Enhanced Photometry of Faint companions

Dan Burke, Nicholas Devaney and Chris Dainty

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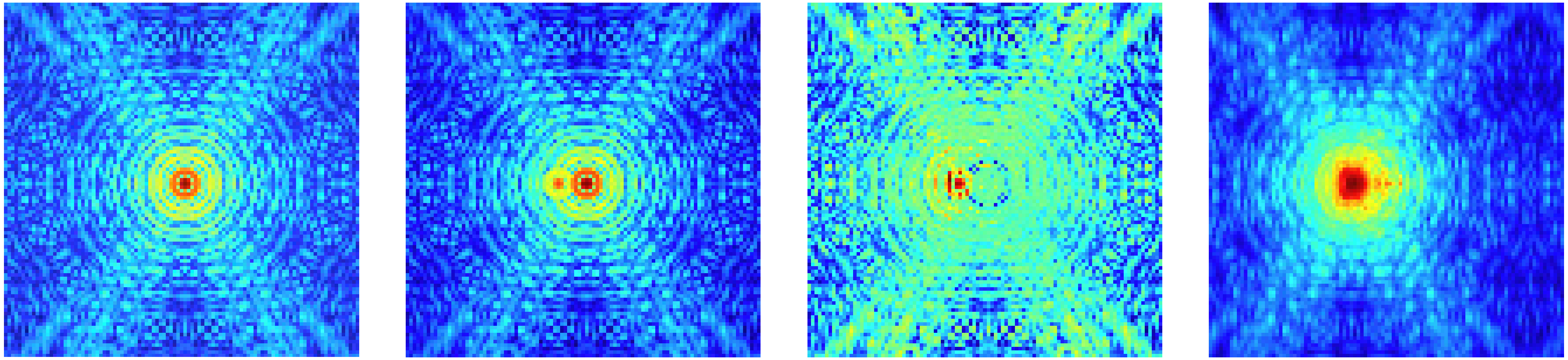
1 *Introduction*

We propose a new approach to differential astrometry and photometry of faint companions in adaptive optics images. It is based on a prewhitening matched filter, also called the Hotelling observer in the literature. We focus on cases when the signal of the companion is located within the bright halo of the parent star.

The direct imaging of faint companions in high contrast adaptive optics images is limited by quasi-static speckles present in the point spread function (PSF) of the parent star (Aime & Soummer, 2004). Our approach to overcoming this limit combines PSF estimation from multi-wavelength data with the Hotelling observer to perform the differential photometry and astrometry.

2 *The Hotelling Observer*

The *Hotelling Observer* (Barrett et al., 2006) is sometimes referred to as a prewhitening matched filter. In the process of prewhitening, the data is divided by the data covariance matrix with the aim of producing spatially stationary, uncorrelated noise. The Hotelling observer provides a framework to include spatial and temporal correlation information about the noise, as well as knowledge about the statistics of the random PSF.



(a) Raw Data (b) PSF Subtracted Data (c) Prewhitened Data (d) Hotelling test statistics

Figure 1: Values of the Hotelling observer around the position of a faint companion.

The observer calculates a linear discriminant of the form $t(g) = w^t g$, where w is called the template, g is the data and $t(g)$ is the test statistic. For each test location the scanning Hotelling observer calculates its test statistic for a set of test intensities. This set of test statistics is at a maximum at the

location of the companion, see figure 1(d).

3 *PSF Reconstruction*

The first step in our approach is to estimate the phase at the pupil from focal plane measurements. We use a wavelength diversity approach to obtain the phase from images obtained simultaneously at two (or more) wavelengths- this data is obtained when Simultaneous Differential Imaging (SDI) (Marois et al., 2000) is performed. The Gonsalves least squares phase diversity approach is used to estimate the phase of the wavefront (Gonsalves, 1984), and the PSF is then estimated by Fourier transformation. Wavelength diversity is introduced by including a known phase function in the system's transfer function:

$$P_k(u) = P(u)\exp\{i[\theta_k(u)\phi(u)]\}. \tag{1}$$

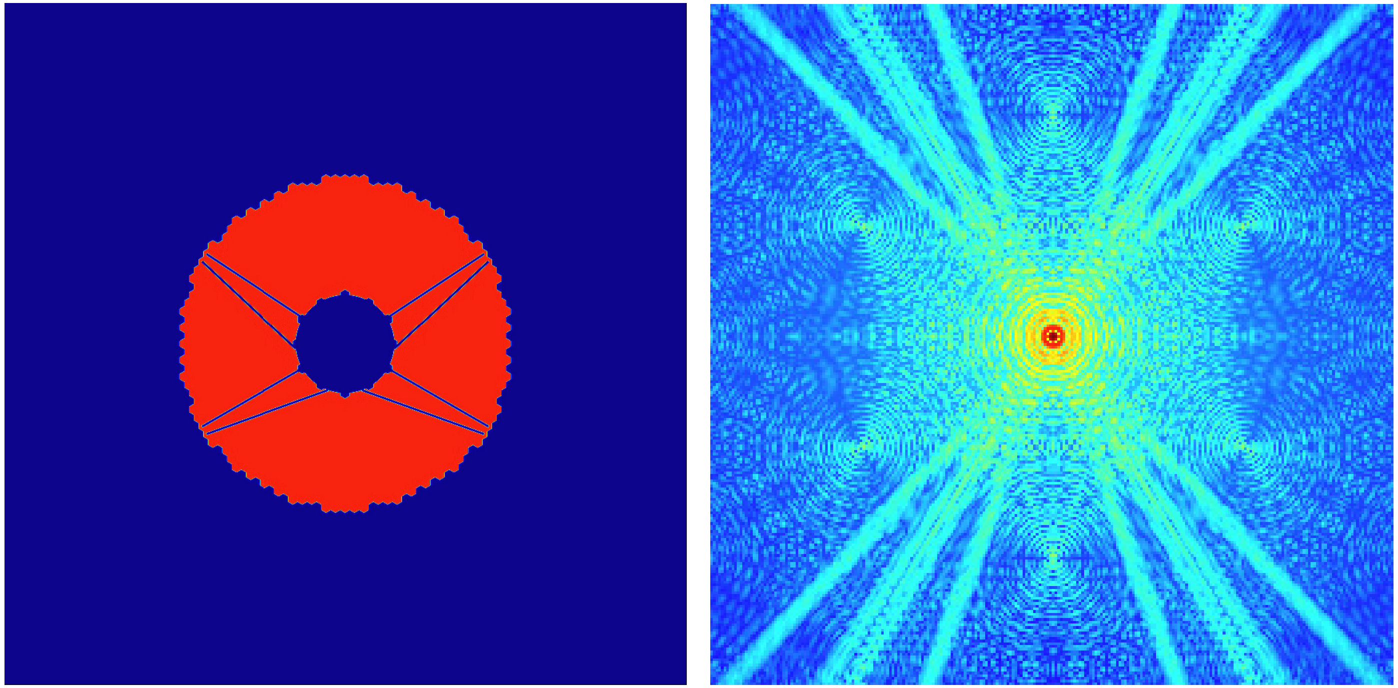
Zernike polynomials were used to expand the phase over a circular pupil:

$$\phi(u) = \sum_{m=1}^{M} \alpha_m \Psi_m(u). \tag{2}$$

The solution to finding the vector of Zernike coefficients which best describes $\phi(u)$ is found by estimating an aberration vector which the minimises an objective function. The objective function we employed (Gonsalves, 1984), minimises the least square error between the data and our model, which relies on a Gaussian noise model.

4 *Simulating an ELT:PAOLA*

To test our combined differential imaging and PSF estimation approach on the task of quasi-static speckle noise reduction and the estimation of the position and intensity of a faint companion in an AO-corrected image we used an end-to-end IDL-based package called PAOLA (Jolissaint et al., 2006) (Performance of Adaptive Optics for Large/Little Apertures) to simulate a PSF based upon the proposed European Extremely Large Telescope (E-ELT) (ref). This method is based on the modelling of the AO-corrected residual phase spatial power spectrum from which a good approximation of the long exposure OTF can be calculated. The telescope was modelled having a 42-m metre primary segmented mirror with a 12.5-m central obscuration and four spider arms, see figure (2(a)). INSERT OBS PARM. Ten PSFs were generated including static and quasi-static speckle noise. This noise was simulated using an aberrated primary mirror figure in the PAOLA package, see figure (2(b)). For each wavelength pair wavelength diversity, was used to estimate the phase in the pupil plane of the telescope. A PSF estimate was then obtained by Fourier propagating this phase to the image plane see, figure (3(b)). A simple angular differential imaging algorithm was used to reduce the speckle noise in the sequence and the images were then de-rotated and co-added, see figure (3(a)).



(a) Simulated E-ELT Pupil

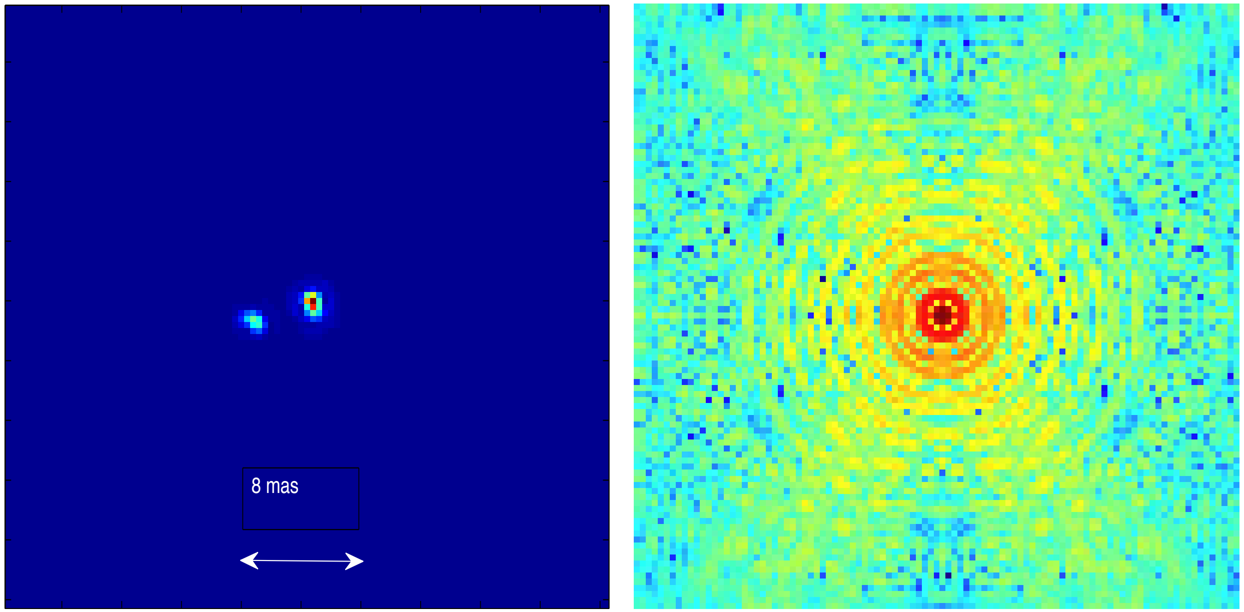
(b) Simulated E-ELT PSF

Figure 2: PAOLA generated images for E-ELT modelling.

For each PSF at $1.64\mu m$ a faint companion, $\triangle m_{1.64\mu m} = 10$ & separation = $0.0442\ arcsec$, was inserted with a field of view rotation of $18°$ from frame to frame in the image sequence. This rotation insured the companion signal did not overlap in successive image frames. For the PSFs simulated at $1.8\mu m$ a fainter companion, $\triangle m_{1.8\mu m} = 15$, was placed in the same locations as in the first sequence.

5 *Results*

The ADI reduced image sequence was processed with the Hotelling observer. The maximum value of the Hotelling data map corresponded to the location and differential magnitude of the faint companion.



(a) ADI reduced image sequence, companion on the left

(b) Estimated E-ELT PSF

Figure 3: ADI reduced image sequence, companion on the left

Error Position Estimation	**Error in Differential Magnitude**
$0.0028\ arcsec$	0.8

Table 1: Photometry and astrometry estimation test.

6 *Conclusion*

Our combination of differential imaging, wavelength diversity and the Hotelling observer has yielded very accurate differential astrometry and photometry of a faint companion in the presence of quasi-static speckle noise. In the future we will investigate the performance of our approach on fainter and closer companions.

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