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FOCAL PLANE WAVEFRONT SENSING WITH A SELF-COHERENT CAMERA

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Abstract. Characterization of exoplanets with long orbital periods requires direct imaging which is challenging. The objective is the suppression of the light of the star that is 10^4 to 10^{10} times brighter than its planet which is at less than 1 arcsec. Coronagraphs were proposed to suppress the stellar light but their performance is strongly limited by wavefront aberrations that induce stellar speckles in the science image. Adaptive optics correct for most of the atmospheric turbulence but quasi-static aberrations still remain because of flexures with pointing, optical aberrations of moving optics, and so on. Classical adaptive optics cannot calibrate the quasi-statics because of differential aberrations between the science image and the wavefront sensing image. Since 2006, our team works on a self-coherent camera (SCC) that estimates both phase and amplitude aberrations from the science image. The SCC creates a reference beam that interferes with the speckles in a Fizeau scheme and spatially modulates them in the science image. Demodulating the signal, we retrieve the complex amplitude of the electric field in the science image and use a deformable mirror to enhance the contrast in a dark hole. We obtained contrasts as high as 10^8 between 4 and $15\,\lambda/D$ in laboratory but chromatism may be an issue working with large bandwidths. In this paper, we present a new version of the SCC that may overcome this limitation. We ran preliminary numerical simulations and obtained preliminary laboratory results.

1 Introduction

Direct imaging of exoplanets is currently the only technique that can discover planets in the outer part of the exoplanetary systems. It is thus the only way to complete the sample of known exoplanets and to constrain the models of planetary formation and evolution. Moreover, direct imaging provides information on the planet photometry or spectrometry, which helps putting constraints on the exoplanetary atmosphere models. The technique has been successful in peculiar cases using current instruments [1–3] but it is so challenging that dedicated instruments as SPHERE [4] and GPI [5] were designed during the last years and are to be on-sky. They will probe Jupiter-like planets around nearby young stars and increase our knowledge about these objects. But, lighter planets as Neptune, Super-Earth, or Earth are $\geqslant 10^7$ fainter than their star and at less than a fraction of arcsec: they will not be detected with these instruments. Thus, the next generation of direct imaging instruments will need new techniques to reach very high contrast levels and detect such faint planets.

In this context, we have been working on a Self-coherent camera (SCC) that can be used as an a posteriori speckle calibrator [6–8] or as a focal plane wavefront sensor for active correction of speckles [8–15]. We demonstrated through numerical simulations and laboratory experiments that the association of a SCC and a four quadrant phase mask [16, FQPM] can be used to detect sources as faint as 10^8 fainter than their hosting star in monochromatic light [17,18]. However,

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the version of the SCC that has been used so far is sensitive to chromatism when the bandpass is larger that ∼ 5%. In this paper, we present a new version of the SCC that may overcome the chromatism limitation. We briefly recall the SCC principle and why it is sensitive to chromatism in § 2. Then, we present the multi-reference SCC and we give a preliminary results obtained in laboratory in § 3. Finally, we conclude in § 4.

2 SCC principle and chromatism

In this section, we briefly recall the principle of the current version of the SCC (§ 2.1) and why it is sensitive to chromatism (§ 2.2).

2.1 Principle

The first version of the SCC has been presented in several papers [11, 17]. Fig. 1 is the schematics of the current version of the SCC associated to a FQPM coronagraph. The telescope beam

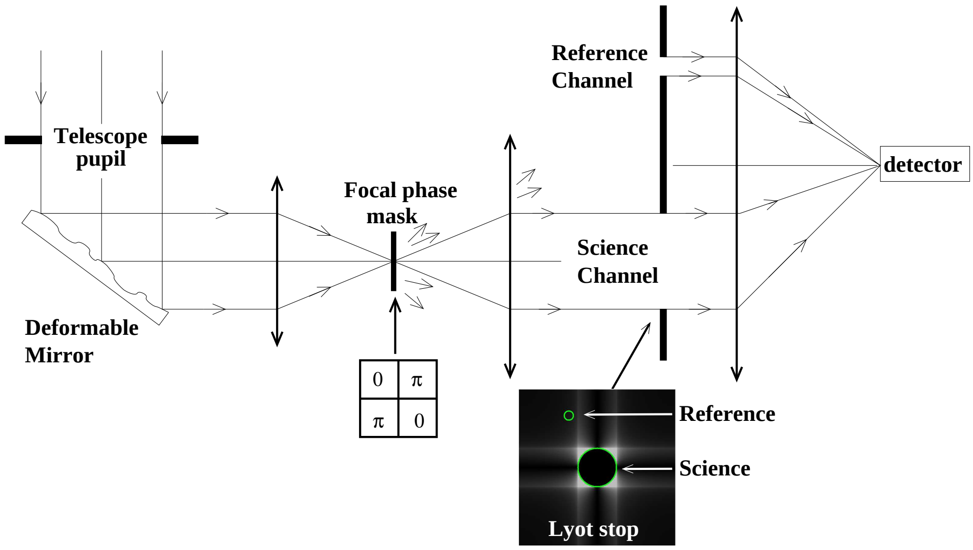

Fig. 1. Schematics of a self-coherent camera associated with a FQPM.

issued from the on-axis star hits a deformable mirror. Then, it converges onto the focal plane mask. The light is diffracted outside the geometrical pupil in the next pupil plane (science channel in the figure). In a classical coronagraph, a Lyot stop is used to block all the diffracted light so that no stellar light reaches the detector if the beam is aberration-free. In a more realistic case, phase and amplitude aberrations exist and a small part of the stellar light goes through the science channel and forms speckles on the detector. To calibrate these speckles, we modified the classical Lyot stop adding a small hole called reference channel that picks up a small amount of stellar light. Making the science and the reference channels interfer in a Fizeau scheme, the so-called SCC spatially modulates the stellar speckles on the detector. If a planet is angularly resolved by the telescope, its light is not affected by the focal plane mask and is only present in the science channel. As the stellar light of the reference channel and the planet light of the science channel are not coherent, the planet image is not spatially modulated on the detector.

Finally, the SCC image is composed of spatially modulated speckles by Fizeau fringes and the planet image.

Taking the Fourier transform of the SCC image, we obtain three peaks in the correlation plane (Fig. 2). Selecting one of the two lateral peaks, we can estimate the complex amplitude

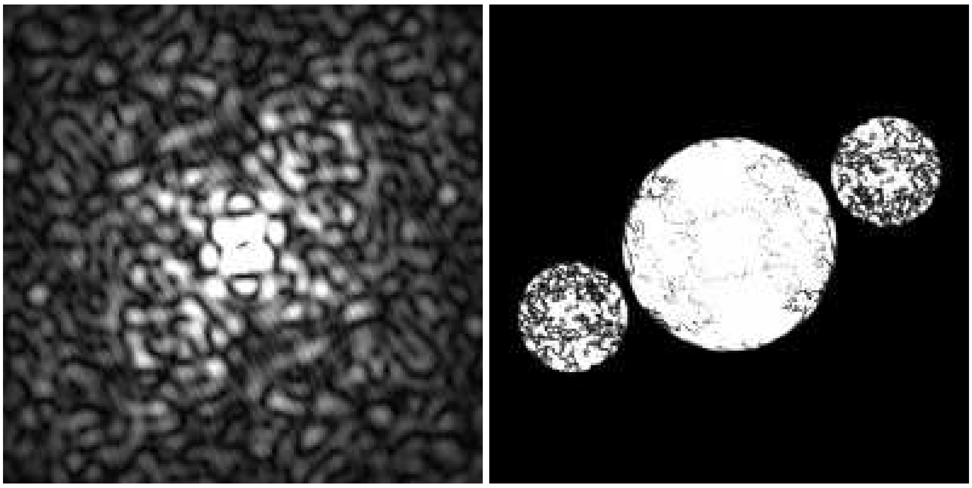

Fig. 2. SCC image in monochromatic light (left) and the modulus of its Fourier transform (right).

of the electric field of the speckles in the detector plane [13,17]. It is then possible to control a deformable mirror (DM) to minimize the stellar energy within a zone of the detector called dark-hole (DH, left in Fig. 3). The size of the DH (32×32 λ/D here) is set by the number $N = 32$

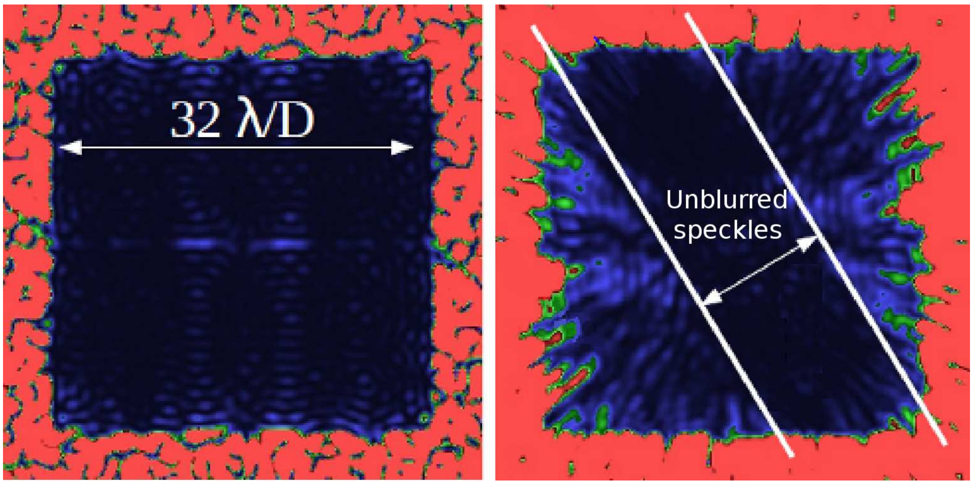

Fig. 3. Dark hole in the SCC image after aberration correction with a 32x32 DM. Left: monochromatic light. Right: 10% bandpass. Numerical simulations with only phase aberrations.

of actuators on the DM and by the choice of correcting the phase aberrations only (full DH) or both the phase and the amplitude aberrations (half-DH). For Fig. 3, only phase aberrations have been considered in the numerical simulations.

2.2 Chromatism impact

The version of the SCC presented in Fig. 1 is chromatic. The fringes that modulate the speckles are perpendicular to the line that joins the centers of the science and the reference channels and their spatial period is λ/ξ_0, where ξ_0 is the separation between the two channels in the Lyot stop plane. In polychromatic light, each wavelength produces a fringe pattern with a different period, which explains the classical property of Fizeau fringes: in polychromatic light, the fringes get blurred going away from the optical axis (where the optical path difference is zero) in the perpendicular direction of the fringes. In the case of the SCC, it means that speckles that are away from the center of the image in the perpendicular direction of the fringes are not well encoded by the fringes whereas speckles in the direction of the fringes are well encoded whatever their distance to the center of the image (Fig. 4). The deformation of the lateral peaks in the correlation plane (right in Fig. 4) corresponds to the blurring of the fringes in the SCC image. As a result, speckles with no modulation (i.e. blurred fringes) cannot be corrected with this version of the SCC as seen in Fig. 3 (right).

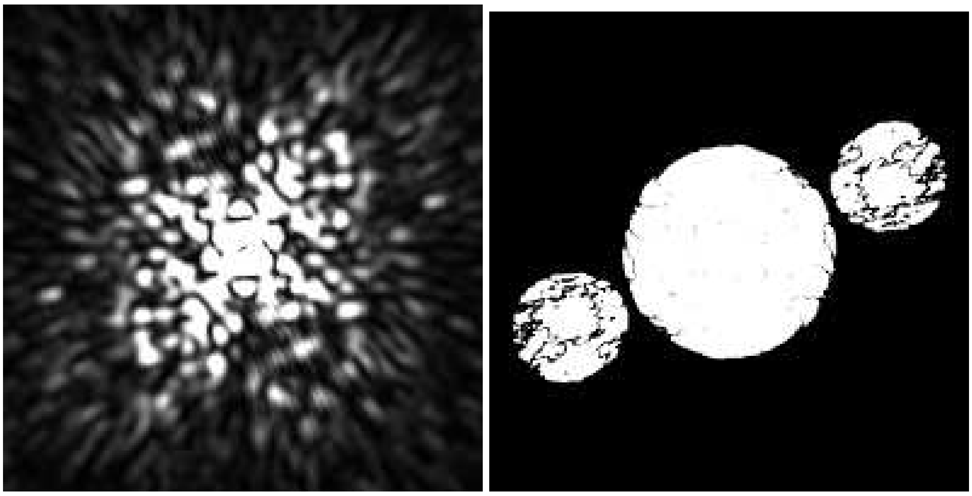

Fig. 4. SCC image for a 10% bandwidth (left) and the modulus of its Fourier transform (right).

3 Multi-reference SCC

We propose an upgrade of the SCC presented in Fig. 1 to overcome its chromatic limitation. We add a second reference channel in the Lyot stop at $\sim$ 90 degrees from the first reference channel (left in Fig. 5). The second reference channel creates fringes that are at $\sim$ 90 degrees from the fringes induced by the first reference channel. Doing so, all speckles in the field of view of the SCC image are modulated by at least one of the fringe pattern. If the bandwidth is very large, the fringes get blurred very fast when going away from the center of the SCC image and a third reference channel (right) and thus, a third fringe pattern, may be needed to cover the full field-of-view with fringes.

Then, as each speckle is encoded by at least one reference, the information on all the speckles is included in the lateral peaks of the correlation plane of the SCC image ; each reference channel giving two symmetric peaks. Selecting one peak of each pair, it is thus possible to

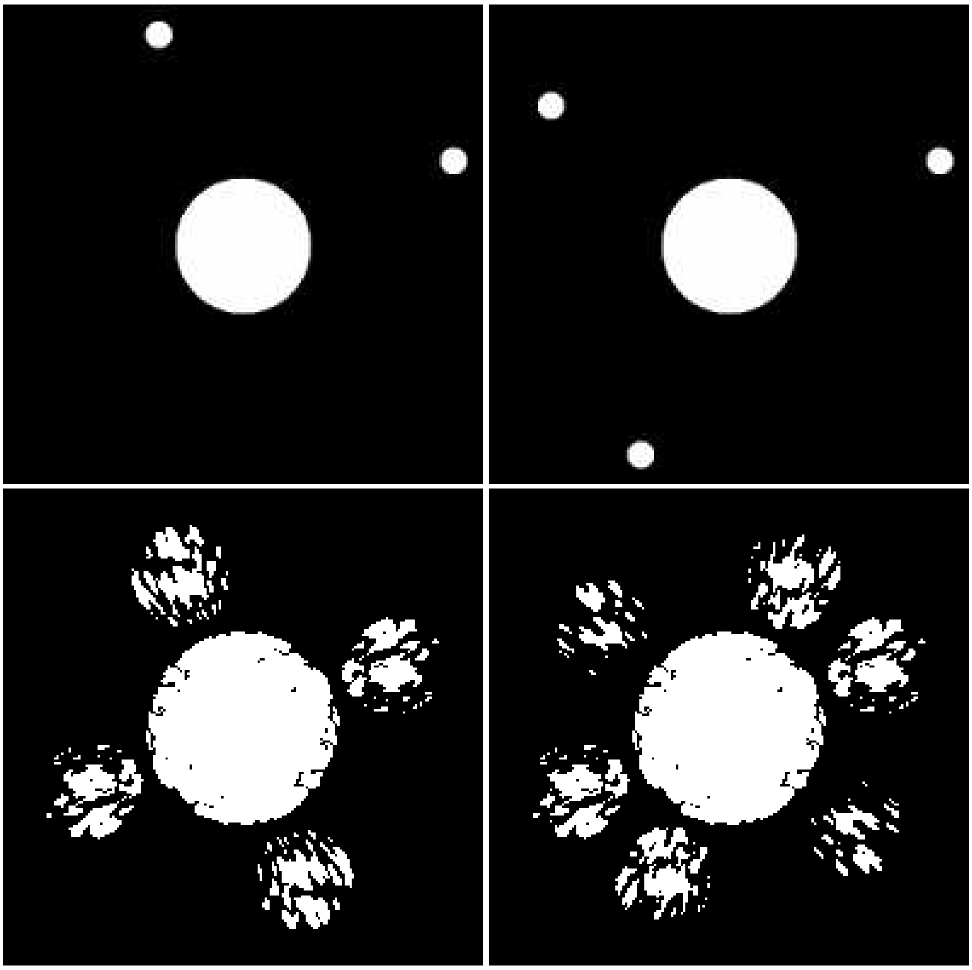

Fig. 5. SCC Lyot stop with two (left) and three (right) reference channels.

estimate the complex amplitude of the electric field associated to any speckle in the SCC image. A forthcoming paper will give the full formalism of the estimation.

Once the complex amplitude of the electric field is estimated, we control the deformable mirror to minimize the speckle energy in the DH. Fig. 6 shows experimental images after correction using one reference channel (left) or two reference channels (right) to control the deformable mirror in polychromatic light ($\sim$ 6% bandwidth). Only one half of the full DH is corrected because there are both phase and amplitude aberrations. In the case of one reference channel, the speckles in the upper left of the DH are not well encoded (fringes get blurred there) and cannot be corrected. In the case of two SCC reference channels, all the speckles are well encoded and the complete half-DH is cleared of speckles. The residuals in this image are dominated by chromatic effects of the FQPM coronagraph, which is not achromatic in this experiment.

4 Conclusions

In previous papers, our team demonstrated from numerical simulations and experimental performance that the self-coherent camera (SCC) can be used as a focal plane wavefront sensor to reach very high contrast images ($\sim 10^8$ between 4 and $13\,\lambda/D$). However, we also confirmed from laboratory results that the SCC is sensitive to chromatism as expected from a theoretical point of view.

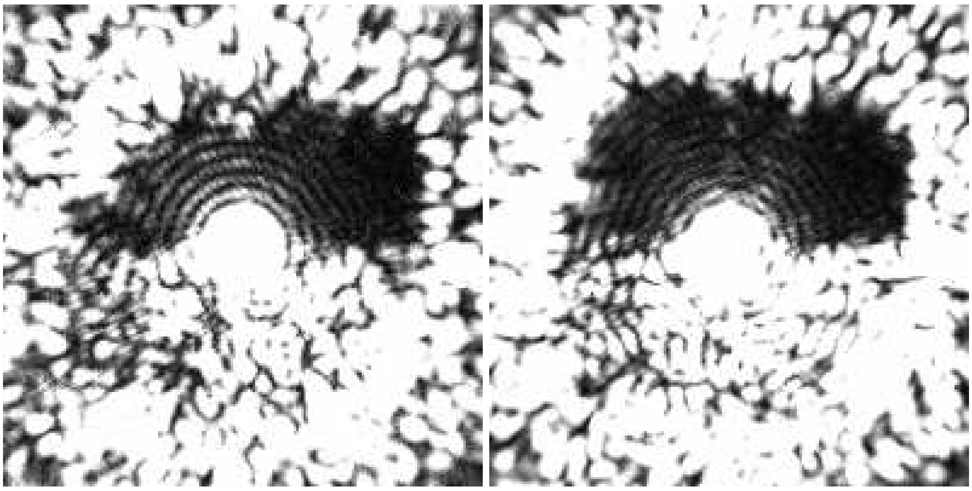

Fig. 6. Laboratory SCC images after aberration correction in polychromatic light (~ 6% bandwidth) using one (left) or two (right) reference channels.

In the current paper, we presented an upgrade of the SCC that makes it less sensitive to chromatism. The upgrade is very easy to implement: a second hole is added to the SCC Lyot stop at roughly 90 degrees from the first reference channel. Thus, two perpendicular fringe patterns spatially modulate the stellar speckles in the SCC images. In polychromatic light, any speckle in the dark hole is modulated by at least one of the two fringe patterns and the complex amplitude of the electric field can be retrieved from the two-reference SCC image. We showed laboratory images obtained in polychromatic light (~ 6%) after correction of both phase and amplitude aberrations with a single deformable mirror. In the case of the one-reference SCC (used in the previous papers), part of the half dark hole cannot be corrected because some speckles are not well encoded (i.e. their fringes are blurred). In the case of a two-reference SCC, the correction is efficient everywhere in the half dark hole. These preliminary results are not quantitative because we had no flux calibration during the experiment. However, they prove that the multi-reference SCC overcomes the chromatic limitation of the one-reference SCC that were used in our previous papers (at least for ~ 6% bandwidth).

In a forthcoming paper, we will describe the complete formalism that is used to estimate the electric field from the multi-reference SCC image. We will also study how achromatic the multi-reference SCC is. Finally, we will give quantitative results obtained in laboratory.

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