Suppressing Speckle Noise for Simultaneous Differential Extrasolar Planet Imaging (SDI) at the VLT and MMT

**Beth A. Biller[1], Laird M. Close[1], Rainer Lenzen[2],
Wolfgang Brandner[2], Donald McCarthy[1], Eric Nielsen[1],
Stephan Kellner[2], and Markus Hartung[3]**

[1]Steward Observatory, University of Arizona, Tucson, AZ 85721
email: bbiller@as.arizona.edu

[2]Max-Planck-Institut für Astronomie, Königstuhl 17, 69117 Heidelberg, Germany
[3]European Southern Observatory, Alonso de Cordova 3107, Santiago 19, Chile

Abstract. We discuss the instrumental and data reduction techniques used to suppress speckle noise with the Simultaneous Differential Imager (SDI) implemented at the VLT and the MMT. SDI uses a quad filter to take images simultaneously at 3 wavelengths surrounding the 1.62 μm methane bandhead found in the spectrum of cool brown dwarfs and gas giants. By performing a difference of images in these filters, speckle noise from the primary can be significantly attenuated, resulting in photon noise limited data. Non-trivial data reduction tools are necessary to pipeline the simultaneous differential imaging. Here we discuss a custom algorithm implemented in IDL to perform this reduction. The script performs basic data reduction tasks but also precisely aligns images taken in each of the filters using a custom shift and subtract routine. In our survey of nearby young stars at the VLT and MMT (see Biller *et al.*, this conference), we achieved H band contrasts >25000 (5σ ΔF1(1.575 μm) >10.0 mag, ΔH > 11.5 mag for a T6 spectral type object) at a separation of 0.5" from the primary star. We believe that our SDI images are among the highest contrast astronomical images ever made from ground or space for methane rich companions.

Keywords. instrumentation: adaptive optics, methods: data analysis, techniques: image processing, (stars:) planetary systems.

1. Introduction

Adaptive optics (AO) systems that are "photon noise limited" can detect an object up to 10^5 times fainter its primary at separations >1" – sufficient to detect a young, self-luminous giant extrasolar planet. However, the contrast problem isn't the only obstacle in directly detecting extrasolar planets – Beyond the contrast limit problem, all AO systems suffer from a limiting "speckle noise" floor (Racine *et al.* 1999). Within 1" of the primary star, the field is filled with speckles left over from instrumental features and residual atmospheric turbulence after adaptive optics correction. These speckles vary as a function of time and color. For photon noise limited data, the signal to noise S/N is proportional to $t^{0.5}$, where t is the exposure time. For speckle-noise limited data, the S/N does not increase with time past a specific speckle-noise floor (limiting contrasts to $\sim10^3$ at 0.5"). This speckle-noise floor is considerably above the photon noise limit and makes planet detection very difficult. Interestingly, space telescopes such as HST also suffer from a similar limiting speckle-noise floor due to imperfect optics and "breathing" (Schneider *et al.* 2003). Direct detection of extrasolar giant planets requires special instrumentation to suppress this speckle noise floor and produce photon noise limited images.
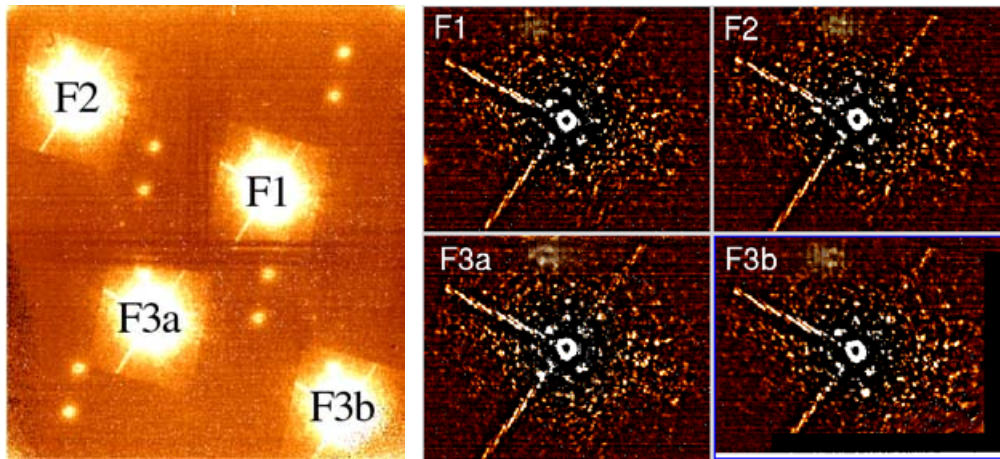
Figure 1. Left: Two minutes of raw SDI data from NACO SDI's 1024×1024 Aladdin array in the CONICA AO camera (Lenzen *et al.* 2004). Right: Same dataset, slightly processed. Apertures have been selected around each filter image. In order to reveal the speckle pattern, a heavily smoothed image was subtracted from the raw images (unsharp masking). The resulting speckle patterns are very similar between the 4 simultaneous images which means that an effective subtraction of speckles can be obtained between the filters.

Simultaneous Differential Imaging is an instrumental method which can be used to calibrate and remove the "speckle noise" in AO images, while also isolating the planetary light from the starlight. This method was pioneered by Racine *et al.* (1999), Marois *et al.* (2000), Marois *et al.* (2002) and Marois *et al.* (2005). It exploits the fact that all cool (T_{eff} <1200 K) extra-solar giant planets are thought to have strong CH_4 (methane) absorption redwards of 1.62 μm in the H band infrared atmospheric window (Burrows *et al.* 2001, Burrows *et al.* 2003). Our SDI device obtains four images of a star simultaneously through three slightly different narrowband filters (sampling both inside and outside of the CH_4 features). These images are then differenced. This subtracts out the halo and speckles from the bright star to reveal any massive extrasolar planets orbiting that star. Since a massive planetary companion will be brightest in the F1 1.575 μm filter and absorbed in the rest, while the star is bright in all three, a difference can be chosen which subtracts out the star's light and reveals the light from the companion. Thus, SDI also helps eliminate the large contrast difference between the star and substellar companions.

2. The SDI AO Cameras at the VLT and MMT

An SDI imaging scheme is currently implemented at the 6.5m MMT (using the MMT AO adaptive secondary mirror and the ARIES AO camera – McCarthy *et al.* 1998) and at the ESO VLT (using the 8m UT4 and the NAOS-CONICA (NACO) AO system) by a group headed by L. Close and R. Lenzen (Close *et al.* 2005, Lenzen *et al.* 2004, Lenzen *et al.* 2005). Both devices are fully commissioned and available for observing.

The SDI technique requires some specialized optics consisting of a cryogenic custom double calcite Wollaston device and a focal plane quad CH_4 filter. Our custom Wollaston splits the beam into four identical beams while minimizing non-common path errors. The *differential* non-common path errors are less than 10 nm RMS per Zernike mode (Lenzen *et al.* 2004). Each of the four beams is fed through one of the filters on the quad filter. Filter wavelengths were chosen on and off the methane absorption feature at 1.62 μm and were spaced closely (every 0.025 μm) in order to limit residuals due to speckle and

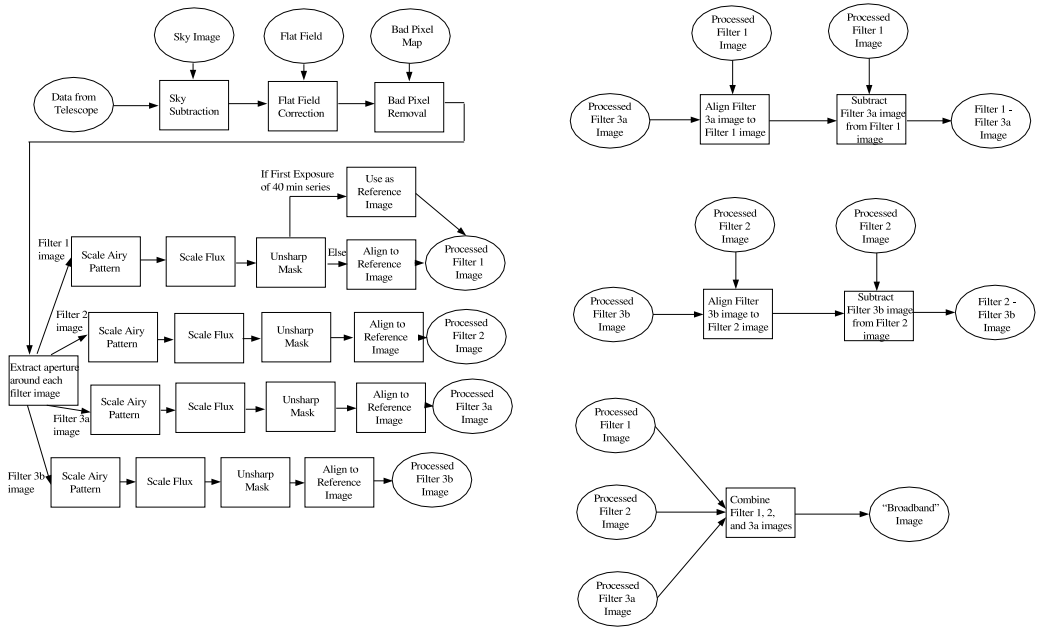**Figure 2.** Pipeline Block Diagrams.

calcite chromatism. We used four filters F1, F2, F3a, and F3b with central wavelengths F1=1.575 μm, F2=1.600 μm, and F3a=F3b=1.625 μm. The filters are approximately 0.025 μm in bandwidth. A cold 5"×5" focal plane mask has been implemented as a field stop for the VLT device. No coronagraph is currently used, since the Strehl ratios ($\sim$20–30%) are too low to increase the contrasts significantly. The SDI camera has a platescale of 0.017″/pix.

3. Observational Technique and Data Reductions

A raw dataset from NACO SDI is shown in Fig. 1. The inner 0.2" diameter core is saturated in each image to increase signal in the halo. After unsharp masking, we find that the speckle patterns in each of the separate filters are nearly identical. (See Fig. 1). This bodes well for our ability to attenuate speckle noise.

To distinguish between faint planets and any residual speckles, we observe each object at a variety of position angles. Instrumental and telescope "super speckles" (Racine *et al.* 1999) should not rotate with a change of rotator angle; however, a real planet should appear to rotate by the change in rotator angle. The data is reduced using a custom IDL script. A pipeline block diagram for this IDL script is presented in Fig. 2. Alignments are performed using a custom shift and subtract algorithm. We calculate 2 differences (and one non-differenced combination) which are sensitive to substellar companions of spectral types "T" ($T_{eff} < 1200$ K), "Y" ($T_{eff} \leqslant 600$ K), and "L" ($T_{eff} > 1200$ K). Data taken at different position angles are subtracted (e.g. 20 minutes of data at 0 degrees minus 20 minutes of data at 33 degrees) in order to further attenuate speckle noise.

A fully reduced dataset from the VLT SDI device as well as the same dataset reduced in a standard AO manner is presented in Fig. 3. Simulated planets were inserted into
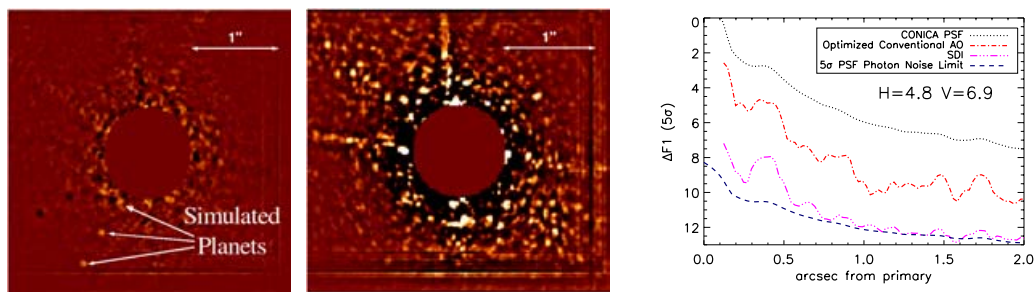
Figure 3. Left: A complete reduced dataset (40 minutes of data at a series of rotator angles –
0°, 33°, 33°, 0°) from the VLT SDI device. Simulated planets have been added at separations
of 0.55, 0.85, and 1.35" from the primary, with $\Delta F1 = 10$ mag (attenuation in magnitudes in
the F1 1.575 μm filter) fainter than the primary. These planets are scaled from unsaturated
images of the example star taken right before the example dataset (and have fluxes in each
filter appropriate for a T6 object). Past 0.7", the simulated planets are detected with S/N
> 10. Center: Standard AO data reduction of the same dataset. Images have been coadded,
flat-fielded, sky-subtracted, and unsharp-masked. Simulated planets have been added with the
same properties and at the same separations as before. None of the simulated planets are clearly
detected in the standard AO reduction. Additionally, numerous bright super speckles remain in
the field. Right: $\Delta F1$ (5σ attenuation in magnitudes in the 1.575 μm F1 filter) vs. Separation
for 40 minutes of VLT SDI data for a 70 Myr K1V star at 15 pc. The top curve is the AO
PSF. The next curve is the "classical AO PSF" unsharp masked. The third curve down is 40
minutes of SDI 0°-33° data. The last curve is the theoretical contrast limit due to photon-noise.
At star-companion separations >0.5", we are photon-noise limited and achieve star to planet H
band contrasts >25000 (5σ $\Delta F1(1.575 \mu m)$ >10.0 mag, $\Delta H > 11.5$ mag for a T6 spectral type
object) at a separation of 0.5" from the primary star.

Table 1. Properties of Example SDI Survey Stars and Comparison Stars.

Case	Spectral Type	Age	Distance	H	V	$\Delta F1$[1]	ΔH[1]	Exposure Time
A	K2V	30 Myr	45.5 pc	7.1	9.1	10.5	12	40 min
B	K1V	70 Myr	15 pc	4.8	6.9	10.5	12	40 min
C	M3V	30 Myr	24 pc	7.1	12.2	10	11.5	40 min
10 K-M stars[2]	K-M	0-1 Gyr	10-50 pc	6.4-8.7	8-12	8.61	10.31	10-25 min
Gl 86[3]	K1V	10 Gyr	10.9 pc	4.2	6.2	12.8	14.3	80 min

[1] 5σ at 0.5"   [2] Masciadri *et al.* IAUC 200   [3] Mugrauer & Neuhäuser 2005.

the dataset pre-reduction. In the SDI reduction, simulated planets (with $\Delta F1=10 - 5\sigma$
attenuation in magnitudes in the 1.575 μm F1 filter) are detected with S/N > 10 past
0.7". In comparison, none of the simulated planets are clearly detected in the standard
AO data reduction and numerous bright super speckles remain in the field. A plot of
$\Delta F1$ (5σ) vs. separation from the primary is presented in Fig. 3. For this dataset, we
achieved star to planet H band contrasts (5σ) >25000 (5σ $\Delta F1(1.575 \mu m)$ >10.0 mag,
$\Delta H > 11.5$ mag for a T6 spectral type object) at a separation of 0.5" from the primary
star – approaching the photon-noise limit in 40 minutes of data. $\Delta F1(1.575 \mu m)$ and
ΔH (for a methane object) for 3 of our survey stars (see Biller *et al.* this conference)
as well as for two other comparison objects are shown in Table 1 – it is clear that the
achievable contrast varies according to the magnitude of the object and total exposure
time. We believe these are among the highest contrast astronomical images taken to date
of methane rich companions.

Acknowledgements

References

Burrows, A., Hubbard, W.B., Lunine, J., & Liebert, J. 2001, *Reviews of Modern Physics* 73, 719

Burrows, A., Sudarsky, D., & Lunine, J. 2003, *ApJ* 596, 587

Close, L.M., Lenzen, R., Biller, B.A., Brandner, W., & Hartung, M. 2005, *Science with AO ESO Workshop September 16-19 2003*, 136

Lenzen, R., Close, L., Brandner, W., Hartung, M., & Biller, B. 2004, *Proc. SPIE* 5492

Lenzen, R., Close, L., Brandner, W., Biller, B., & Hartung, M. 2005, *Science with AO ESO Workshop September 16-19 2003*, 46

Masciadri, E. *et al.* 2006, IAUC 200 proceedings

Marois, C., Doyon, R., Racine, R., & Nadeau, D. 2000, *Proceedings of the Astronomical Society of the Pacific* 112, 91

Marois, C., Doyon, R., Racine, R., & Nadeau, D. 2002, *Proc. SPIE* 4008, 788

Marois, C., Doyon, R., Nadeau, D., Racine, R., Riopel, M., Vallée, P., & Lafrenière, D 2005, *Proceedings of the Astronomical Society of the Pacific*, 117, 745

McCarthy, D., Burge, J., Angel, R., Ge, J., Sarlot, R., Fitz-Patrick, B., & Hinz, J. 1998, *Proc. SPIE* 3354, 750

Mugrauer, M. & Neuhäuser, R. 2005, *MNRAS*, 361, L15

Racine, R., Walker, G.A.H., Nadeau, D., Doyon, R., & Marois, C. 1999, *Proceedings of the Astronomical Society of the Pacific* 111, 587

Schneider, G., Becklin, E., Close, L., Figer, D., Lloyd, J., Macintosh, B., Hines, D., Max, C., Potter, D., Rieke, M., Scoville, N., Thompson, R., Weinberg, A., & Windhorst, R. 2003, *solicited by STScI in preparation for HST Cycle 12*
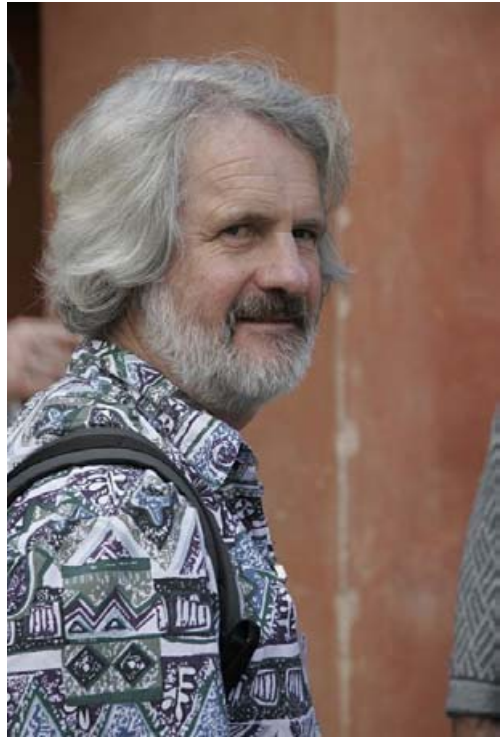
All photographs: Laurent Thareau [`l.thareau@free.fr`].