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MULTI-CHANNEL ALGORITHM FOR EXOPLANETS DETECTION BY ANGULAR DIFFERENTIAL IMAGING.

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Résumé. In the frame of the SPHERE planet finder project, we propose a novel method, based on detection theory, for the efficient detection of planets using angular difference imaging, and we validate it by simulations. This method uses a multi-channel correlation algorithm, and presents a noticeable gain on detectivity profiles compared to previous studies on angular differential imaging.

1 Introduction

The direct detection of exoplanets from the ground is a very promising field of astronomy today. The light emitted by exoplanet is related to the composition of their atmosphere. This detection from the ground is a technological challenge, since the contrast between the star and its companion is no less than 10^6 in IR bands. The European project SPHERE 1 is the planet searcher of VLT (ESO), based on direct imaging is the near-IR. The goal of SPHERE is to detect hot Jupiters, orbiting sun-like stars at $10pc$ from the Sun. These planets present atmosphere rich in methane, and present therefore interesting spectral signatures around $1.6\mu m$. The planest are searched for at a few diffraction elements (λ/D) from their parent star.

The SPHERE instrument is the combination between several optical features, all of them optimised toward the final goal, which is exoplanet detection.

First of all, the extreme adaptive optics system concentrates the light into a coherent Airy pattern, performing a real-time correction of atmospheric turbulence. The optical quality is a key factor in direct exoplanet detection, since the main limitation of faint objects is demonstrated to be the residual speckles in images. These speckles are the consequence of an imperfect correction of statics aberrations.

Then, the coronagraphic stage allows to deeply attenuate the star flux. The photons are physically removed, allowing the reduction of the photon noise in the final image. The considered coronagraphs in the SPHERE project are a Lyot coronagraph (2), a Four Quadrant Phase Mask (FQPM, 3), or an apodized Lyot coronagraph (APLC, 4).

The combination of XAO and coronagraphic device is necessary to reduce both speckle and photon noise in the final image, but is not sufficient. The contrast between the star and the planet at $1.6\mu m$ is next to 10^6 ! In order to reach the ultimate detection performance needed to detect Hot Jupiter, it is mandatory to combine the optical devices to an *a posteriori* smart calibration of all residual features present in the final image. The static or quasi-static speckles are still the main noise source and their calibration is needed to obtain the required calibration. In order to perform this calibration, the SPHERE instrument includes the ability to perform spectral and angular differential imaging 5, 6.

Spectral differential imaging consists in acquiring simultaneous images of the system star-companion at different wavelengths. The spectral signatures of the exoplanet's atmosphere ensures that the planet's response will significantly vary in the images, while the star response and therefore the speckles remain the same.

Angular differential imaging is a method originally designed for the calibration of residual static speckle of the Hubble Space Telescope. The idea was to perform a rotation of the entire telescope, and therefore of the observed field on the detector, whereas the static speckles remain the same. In the frame of SPHERE and therefore of a ground based observation, the field rotates naturally as the instrument follows the object in the sky.

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2 Problematic

The main problematic of companion detection is to disentangle the companion's signal from the static speckles due to residual aberrations. These speckles present the same characteristic angular size as the diffraction element, λ/D, and the same size as the companion's signal. With no more information, it is impossible to discriminate between the speckles and the companion.

In the case of spectral imaging, we make use of two spectral channel, between bands $H2 = 1.5905\,\mu$m and H3=$1.6435\,\mu$m. These channels supply images of the system star-companion centred in these bands.

In the case of angular imaging, we additionally make use of moreover of several images where the companion has moved by a few pixels (depending on the delay separating two images). The additional information we have is therefore the expected trajectory of the companion in these numerous « temporal channels ».

In this paper, we investigate the processing of angular images.

3 Adopted approach for angular differential imaging

The different possible approaches are the following ones :

- jointly estimate the coronagraphic response of the star, and the companion itself (position and amplitude). This approach has been adopted in 7.
- numerically remove the star signal, and only estimate the planet.

In the framework of the SPHERE project, the static aberrations are assumed not to be perfectly known. Even if they are precisely calibrated off-line, the static aberrations are known to evolve during observing time, and the estimation of the star signal should therefore be done several times during night. We therefore chose the second option, which consists in cancelling the star image numerically.

This suppression is done by combining the successive images in a moving subtraction, as shown in Figure 1. Hereafter, the new data are the images differences. The estimation of the companion's position and amplitude is done on these new data, through a Maximum Likelihood approach.

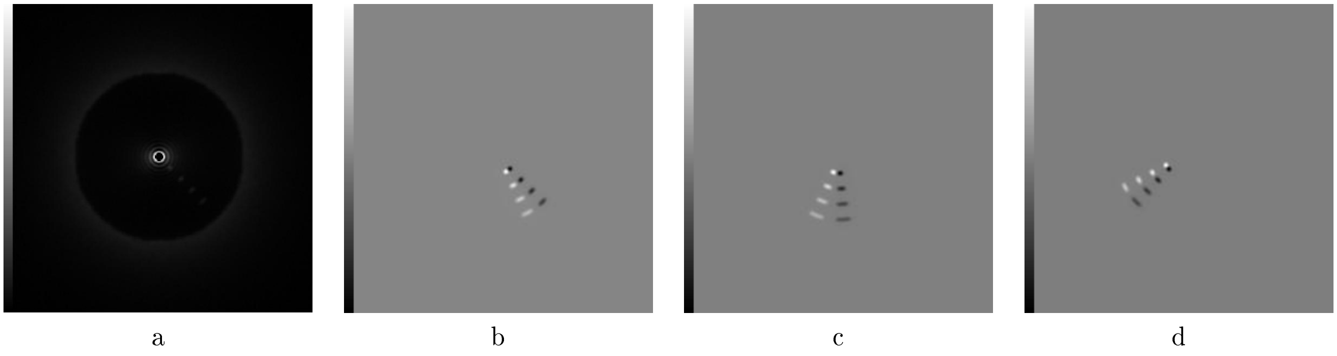


Fig. 1. [a] One raw noiseless coronagraphic image with 4 companions at 4, 8, 12 and $16\lambda/D$. [b,c,d] Moving difference of 6 successive images. The images are subtracted two by two, cancelling completely the star response in this UN-noised case.

4 ML estimation for position and amplitude of the companion

The new data are the differential images. These data are time-dependent and are composed of a point-like source at an unknown position, and of an unknown amplitude.

$$\boldsymbol{i}_t(\boldsymbol{r}) = a.\boldsymbol{p}_t(\boldsymbol{r};\boldsymbol{r}_0) + \boldsymbol{n}_t(\boldsymbol{r}). \tag{4.1}$$

with, as unknowns : the amplitude a and the initial companion position $\boldsymbol{r}_0$, and with $\boldsymbol{p}_t$ being the known pattern of the companion. It is given by the difference of two PSFs.

The assumed hypothesis are the presence of one companion, and a white Gaussian stationary noise. The noise statistics hypothesis may be refined without complexity to account for both photon and detector noises.

The maximum likelihood approach consists in searching $(\hat{a}, \hat{\boldsymbol{r}}_0)$ that maximise the likelihood $L(a, \boldsymbol{r}_0)$. The optimal value for a is computable analytically for each given $\boldsymbol{r}_0 : \hat{a}(\boldsymbol{r}_0)$.

$$\hat{a}(\boldsymbol{r}_0) = \frac{\sum_t \sum_{\boldsymbol{r}} p_t(\boldsymbol{r};\boldsymbol{r}_0) i_t(\boldsymbol{r};\boldsymbol{r}_0)}{\sum_t \sum_{\boldsymbol{r}} p_t^2(\boldsymbol{r};\boldsymbol{r}_0)} \tag{4.2}$$

The likelihood $L'(\boldsymbol{r}_0) \triangleq L(\hat{a}(\boldsymbol{r}_0), \boldsymbol{r}_0)$ is an increasing function of

$$C(\boldsymbol{r}_0) = \sum_t \sum_{\boldsymbol{r}} \boldsymbol{i}_t(\boldsymbol{r}) \, . \, \boldsymbol{p}_t(\boldsymbol{r};\boldsymbol{r}_0). \tag{4.3}$$

with $C(\boldsymbol{r}_0)$ being the multi-channel correlation between the data and the pattern of the companion 8. This co-added correlation signal informs about the companion parameters : the position of correlation peak gives the position of companion in the field of view, and the amplitude of the peak gives the estimation of the amplitude of the companion.

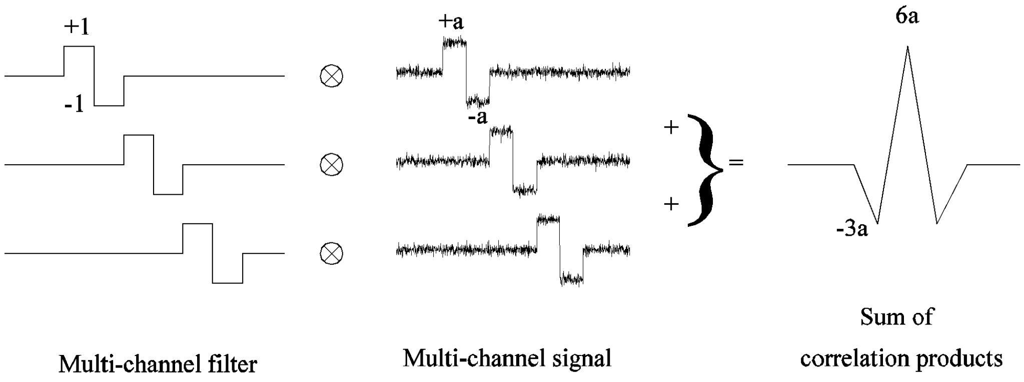


FIG. 2. Principle of multi-channel correlation. The individual correlation signals are co-added in one correlation signal.

5 Implementation

Our implementation of this method consists in the following points :
- for each initial supposed position of the companion $\boldsymbol{r}_0$, we compute the pattern of the planet $\boldsymbol{p}_t(\boldsymbol{r};\boldsymbol{r}_0)$ for each moment t,
- as the correlation in a Cartesian referential needs sub-pixellic shifts of the pattern, the computing cost is too high. The implemented solution consists therefore in projecting both the data and the patterns in a polar referential, where the correlation of the images by the rotated pattern resumes to a simple and low-cost translation computation, as seen in Figure 3
- for each radius ρ,
  - the pattern of the companion is computed (this pattern is almost independent of θ,
  - the likelihood is computed (Figure 5),
  - then, the correlation map is thresholded.

6 Conditions of simulation

The conditions of simulation are summed up below :
- 4 companions are introduced, respectively situated at 4, 8, 12 and $16\lambda/D$ from the star, the flux ratio of each companion with respect to the star flux is 3.10^5,

$\boldsymbol{i}_t(\boldsymbol{r}) \to \boldsymbol{i}'_t(\rho,\theta)$:

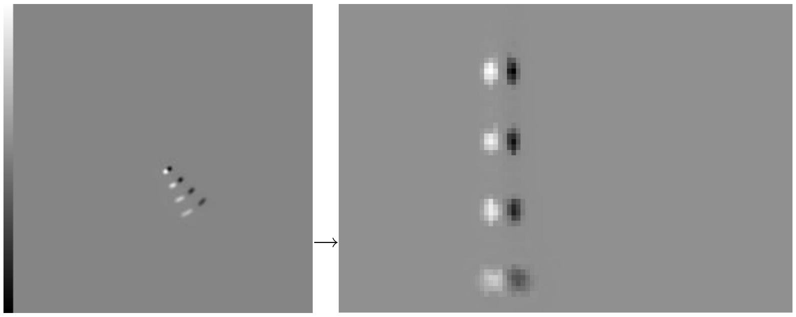


Fig. 3. Change of coordinates for the computation of the multi-channel correlation.

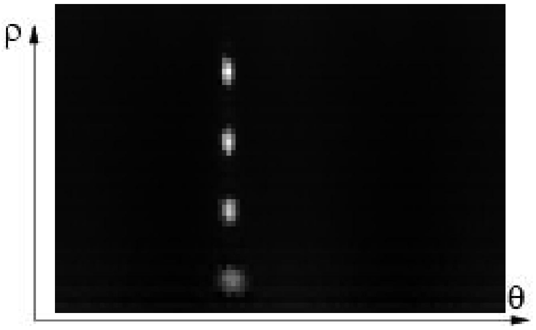
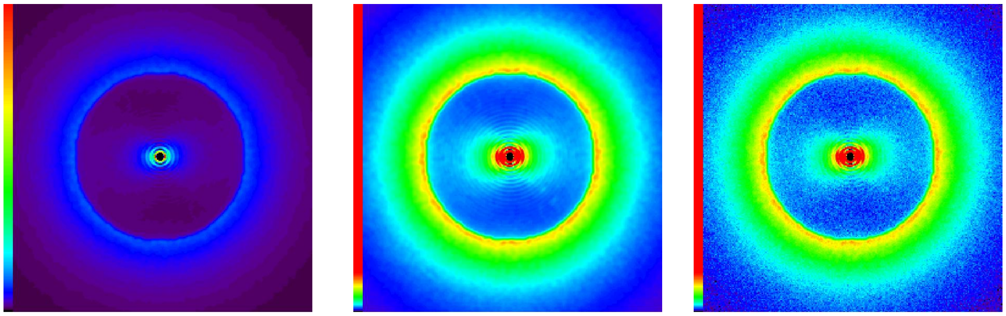


Fig. 4. Principle of multi-channel correlation computation.

- the wavelength is $\lambda = 1{,}6\,\mu$m, and the acquisition is composed of 6 periods of 20 minutes each (one period is composed of 72 images of 17 seconds each,
- the images are corrupted with both detector and photon noise,
- the companion integrated signal is less than $50e^-$ in each image.

Typical images are shown in Figures 5



Coronagraphic image, AO-corrected, without noise

Same as previous, but with different LUT

Same with noise

Fig. 5. Example of simulated images, with perfect coronagraph and AO correction.

7 Results

The results presented here show the correlation map (Figure 6, [left]), computed as explained in section 5 and with the simulation parameters are given in section 6. The correlation map is presented in polar coordinates, with

θ in horizontal axis and ρ in vertical axis. The correlation map clearly shows the presence of the 4 companions, situated at $\theta = 0$ and at their respective radial positions.

The signal to noise of the companions is above 3 times the noise RMS value, and each of the 4 companions therefore clearly appears in the detection map (Figure 6 [right]).

It is worth noting that the signal for each companion does not present the same width. The correlation peak is wider for companion close to the star, and thinner for companions far from the star. This is explained as follows : actually all the companions present the same angular size (λ/D), but this angular size is « seen » smaller far from the star.

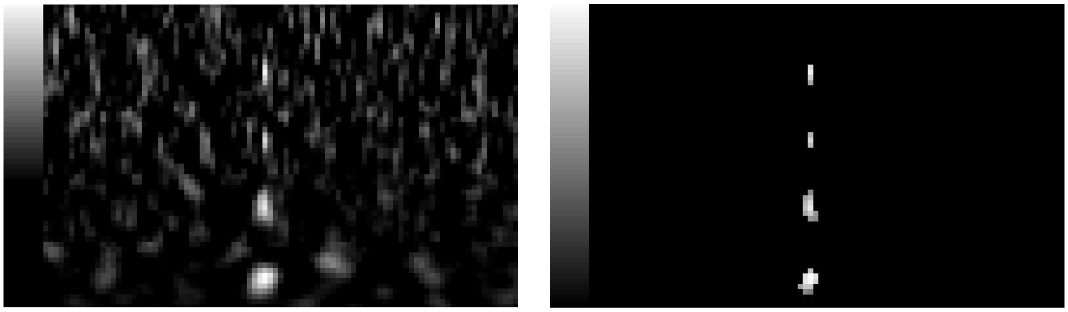

Likelihood map Detected companions (at 3σ).

Fig. 6. Correlation map [left] and detection map [right].

8 Conclusion and perspectives

We presented in this paper a new method of exoplanet detection, based on maximum likelihood. This method makes use of the temporal dimension in order to disentangle planets from speckle signal. The method has been validated numerically by realistic simulation of contrast, and may be easily generalised to multi-spectral images. The contrast of the planet detected is up to 3.10^5 in the simple hypothesis (white uniform Gaussian noise, perfect coronagraph). The short term perspectives include an improvement of the noise model (non uniformity), and of the threshold detection. Moreover, the method has to be validated in the case of slowly evolving aberrations.

Authors are members of the Groupement d'Intérêt Scientifique PHASE

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