Focal plane wavefront sensing and control for ground-based imaging

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Abstract

We evaluate the performance of existing wavefront sensing and control techniques such as speckle nulling, and discuss their applicability to high-contrast imaging spectrographs like the Gemini Planet Imager (GPI). These techniques can be highly useful in correcting system phase errors, and can potentially improve instrument operating efficiency by working in conjunction with the dedicated adaptive optics (AO) wavefront sensor. We discuss the specifics of our implementation of speckle suppression for GPI and present lab demonstrations with average contrast improvements from 5.7×10^{-6} to 1.03×10^{-6}.

Gemini Planet Imager

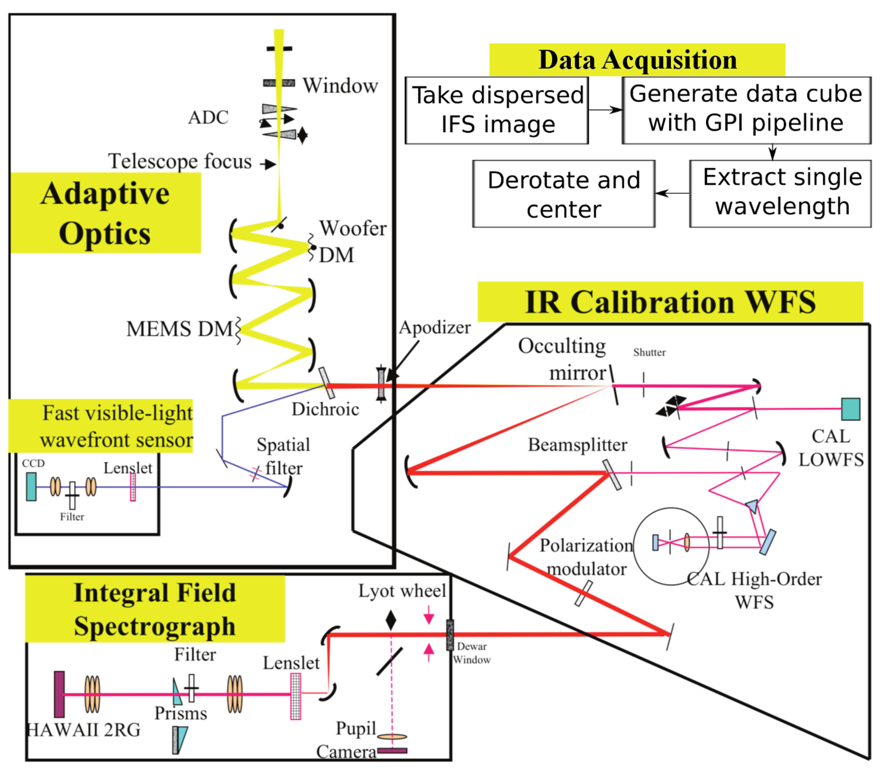

Figure : GPI light path [Macintosh et al., 2008] and data acquisition schematic.

- AO system - MEMS deformable mirror (DM), piezo-electric DM & Shack-Hartmann wavefront sensor correct for atmospheric turbulence
- CAL system - IR interferometer reconstructs post-coronagraph wavefront and sends updates to AO
- IFS - science instrument produces dispersed spectral images
- Apodized Pupil Lyot Coronagraph (APLC) for diffraction control [Soummer, 2004]
- GPI Pipeline - Produces reduced 3D data cubes ($x \times y \times \lambda$) in realtime as data is collected [Maire et al., 2010]
- Dispersed images take in H band, with 1.5 to 1.512 μm slice used for the phase estimate.

Goal:
Use IFS and AO to correct for non-common path errors in system.

Speckle Formation

- The electric field at the DM is determined by the pupil apodization A, the complex pupil aberration function ϕ and the DM phase function ψ:

$$E_0(u,v) = A(u,v)e^{\phi(u,v)}e^{2\pi i \psi(u,v)/\lambda}$$

- Scattering from each of the sinusoidal components of ϕ generates a speckle [Perrin et al., 2003]
- We can find DM shapes to cancel these [Malbet et al., 1995, Bordé and Traub, 2006]

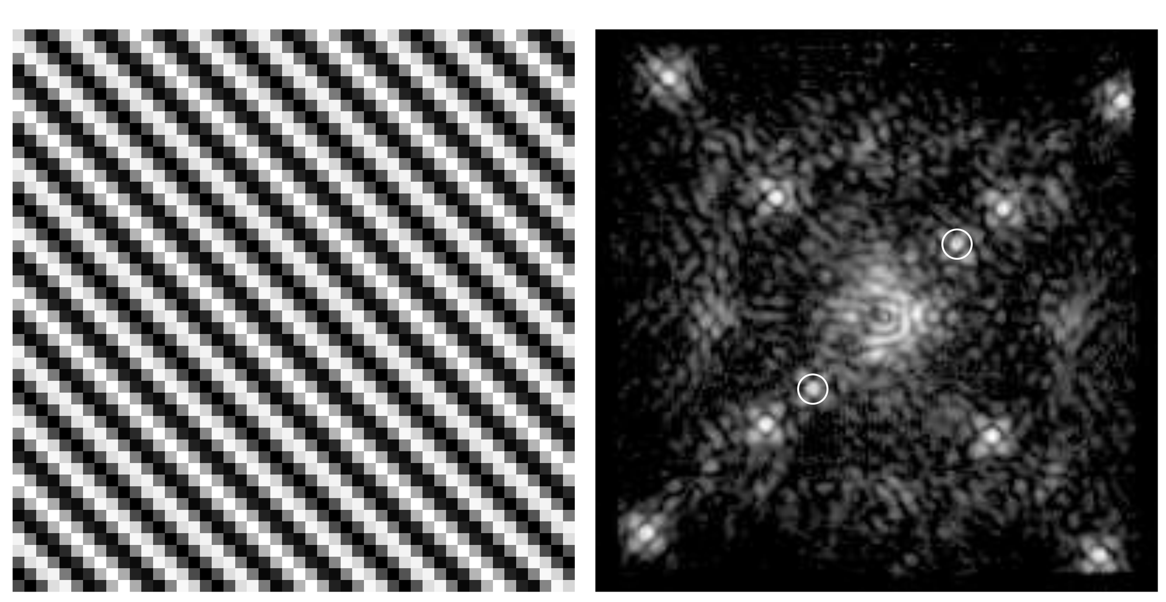

Figure : (*Left*) A pure sinusoid applied to the DM producing (*Right*) speckles in the image (circled).

Calibration

- We need to know how the DM phase maps to the image location and intensity
- To calibrate location, drive the DM at the highest spatial frequency
- To calibrate intensity measure some of the spatial frequencies and interpolate the rest

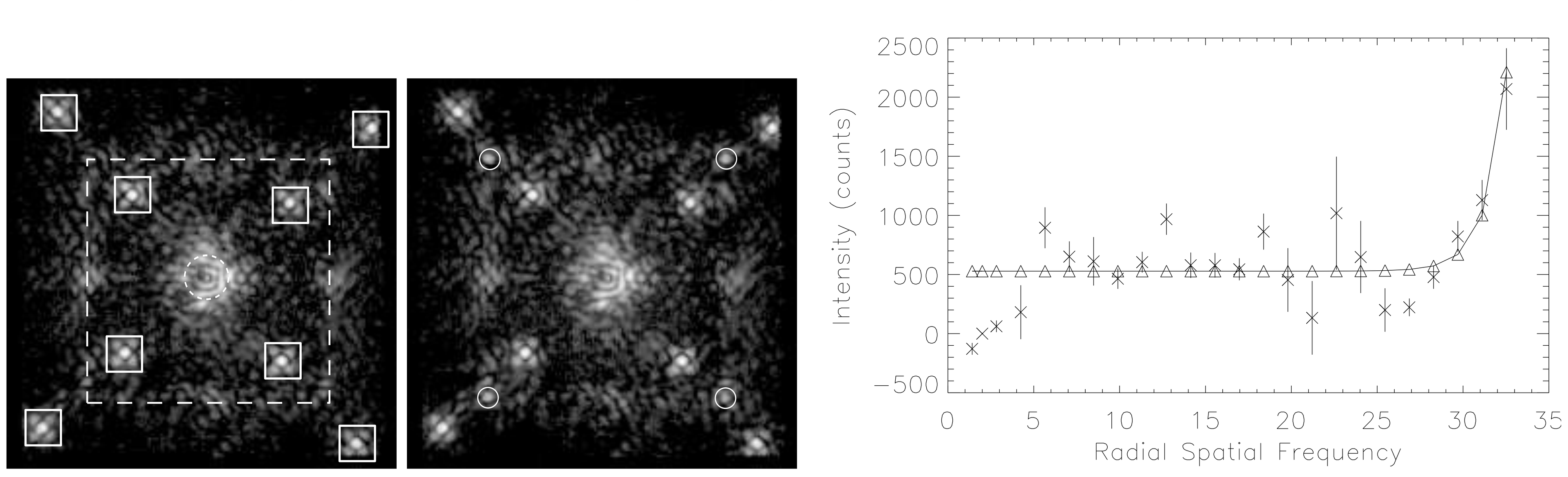

Figure : (*Left*) Image with flat DM. The bright boxed regions are astrometric calibration spots generated by a grid pattern on the apodizer. The dashed box indicates the high contrast region created by the diffraction control system and the dashed circle shows the extent of the focal plane mask. (*Middle*) Image with DM neighboring actuators driven in opposite directions. This results in the circled speckles at the highest spatial frequency. (*Right*) Intensity interpolation. Points marked with an 'x' are intensity measurements at spatial frequencies $k = l$. The solid line with triangle markers is the fit to these points. Spatial frequencies $k = l < 4$ fall behind the focal plane mask and are not used in the fit.

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Phase Estimation

- Take a series of 8 images with evenly spaced input phases in $[0, 2\pi]$ and a random offset phase by sending references to the AO system

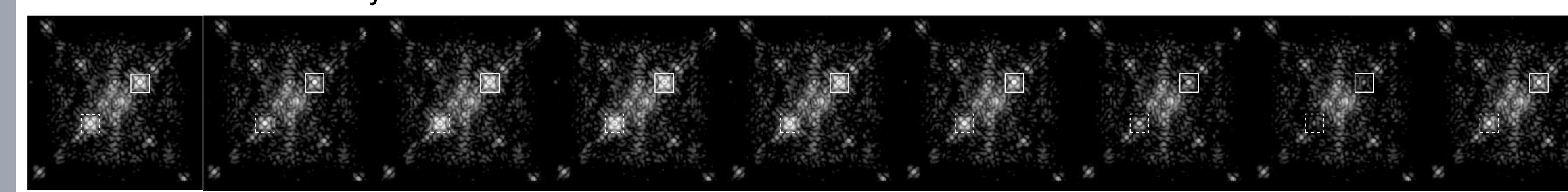

Figure : Initial reference image with artificial speckle injected via reference offset (solid box is I_1 and dashed box is I_2) and 8 phase probes with corresponding intensity variations at the speckle location.

- For each spatial frequency measure intensity on either side of the image plane I_1 and I_2
- Fit sinusoid to $I_1 + I_2$ to find the phase of the speckle canceling shape
- Alternatively, fit independently to $I_1 + I_2$ and $I_1 - I_2$ to estimate both amplitude and phase

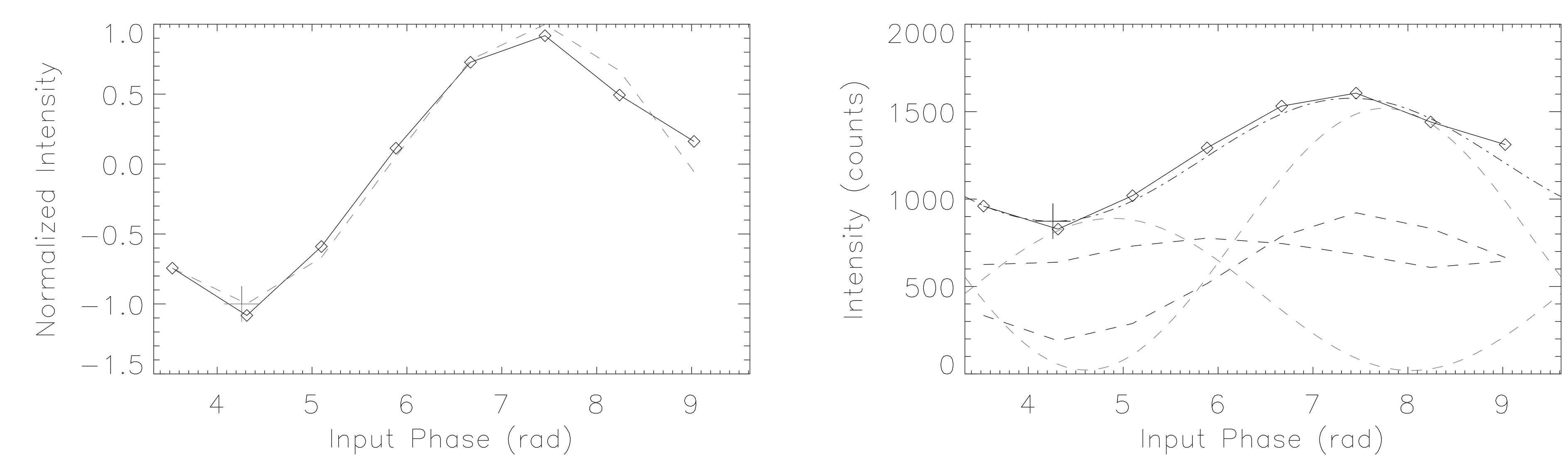

Figure : (*Left*) The normalized measured intensities ($\langle I_1 + I_2 \rangle$) are represented by the solid line with diamond markers, while the best fit sinusoid is given by the dashed line. The plus marker indicates the best fit phase. (*Right*) The solid black line with diamond markers represents the summed measured intensities ($I_1 + I_2$) and the black dashed lines are I_1 and I_2, respectively. The gray dashed lines represent best fits to $I_1 + I_2$ and $I_1 - I_2$ and the black dash-dotted line represents the total amplitude and phase fit to the data. The plus sign denotes the best found amplitude (mapped to intensity) and phase.

Results

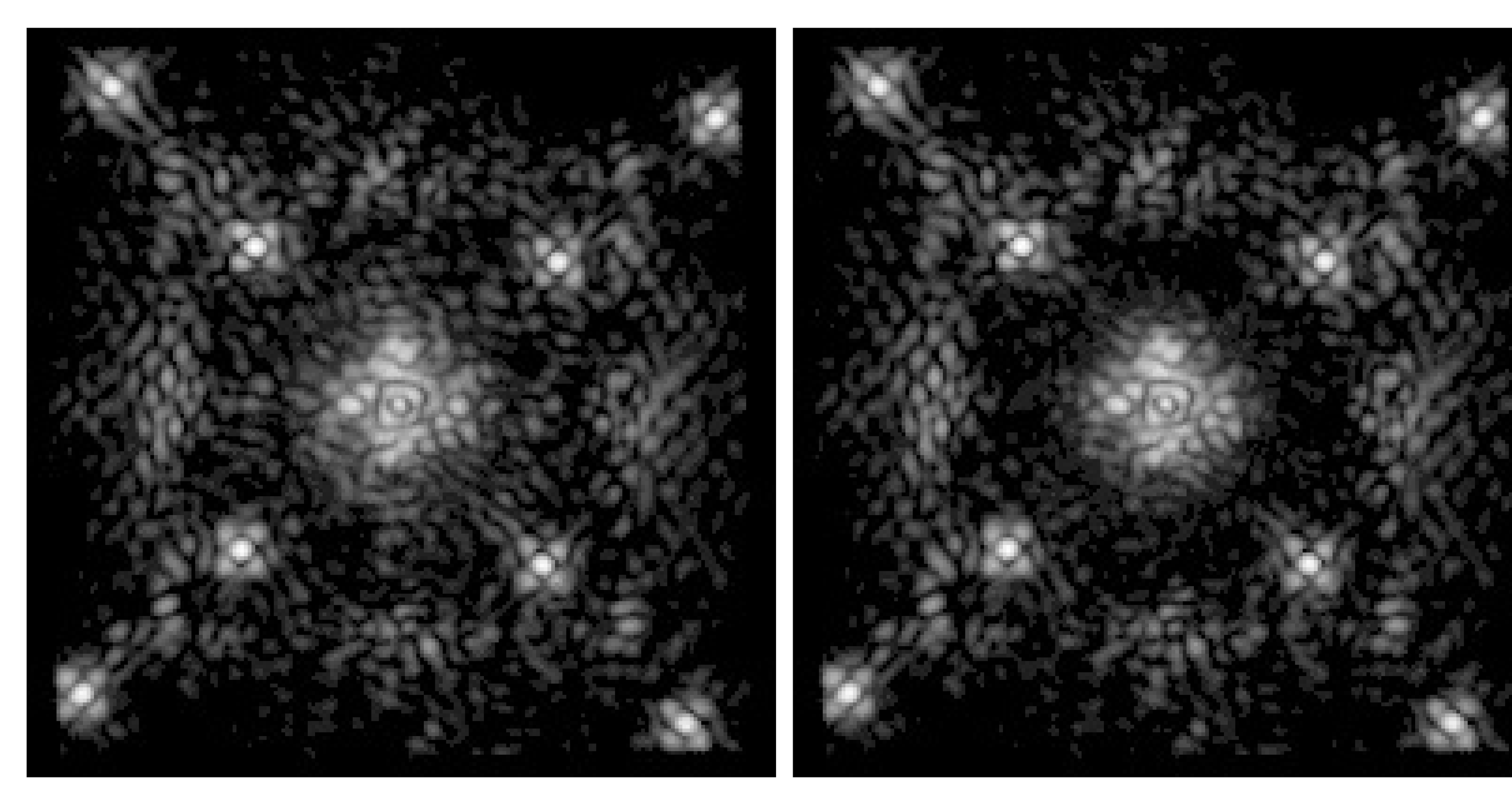

Figure : (*Left*) Initial focal plane image. (*Right*) Focal plane image after six iterations of speckle nulling.

- Experiments performed with no external aberrations. Atmospheric turbulence will add noise, but contrast will be primarily limited by internal quasi-static errors

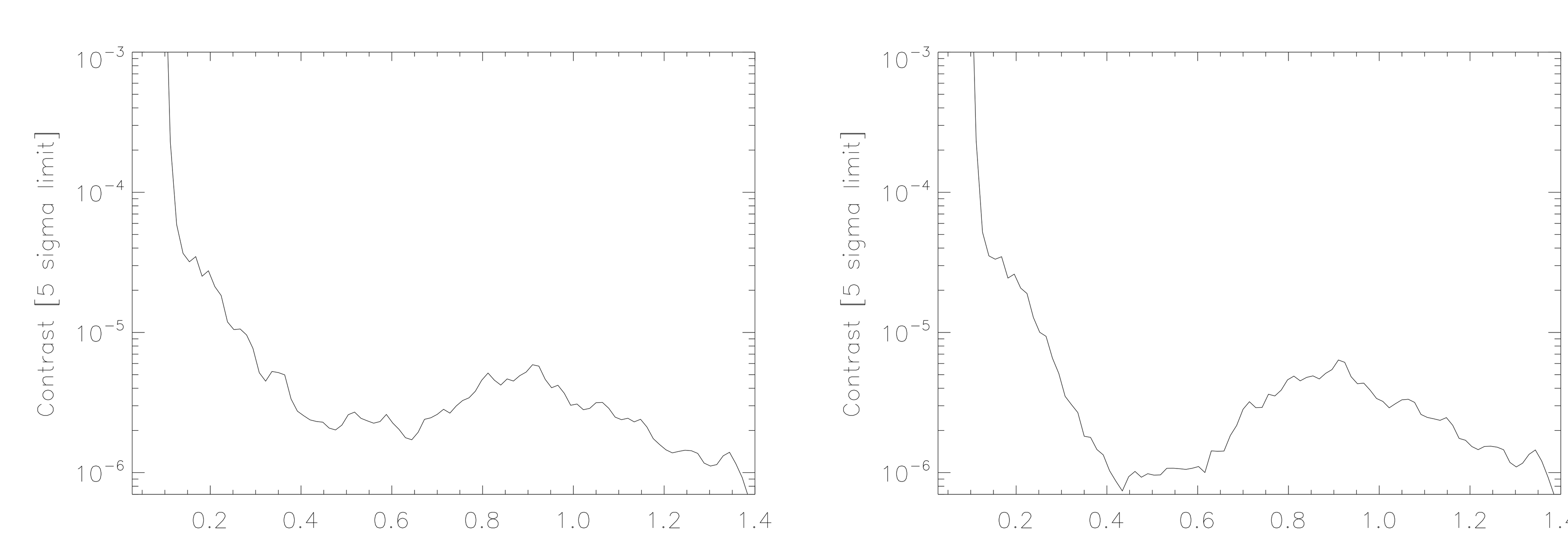

Figure : (*Left*) Initial contrast. (*Right*) Contrast after six iterations of speckle nulling. Both images are in H band with 15 s exposure times. Contrast is defined as 5 times the standard deviation of the intensity in an annulus of radius equal to the angular separation.

Conclusions and Future Work

- Speckle nulling can be used with IFS data to correct for non-common path errors
- Good contrast improvement in relatively small number of iterations
- Resulting PSF is relatively stable and achromatic so speckle noise can be further attenuated by ADI and SDI techniques. See Macintosh, et al. (this conference, 8446-65) for details
- Need to evaluate other speckle suppression techniques such as EFC
- May be possible to use amplitude estimates to identify uncorrectable speckles
- Need to combine with other methods to reduce low spatial frequency noise