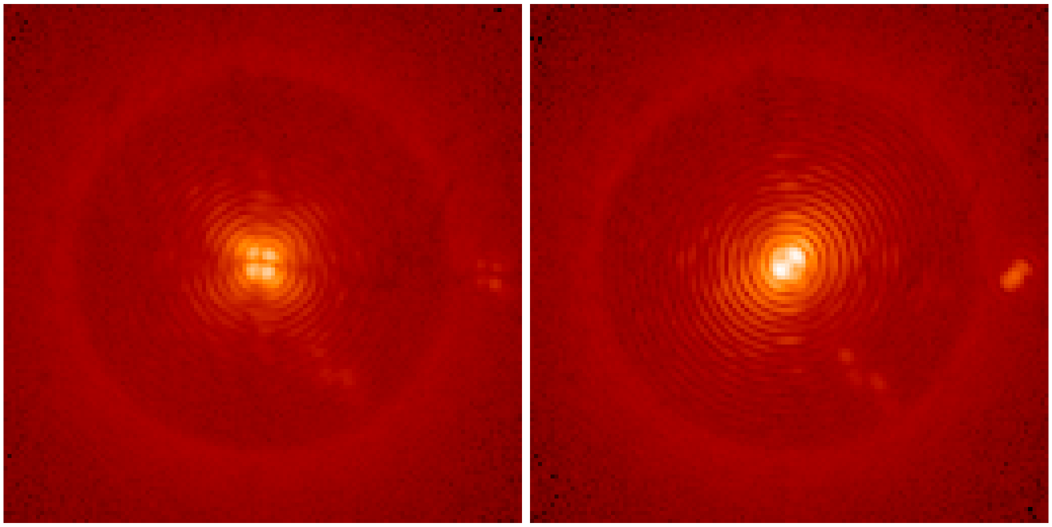

Figure 3. Focal (left) and diversity (right) images obtained with an F-shape on the spatial light modulator

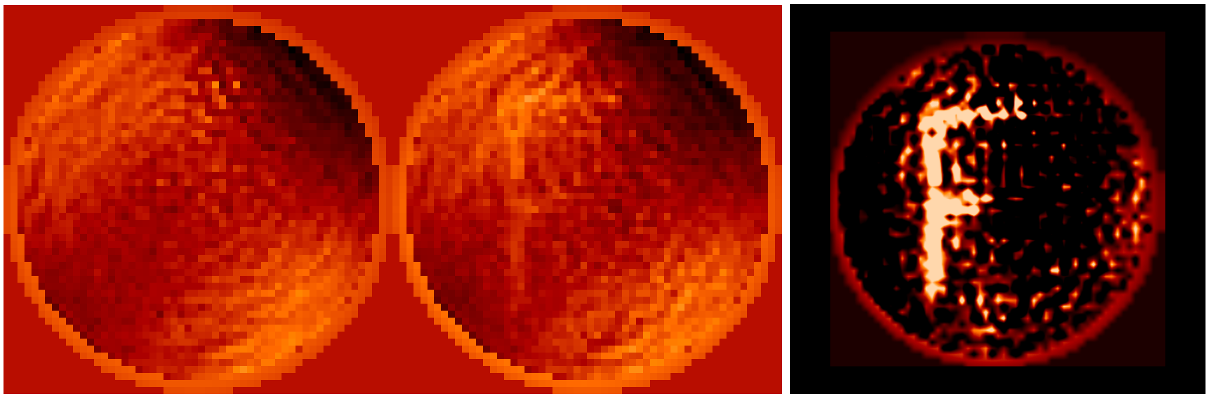

Figure 4. Left: COFFEE reconstruction of the upstream phase with a flat on the SLM. Middle: COFFEE reconstruction of the upstream phase with an F-shape on the SLM. Right: Difference between middle and left.

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