DEFEATING SPECKLE NOISE IN FAINT COMPANION IMAGING

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ABSTRACT

Speckle noise vastly dominates shot noise in the halo of the AO-compensated image of a bright star and limits the detection of faint, close companions. We present an observing technique which eliminates speckle noise and we illustrate the gain achieved through its use with the CFHT AO system.

1. The problem

Close to the center of a bright star image, individual speckles contain many coherent photons:

$$N(\text{photons/speckle}) \approx \frac{N(\text{photons/image})}{N(\text{speckles/image})} \approx \frac{qn_o D^2 10^{-0.4m_*} t}{(D/r_o)^2 (t/\tau_o)} \tag{1}$$

where qn_o is the counting rate for a star of magnitude $m_* = 0$, t the integration time, τ_o the speckle lifetime and (D/r_o) the ratio (telescope aperture)/(Fried parameter). Thus, the AO compensated image of a faint companion to a bright star appears as a single central speckle lost in a sea of boiling speckles. In the H-band (1.6 μm), for typical values of the parameters with an 8-m telescope,

$$N(\text{photons/speckle}) \approx 10^{(5.0-0.4m_*)} \tag{2}$$

and noise from speckle boiling dominates Poisson photon noise for $m_H < 12.5$. Figure 1 shows the results of detection limit calculations, expressed as magnitude differences with respect to the primary, using a model developed by Racine et al. (1999). For the parameters given in the caption, speckle noise entails a loss of ~ 6 magnitudes in detectivity at small offsets.

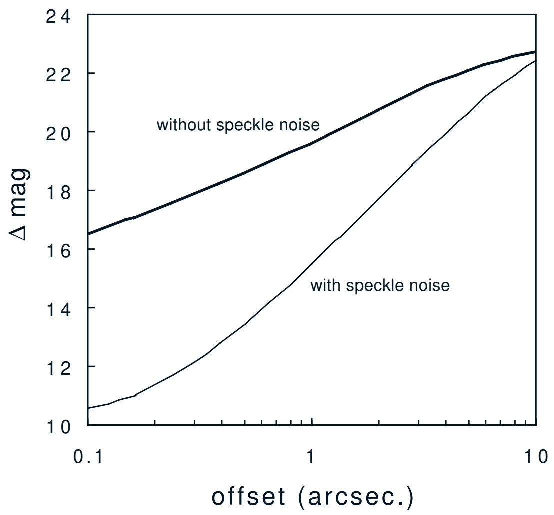

Fig. 1.— Calculated 3σ detection limits with and without speckle noise; 8 m telescope, m_H=5 primary, 10 000 sec. exposure, Strehl = 0.7.

2. Life in the speckle-limited regime

It can be shown (Racine et al. 1999) that, when speckle noise dominates, the signal-to-noise ratio of the faint companion's central speckle of flux SF_c is

$$SNR \simeq 0.43\frac{S}{1-S}\left(\frac{D}{\lambda}\right)^2\frac{F_c}{F_*}\frac{1}{f_{halo}\theta)}\left(\frac{t}{\tau_o}\right)^{1/2}, \tag{3}$$

where $(1-S)F_* f_{halo}(\theta)$ is the intensity profile of the residual halo, in photoevents/steradian. SNR is independent of qn_o and increases dramatically as the Strehl ratio $S \to 1$. Furthermore, the achievable brightness ratio is independent of F_*. Large apertures D and short wavelengths λ are, in principle, preferable *if* the Strehl ratio of the compensated image can be maintained. With a halo profile of full width at half peak intensity $FW_{halo} \approx 0.3r_o/\lambda$ (Rigaut et al. 1998) and an approximate expression for its intensity profile, one has

$$SNR \simeq 1.2\,\frac{S}{1-S}\left(\frac{D}{r_o}\right)^2\frac{F_c}{F_*}\left(1+2.35\left(\frac{\theta}{\lambda/r_o}\right)^2\right)^{3/2}\left(\frac{t}{\tau_o}\right)^{1/2}. \tag{4}$$

One can thus estimate the (D/r_o) at which an AO system with an effective number N_e of actuators will give optimal performance at a separation $\theta/(\lambda/r_o)$. Indeed (Roddier 1998),

$$S \simeq \exp\left[-0.3(D/r_o)^{5/3}N_e^{-5/6}\right] \tag{5}$$

and the value of (D/r_o) which maximizes the product of the first two terms in Eq. (4) is

$$(D/r_o)_{\text{optimal}} \simeq 1.15\sqrt{N_e}. \tag{6}$$

Thus, with the 3.6 m CFHT AO system, for which $N_e \simeq 9$, $(D/r_o)_{\rm optimal} \simeq 3.5$ and is obtained in the H-band by typical 0.5 arcsec seeing at 0.5 μm.

3. Defeating speckle noise

It is possible to defeat speckle noise by subtracting from one another two images taken *simultaneously* (identical speckle patterns) through two filters closely adjacent in wavelength. If primary and secondary have very different flux ratios through these filters, the subtraction, after equalization of the primary fluxes in each frame, will leave an image of the companion alone. The sharp CH_4 absorption band head at 1.60 μm in cool brown dwarfs or Jupiters provides a suitable spectral region (Rosenthal et al. 1996). Figure 2 schematically illustrates the instrumental set up and shows resulting short exposure images

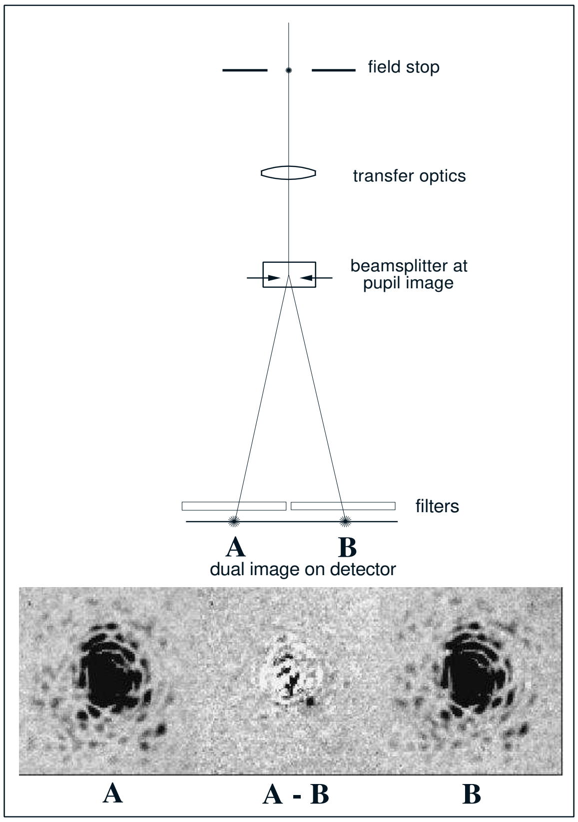

Fig. 2.— Dual imaging arrangement, resulting images and their difference.

(2 sec., to clearly show the speckles) obtained with the Montréal infrared camera MONICA (Nadeau et al. 1994) behind the CFHT AO system. The 'companion' which appears in the difference image has been artificially added to image A for illustration purpose. It is 5 mag. fainter than the primary at a separation of 0.5 arcsec.

A quantitative measure of the detection gain realized in practice with more realistic, longer exposures was made as follows. First, a heavily smoothed version of one of the dual, long exposure PSF images was subtracted from itself and the r.m.s. noise level in the difference image was measured in annuli of increasing radii. The ratio of this noise level to the peak intensity of the original PSF measures the detection threshold as a function of radius in the conventional, single frame observing mode. Second, one of the two simultaneous images was subtracted from the other and the r.m.s. noise in the difference image was measured, thereby yielding the detection threshold in the dual frame observing method. The results of this exercise are shown in Fig. 3. It is seen that 'speckle subtraction' has achieved a detection gain of nearly 3 magnitudes at small offsets. These experimental results are in good agreement with models that take into account speckle noise, photon noise, read and sky noise (Racine et al. 1999) and use actual values of the observational parameters as inputs. This demonstrates that, as expected, speckle noise is the dominant factor at smaller offsets and that the dual image technique is effective at reducing it.

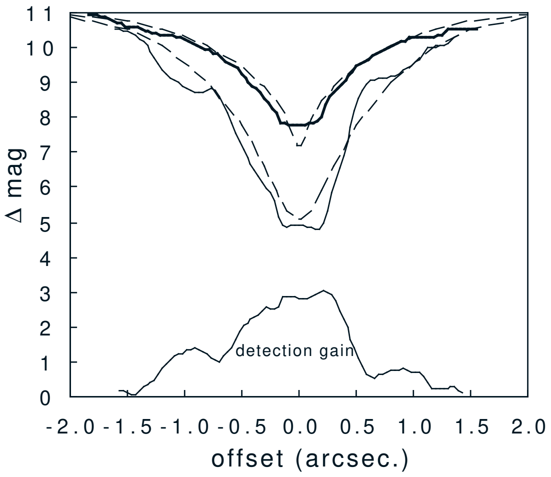

Fig. 3.— Measured 3σ detection thresholds, given as magnitude differences (companion - primary) in a raw (thin line) and a 'despeckled' (thick line) PSF. CFHT AO system, $m_H = 7$, 400 sec. exposure. Dashed lines are model calculations.

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