Achieving High Contrasts With Slicer Based Integral Field Spectrographs

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Abstract. We demonstrate experimentally that slicer based integral field spectrographs are an attractive choice for the next generation of exoplanet direct detection instruments. By propagating a single simulated speckle though a slicer based integral field spectrograph (IFS) and performing the post processing technique of spectral deconvolution we are able to achieve a speckle rejection factor of ~600 in broadband images (and ~100 in individual wavelength channels) with contrasts only appearing to be limited by calibration errors in the IFS datacube. This is over an order of magnitude improvement on the current state-of-the-art and well within the requirements of EPICS (Exo Planet Imaging Camera and Spectrograph for the E-ELT) for post coronagraphic speckle rejection thus proving that slicers will not impose a limit on the achievable contrast. When using prior knowledge of the diffraction-limited size of real objects we further improve the speckle rejection factor such that it exceeds 10^3.

1. Introduction

Future instrumentation for the direct detection of exoplanets on ELTs, such as EPICS (Exo Planet Imaging Camera and Spectrograph for the E-ELT) [1], is looking to reach contrasts of $\sim10^9$ so as to probe the parameter space of the super earths. In order to achieve this, each subsystem of the instrument must contribute to the final contrast. With current studies suggesting that extreme adaptive optics and coronagraph/apodizer systems could provide contrasts of $\sim10^{6-7}$, the back-end instrument (and post processing speckle rejection techniques) still need to provide a factor of at least 100. Contrasts of >20 from the back end instrument (and post processing) have not been achieved by any on-sky system to date (for a single observation) [2] and prior to this work it was not clear whether slicer based IFSs would be able to achieve the goal factor of >100.

The viability of using a slicer based integral field spectrograph (IFS) for high contrast observations has been under scrutiny in the recent past. It has been assumed (without verification by simulations or laboratory experiments) that the one dimensional coherence that

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persists along the slice to the point of sampling at the detector, will cause the creation of secondary speckles. Such speckles will not have the same characteristics as normal speckles, thus stopping us from being able to calibrate them out. It has also been previously assumed that a suitably low differential wavefront error when moving from slice to slice was not guaranteed by design. It was for these reasons that slicer based IFSs were not selected for the current generation of planet finding instruments (GPI [3], SPHERE [4]), lenslet based IFS were selected instead.

As part of the EPICS design study it was decided that slicers should be re-investigated due to a number of reasons;

- No investigations, simulations or otherwise, into the actual performance of a slicer based IFS had taken place. It was just assumed the differential wave-front error would be too large.
- A detailed look into the design of slicers suggest that these concerns may not be justified, described in §4.
- Thatte et al 2007 [5] were able to achieve 9 magnitudes of contrast at 0.2" for observations of the ABDor system using the SINFONI instrument on the VLT (a slicer based IFS). This is a very impressive result considering SINFONI has not been designed for high contrast observations and contains no coronagraph/apodizer, or extreme AO system.
- Slicers are not subject to the cross talk associated with lenslet IFSs and can provide >2x fill factor on the detector with a longer wavelength coverage or higher spectral resolution.

2. Experiment Description

The aim of our experiment was to propagate a single bright speckle through a slicer based integral field spectrograph and analyse any modification introduced by the slicer.

The SWIFT slicer integral field unit [6] was used for the experiment. A replica of one arm of the SWIFT spectrograph [7] was built for the experiment. Figure 1 shows a schematic view of this setup. Instead of a science grade SWIFT detector a 3kx3k Apogee ALTA U9000 CCD was used (loaned to us by LOAG).

Our single 'simulated' speckle would have to be a Nyquist sampled, diffraction limited point source that moved across slices as a function of wavelength. To achieve this, simply and inexpensively, we designed a pre-optics system whereby a pin hole focal plane mask was positioned at our light source and a pupil stop and diffraction grating were located in the collimated beam. The focal plane mask and pupil stop provided the diffraction limited point source and the first (blazed) order of the diffraction grating provided the movement we needed. A cartoon of the setup and an image taken at the location of the slicer stack can be seen in Figure 2.

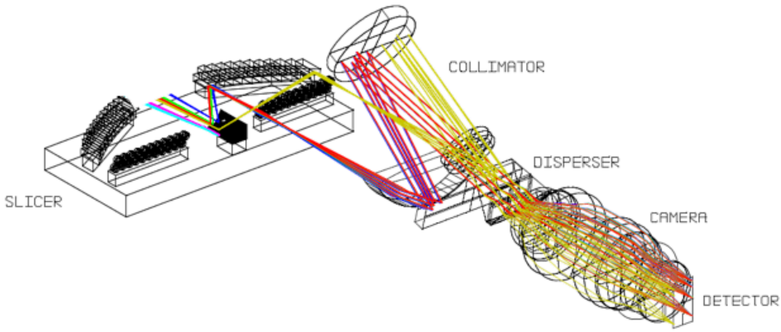

Fig. 1. Schematic view of the SWIFT slicer spectrograph that was used for this experiment.

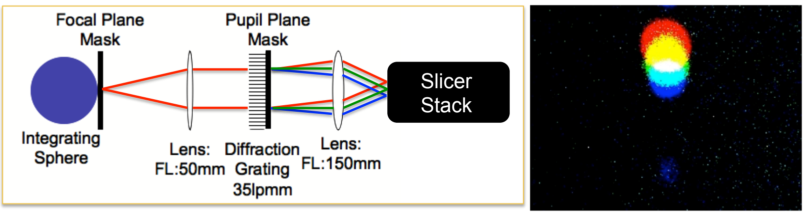

Fig. 2. Right: Cartoon depicting our pre-optics setup that creates our single 'simulated' speckle. Left: RGB image taken at the location of the slicer stack, after the pre-optics, showing our speckle as the diffraction limited point source that is moving with wavelength.

We planned on applying the post processing method of spectral deconvolution to analyse the resultant datacube. Spectral deconvolution uses the wavelength dependence of speckles to fit and remove them. For an in-depth description of the spectral deconvolution technique we direct the reader to Sparks & Ford 2002 [8] and Salter et al 2008 [9]. We then determine the rejection factor of our simulated speckle. Any flux remaining, limiting the achievable rejection factor, would be due to the speckle PSF being modified as it passed through the slicer.

3. Results

In this section we very briefly describe the final results from our investigation. Full details of these results can be found in Salter et al 2012 (in prep) and intermediate results are detailed in Salter et al 2010 [10].

Figure 3 shows the three stages of data reduction; the original datacube, the data after spatially scaling with respect to wavelength (needed for spectral deconvolution) and the result after performing spectral deconvolution. It is clear that no significant secondary speckles have been produced.

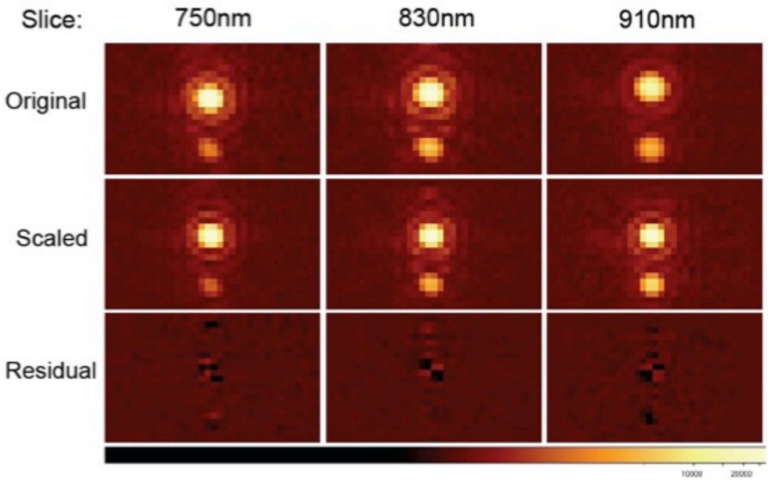

Fig. 3. Results are split into three columns, each of which represents a single wavelength channel, from left to right these are 750nm 830nm and 910nm. Titles to the left of the images indicate what stage in the reduction is being shown: Original - the original datacube, Scaled - the datacube after each wavelength channel has been scaled with respect to wavelength and Residual - what is left over after performing spectral deconvolution. All images have the same logarithmic stretch (look up table is along the bottom of the image).

For this experiment, where only a single bright speckle has been generated, the standard methods of defining achieved speckle rejection ratios are not applicable. Instead, for each wavelength channel we define the speckle rejection ratio as the ratio of the total speckle flux to the total amplitude of residuals, evaluated over the central four spaxels (spatial pixels) – the speckle is perfectly centred on these four spaxels as a result of the wavelength scaling – see Equation 1.

$$Speckle\ Rejection\ Ratio = \frac{\sum_1^4 Spaxel\ Flux}{\sum_1^4 |Residual\ Flux|} \quad (1)$$

Following this method we achieve a speckle rejection ratio of ~100 per wavelength channel. If we then combine all wavelength channels to produce a reconstructed broadband image we get a speckle rejection factor of ~600. This is a marked improvement over the current state-of-the-art. The remaining flux has several contributions, foremost the photon noise and spectral fitting errors from the application of spectral deconvolution (which stem from the calibration errors in the creation of the data cube). However, photon noise does not correlate from spaxel to spaxel, this results in noise that has a spatial extent of a single spaxel and cannot therefore be plausibly mistaken for the signal of a real companion (which would have a diffraction limited size). To account for this *prior knowledge* we smooth each wavelength channel with a Gaussian kernel with a 2 spaxel FWHM. After Gaussian smoothing, the speckle rejection ratio was calculated to be nearly 300 per spectral channel and to exceed 10^3 after combining all of the channels into a broadband image.

4. Discussion & Conclusion

We have conclusively demonstrated that a slicer based IFS does **not** pose any limitations to the achievable contrast, contrary to naïve expectations. When looking into the slicer IFS design in more detail you can see some reasons as to why this may be the case; Although our spectrograph optics are not optimized for high contrast applications they are designed for fast focal ratios as the SWIFT IFS is designed for larger pixel scales. The PSF of the spectrograph is tightly controlled due to the need for a clean image of the slit at the detector and in order to retain the designed spectral resolution. In the case of our experiment the spectrograph is actually oversized by a factor of ~15x the geometrical pupil. This oversizing reduces the light loss due to diffraction at the slicer mirrors. Also, by using oversized optics we benefit from the f^{-2} error profile of optical polishing, i.e. although the optics have not been manufactured with tolerances typical of high contrast instruments, our geometrical footprint on the lens is small enough to ensure a low differential WFE.

We have shown, via laboratory experiments, that speckle rejection factors of ~600 (>10^3 after Gaussian smoothing) can be achieved in broadband images using a slicer based integral field spectrograph and the technique of spectral deconvolution. This implies that, at least in the case of EPICS on the E-ELT, when coupled with an extreme adaptive optics system and high performance coronagraph/apodizer, overall contrasts exceeding 10^9 could be achievable. Slicers should be a favourable choice of IFU technology for such an instrument as they would not limit the achievable contrasts and have may other benefits as have been described in §1.

It should be noted that we are not suggesting that inserting slicers into current instruments will result in an extra order of magnitude in achievable contrast. There are many other factors that contribute to the limiting contrast, namely speckle chromaticity introduced upstream from the integral field unit (where a coronagraph or Fresnel diffraction will have a significant effect) and calibration errors (wavelength and spatial reconstruction has to be very accurate and high fidelity flat field and dark calibration frames are needed).

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