Formation, Detection, and Characterization of Extrasolar Habitable Planets
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Direct Detection of Nearby Habitable Zone Planets Using Slicer Based Integral Field Spectrographs and EPICS on the E-ELT

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Abstract. Early design studies for the future Exo-Planet Imaging Camera and Specrotgraph (EPICS) on the European Extremely Large Telescope (E-ELT) show the ability to probe the region of super-Earths in the habitable zone of stars within 5pc (including Gilese 581d). However, these planets will be lost to us if the correct choice of integral field spectrograph (IFS) technology is not selected for such an instrument the ability to fit and remove the speckle noise that remains is crucial to reaching these contrasts.

We conclusively demonstrate, though the use of an experimental setup producing an artificial speckle, that slicer based IFSs and post-processing using spectral deconvolution can achieve speckle rejection factors exceeding 10^3. Contrary to popular belief, we do not find any evidence that this choice of IFS technology limits the achievable contrast. Coupled with extreme adaptive optics and high performance coronographs, a slicer based integral field spectrograph could achieve contrasts exceeding 10^9, enabling these super-Earths to be detected in the habitable zone of nearby stars, making it an attractive option for the next generation of instruments being designed for the direct detection of extra solar planets.

Keywords. Integral Field Spectrograph, Direct Detection, Exoplanet

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1. Introduction

Instruments such as EPICS (Exo-Planet Imaging Camera and Spectrograph; Kasper *et al.*, 2010) for the 39-meter E-ELT are currently being designed to achieve contrasts of 10^{8-9} just a few tenths of an arcsecond away from the host stars. Thus allowing the direct detection and characterisation of cold Jupiters, Neptunes and super-Earths (Vérinaud *et al.*, 2010). Achieving such contrasts requires an exquisite correction and/or understanding of any aberrations in the optical path. Both current and future instruments take a cumulative approach to this, whereby each sub-system; extreme adaptive optics, coronagraph and/or speckle suppression system, back-end instrument and post-processing, each contribute to the final contrast. Current studies suggest that the extreme adaptive optics and coronagraph/apodizer systems that would be employed on such instruments will deliver contrasts of 10^{6-7} (Kasper *et al.*, 2010). This means that the back-end instrument and post processing speckle rejection techniques still need to contribute at least 10^2, and maybe even up to 10^3 in contrast. The major factor limiting the contrast of back-end instruments is speckle noise (Soummer *et al.*, 2007). Speckles are created by high order quasi-stable aberrations in the telescope/instrument optical path. They are typically diffraction limited in size and hence can be confused with real unresolved

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objects. Post processing methods such as Spectral Deconvolution (SD) (Sparks & Ford 2002) are required to surpass the speckle noise limit.

Integral field spectrographs (IFS) are the ideal instruments to perform spectral deconvolution (SD) with as they provide the required simultaneous spectrum for every point of a 2D field of view. A key issue to be studied however, is whether the IFS modifies the post-coronagraphic speckle pattern in any way, and if so, to quantify the impact that these modifications have on the ability to identify and eliminate the speckles. Indeed, conceptual arguments about the likely performance of image slicer based IFS led to the selection of lenslet based systems for the upcoming generation of planet hunting instruments (GPI & SPHERE), despite their relative limitations in simultaneous spectral coverage and detector filling efficiency.

Lenslet based IFS employed in the current generation high contrast instruments sample the field at a single location in the lenslet focal plane. In contrast, image slicer based IFS sample the two-dimensional field at different locations across the slices (at the image slicer focal plane) and along the slices (only at the detector). Based on this, a simple conceptual argument is that the optics between the image slicer focal plane and the detector focal plane (i.e. the spectrograph) can affect the speckle pattern in different ways across and along the slices. This modification would be hard to quantify, and limit the ability of SD to remove speckles from the data. A more detailed argument of how image slicer spectrographs are designed however, suggests that the spectrograph should not significantly modify the speckle pattern. Detailed simulations (Salter *et al.*, 2010) have also shown that this should be true. The aim of the experiment described here is to test how/if an image slicer IFS affects the ability of SD to reject speckles. We chose to implement SD and not the adapted LOCI of Crepp *et al.* (2011) as there is a possibility that LOCI will over-fit the data and be able to remove a modified speckle pattern giving in a misleading result.

2. Method

Our experimental set-up is designed to simulate a diffraction limited observation on sky. To achieve this, we create a single artificial speckle that we can track through a slicer based IFS and thus determine to what accuracy we can fit and reject it. This artificial speckle is defined as a spatially Nyquist sampled, diffraction limited point source that moves across slices as a function of wavelength. This simulates a real speckle scaling radially outward from the central star as λ/D. Just as only a single source is needed to produce the initial speckle pattern in a real observation, no more than one simulated speckle is needed to investigate whether or not secondary speckles are being produced from it. We produce our artificial speckle by using a pin hole focal plane mask and a ruled diffraction grating. The speckle generator grating is placed at a pupil, appropriately sized to provide the required diffraction limited beam. The first order of the speckle generator grating provides us with our artificial speckle. Furthermore, the speckle generating grating is blazed such that the speckle is brighter than the central source, making it easier to observe.

The spectrograph was based on the SWIFT instrument (Thatte *et al.* 2006), currently on the Palomar 200", design producing R$\sim$ 4000 over the wavelength range 0.65 to 1.0 microns. This is bluer and higher resolution than a typical high contrast instruments (typically 0.9-1.6 microns at R $<$ 100), but the costs of building a dedicated near-infrared system were prohibitively high. The heart of the instrument was the actual SWIFT slicer and the detector was a 3Kx3K Apogee ALTA U9000 CCD which restricted the usable wavelength range to 730 nm-980 nm.

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Speckle Rejection Factor		
Binning	Normal	Gaussian convolved
$\Delta\lambda = 0.1\,\mathrm{nm}$	99	283
$\Delta\lambda = 1\,\mathrm{nm}$	100	264
Collapsed cube	611	3944

Table 1. Speckle rejection ratios achieved using spectral deconvolution. Values shown for the narrow band ratios are mean values.

3. Results

For our experimental set-up, where a single, extremely bright speckle has been generated to ascertain limits on the achievable contrast, the standard methods of defining speckle rejection ratios (typically used on images with a large number of speckles) are not applicable. Instead, for individual channels, we define the speckle rejection factor as the ratio of the total speckle flux to the total amplitude of residuals, evaluated over the central four spaxels (the speckle is perfectly centered on these four spaxels). Results are shown in Table 1.

The residual flux, after applying SD, has several contributions, chief amongst these being photon noise and spectral fitting errors from SD (themselves stemming from calibration errors in the creation of the data cube). However, the photon noise does not correlate from spaxel to spaxel, resulting in residual structures that have an extent of a single spaxel. These cannot plausibly be mistaken for signal from a real companion. Therefore, to correctly account for the prior knowledge of the minimum (diffraction limited) size of real sources in the residual image, we smooth each channel with a Gaussian kernel with a 2 spaxel FWHM. This markedly improves the achieved contrast, as is seen in Table 1.

We have conclusively demonstrated, through laboratory experiments, that in the absence of upstream chromaticity an image slicer based IFS, coupled with an implementation of spectral deconvolution, can achieve contrasts exceeding 10^3 for detection of faint companions in the near-vicinity of very bright point sources, thus surpassing the requirements for EPICS.

Slicer based technology does not pose any limitations to the speckle rejection capability of an IFS, contrary to naive expectations.

For further information on this experiment and its results we direct the reader to Salter *et al.* 2013.

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