Multi-Channel Planet Detection Algorithm for Angular Differential Imaging

L. M. Mugnier[1], J.-F. Sauvage[1], T. Fusco[1] and G. Rousset[2,1]
1: ONERA/DOTA, BP 72, 92322 Chtillon cedex, France.
2: Observatoire de Paris / LESIA, 5, place Jules Janssen 92195 Meudon Cedex.
All authors are member of the Groupement d'Intérêt Scientifique PHASE.
Tel: +33-1 46 73 47 47. Fax: +33-1 46 73 41 71. E-mail: lastname@onera.fr

Abstract: 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.

OCIS codes: (100.3190) Inverse problems; (100.5010) Pattern recognition and feature extraction.

1 Introduction

Direct detection and spectral characterisation of extrasolar planets is one of the most exciting but also one of the most challenging areas in modern astronomy. Sphere [1] (for Spectro-Polarimetric High-contrast Exoplanet REsearch) and GPI (for Gemini Planet Imager) are two current instrument projects being developed for this purpose. The challenge consists in the very large contrast between the host star and the planet. To meet this challenge, these instruments include an extreme adaptive optics system and a coronagraph so as to attenuate, at possible planet locations, the light emitted by the star. In order to further reduce the contrast between star and planet, differential imaging will be used in the case of the Sphere project. This consists in recording images simultaneously in several channels, either at several wavelengths or in several polarizations, and taking advantage of the different spectral or polarization properties of the star and the planet. A limiting factor for these differential imaging techniques is the fact that different channels will necessarily have different aberrations, which will preclude the perfect cancellation of the star image by subtraction of images acquired in different channels. With instruments such as Sphere, for which the pupil is stabilized whereas the field rotates, there is yet another degree of freedom to help one disentangle star photons from planet photons: time. Indeed, due to pupil stabilization, the image of the star remains the same (as long as the quasi-static aberrations and the turbulence strength do not evolve) while the image of a planet rotates with time. This use of the planet motion in time has been developed recently by Marois *et al.* [2] and termed "angular differential imaging" (ADI). In this paper, we build on this technique by suggesting a method to use the same temporal information in a manner that should prove more effective at suppressing noise than the original implementation of this idea. The method is developed for a single wavelength/polarization but can and will be combined with wavelength/polarization coronagraphic differential imaging.

2 Description of the algorithm

We define the region of interest as an annulus where planets are searched for; this annulus has an inner radius called the Inner Working Angle (on the sky) IWA, and an outer radius called the Outer Working Angle OWA. We assume that we have at hand a series of N "elementary" images, which are long-exposure images with respect to turbulence but short enough so that the image of a planet at the OWA (preferably) moves by no more than a fraction of its FWHM (corresponding to an angle λ/D) between two successive images. We assume also that the time elapsed between the first and the last image is sufficient to have a rotation of at least several FWHM's between these images for a planet at the IWA.

In the Marois approach [2], an estimate of the star image is built by median filtering all the images[1]. This estimate is then subtracted to all the elementary images, which are then counter-rotated and added together. The median filter is known for its "robustness", *i.e.,* its ability to reject outliers. In this approach, the outliers at a given pixel are high intensity values in one or a few images due to the crossing of this pixel by a planet. This robustness has a price: a median filter is less effective than the mean in averaging out noise.

[1] For the clarity of the exposition, we assume here that the quasi-static speckles are indeed static during the whole series of N elementary images, so that there is no short-term median filtering to be applied on top of the long-term median filtering.

We suggest a method that removes the star image rather than trying to explicitly estimate it. Additionally, adding up all the images after counter-rotating them does compensate for the planet rotation, but it also removes all the temporal information on the path followed by a planet (if it is present). In the method we suggest below, we combine images so as to remove the star image but process jointly a series of such combined images in order to retain and take advantage of the temporal information.

We consider a given annulus for the planet search around a distance $r \pm \delta r$ of the star; this annulus is to be varied to explore the whole region of interest, although for simplicity the annulus is taken as the whole region of interest in the simulations presented herein. We group together batches of the N elementary images into $N' \leq N$ images (called "individual" images in the following) denoted by $i_1, i_2, \ldots, i_{N'}$, each averaged image corresponding to a rotation of a potential planet that is at most of the order of a FWHM. Of course, N' will be larger if the considered annulus is far from the star and smaller if it is close to the star.

We then build the series of difference images $i_n^d = i_n - i_{n-p}$, where p is a fixed integer. p should be chosen so that the angular separation between images n and $n-p$ ensures that each difference $i_n - i_{n-p}$ is entirely constructive, in the sense that no planet signal is lost in the difference. For simplicity of the exposition we take $p = 1$ in the simulations presented hereafter although it is sub-optimal.

These difference images all have the star signal cancelled (provided the quasi-static aberrations and the AO correction quality have remained identical between images $n-p$ and n). If a planet is present, they also all bear the planet's signature in the form of two close shifted Airy patterns (at known relative locations). Our method then consists in detecting the planet's presence by a joint processing of all these difference images (in the considered annulus). There are several ways to perform this joint processing. A relatively simple one is to (a) resample the difference images $i_n^d(x, y)$ onto a polar grid so as to obtain "de-warped images" $i_n^d(\rho, \theta)$ in which the trajectory of a planet is linear, and (b) to perform a multi-channel matched filtering of these de-warped images. The multi-channel matched filter, as analyzed by Guillaume *et al.* [3], is derived from detection theory and is the Maximum-Likelihood estimator for the planet position if the noise is stationary white Gaussian.

3 Validation by simulations

We have developed a realistic simulation code that allows for several optical and astronomical parameters to be varied. The simulations account for an eight meter telescope installed at Paranal latitude, the extreme AO system of SPHERE (41x41 actuator DM, 40x40 subaperture SH), a 100 nm static residual WFE simulated on 1500 Zernike polynomials (following a f^{-2} power spectrum). Images are corrupted with both photon and detector noises (25 e-/frame RON). The observed source is a star of magnitude 10 observed from -2h to +2h. The contrast (ratio of total star flux with total companion flux) is taken as 10^4 for all companions. The annulus of interest is determined by the AO halo, and therefore by the inter-actuator size. For the considered simulations, it ranges from $4\lambda/D$ (IWA) to $20\lambda/D$ (OWA). In the present simulations we do not include a coronagraph, but the method developed here can of course be easily applied to coronagraphic imaging, and in particular to the IRDIS instrument of SPHERE.

The total exposure time (4 hours) is divided into 8 individual images of 28 minutes, ensuring that the displacement of a companion at IWA is around one FWHM between two individual images. Each individual image is composed of the accumulation of 10 elementary images of 17 seconds each. The field of view is supposed to be fixed during one elementary image but evolves from one image to another. Therefore a companion at OWA spreads on several pixels in one image as visible on Figure 1. The sum of the de-warped images is shown on Figure 2 [left]. The radial variable ρ extends from IWA (at the bottom of the figure) to OWA (at the top of the figure). The angular variable θ has been re-sampled to a regular grid. The trajectories of the companions are linear and parallel. The simulation code is also used to produce the multi-channel matched filter. This filter is the noiseless image of one difference image i_n^d, simulated in the annulus of interest. Then, this filter is used to compute the multi-channel correlation product as illustrated by Figure 3. This multi-channel correlation is the sum of the N' individual correlation signals, and is shown in Figure 2 [right]. It clearly detects the presence of the four companions. More quantitatively, the SNR of this detection (ratio of height of correlation peak to noise RMS value) is 10 for the companion at IWA, and 15 for the one at

OWA, about two times better than our implementation of the Marois method.

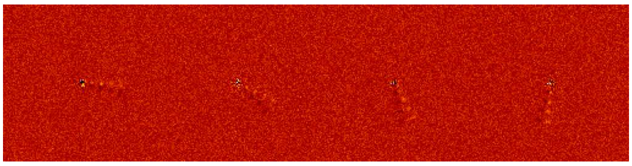

Fig. 1. Three consecutive differences of individual images. The scale is linear

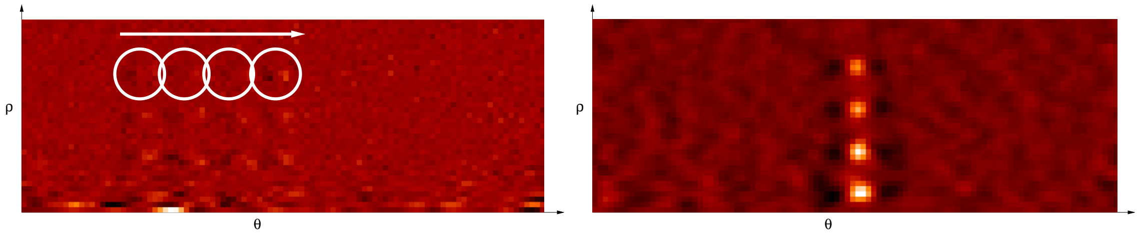

Fig. 2. [Left] Sum of "de-warped images" $i_n^d(\rho, \theta)$ onto a polar grid. The trajectories of the companions are linear, and hardly visible. The white circles show the 4 alternances positive-negative $i_{1..4}^d$ of the companion near the OWA. [Right] Sum of multi-channel correlations product. The presence of the four companions (contrast 10^{-4}) is clearly visible.

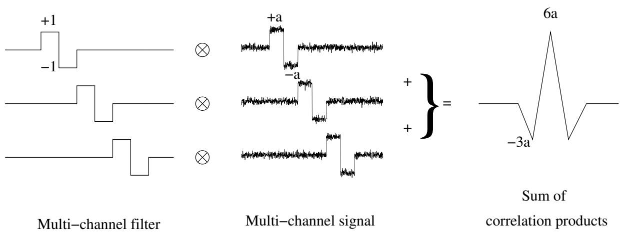

Fig. 3. Principle of multi-channel adapted filtering. All the contribution of multi-channel correlations product are summed in phase.

4 Conclusion

We have proposed a novel method, based on detection theory, for the efficient detection of planets using angular difference imaging, and we have validated it by simulations. Work in progress seems to indicate that our method is, as expected, more efficient with respect to noise suppression than the reference method [2]. Further work is needed to test this method under different conditions.

References

1. K. Dohlen, J.-L. Beuzit, M. Feldt, D. Mouillet, P. Puget, J. Antichi, A. Baruffolo, P. Baudoz, A. Berton, A. Boccaletti, M. Carbillet, J. Charton, R. Claudi, M. Downing, C. Fabron, P. Feautrier, E. Fedrigo, T. Fusco, J.-L. Gach, R. Gratton, N. Hubin, M. Kasper, M. Langlois, A. Longmore, C. Moutou, C. Petit, J. Pragt, P. Rabou, G. Rousset, M. Saisse, H.-M. Schmid, E. Stadler, D. Stamm, M. Turatto, R. Waters, and F. Wildi. SPHERE: A planet finder instrument for the VLT. In *Ground-based and Airborne Instrumentation for Astronomy. Edited by McLean, Ian S.; Iye, Masanori. Proceedings of the SPIE, Volume 6269, pp. 62690Q (2006).*, July 2006.
2. C. Marois, D. Lafrenière, R. Doyon, B. Macintosh, and D. Nadeau. Angular Differential Imaging: A Powerful High-Contrast Imaging Technique. *Astrophys. J.*, 641:556–564, April 2006.
3. M. Guillaume, Ph. Réfrégier, J. Campos, and V. Lashinr. Detection theory approach to multichannel pattern location. *Opt. Lett.*, 22(24):1887–1889, December 1997.