Advanced Photonics in Application to Astrophysical Problems

Electronic Proceedings of the

Third Joint NSF-DFG Research Conference
Washington, DC, USA • 10 - 12 June 2007

Speckle Interferometry of Solar Adaptive Optics Imagery

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Abstract. To advance our understanding of small-scale magnetic fields, high light-gathering capacity and spatial resolution are essential. This has led to several initiatives for a new generation of solar telescopes with 1 m apertures and beyond. These efforts include the new Swedish 1 m Solar Telescope (SST), which is already operational; the German 1.5 m GREGOR telescope and the 1.6 m New Solar Telescope (NST) at Big Bear Solar Observatory, which are currently under construction; and the 4 m Advanced Technology Solar Telescope (ATST) under NSO stewardship, which approaches the end of its design and development phase.

This new or next generation of solar telescopes can only achieve its potential by relying on extensive use of *in situ* and/or post-facto image correction. Correlation tracking, spot tracking, and adaptive optics (AO) systems belonging to the aforementioned class, while blind deconvolution algorithms, (speckle) phase diversity techniques, speckle deconvolution, speckle holography, speckle masking method, etc. comprise the latter. The next steps in image reconstruction can be separated in two categories: (1) implementing post-facto techniques on parallel processors pushing image reconstruction toward real-time applications and (2) efficiently combining *in situ* and post-facto image correction.

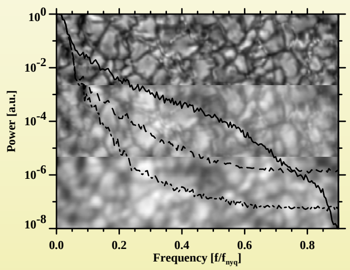

Figure 1. Average power spectra of solar granulation have been obtained from 90 individual, one-dimensional, 28″-long intensity profiles for the speckle reconstruction *(solid line)*, short-exposure image *(dashed line)*, and long-exposure image *(dashed-dotted line)*, respectively. The spatial frequencies on the abscissa have been normalized with respect to the Nyquist frequency f_{Nyq} and the power values are given in arbitrary units normalized to the first order Fourier component. The three background panels show from top to bottom the same area of granulation in the speckle reconstruction, the short-exposure image, and the long-exposure image. The panels have been independently scaled between maximum and minimum brightness, thus, contrasts are not directly comparable (Denker *et al.* 2005).

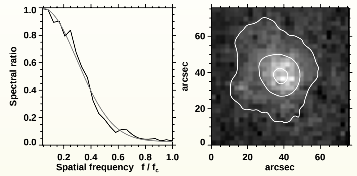

Figure 3. (*left*) Azimuthal average of the spectral ratio (SR) for a single isoplanatic patch. (*right*) Field dependence based on the standard deviation of the SR $f = f_c$. SRs were determined for 30 × 30 isoplanatic patches covering a FOV of about 76″ × 76″. The white contour lines correspond to $f = f_c$ = 0.20, 0.25 and 0.30, respectively. The data was smoothed before computing the contours (Denker *et al.* 2007a).

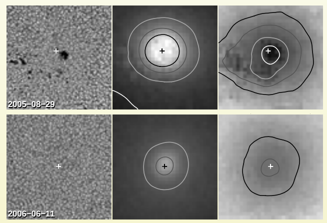

Figure 4. Variation of the BBSO (*top*) and DST (*bottom*) AO systems' correction across the field. (*left column*) Speckle restored image, (*middle column*) field dependence derived with SRT, and (*right column*) from differential image motion. The crosses mark the AO lock point (Denker *et al.* 2007a).

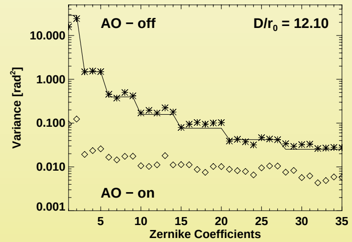

Figure 5. Comparison of the variance of the Zernike coefficients for open- (∗) and closed-loop (◇) data determined from AO WFS data. The solid curve represents a fit to the Kolmogorov spectrum of the open-loop data for D / r_0 = 12.1 (Denker *et al.* 2007b).

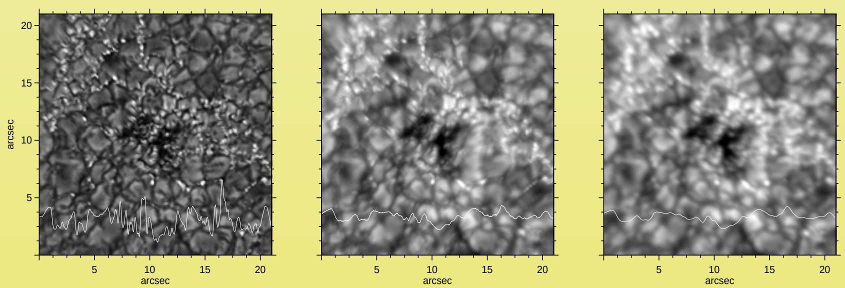

Figure 2. Average (*right*), reference (*middle*), and reconstructed (*left*) images of a small solar pore observed close to disk center on October 24, 2005 at the Dunn Solar Telescope (DST) of the National Solar Observatory at Sacramento Peak. The data were collected taking advantage of the high-order AO system and a high speed 2k × 2k detector with 12 micron pixels manufactured by DALSA. A 1 nm wide interference filter centered around 430.5 nm was used in front of the detector to select the G-band wavelength range. In order to allow for speckle reconstruction the data was recorded in bursts of 80 images, which were acquired within 3.5 s and saved to hard-disk within 30 s. The exposure time for an individual frame is 10 ms. The whole data set consists of about 100 bursts with a mean cadence of 67 s covering a time period of almost 2 h. The curve at the bottom of each panel represents a cross section of the G-band intensity illustrating the recovery of high-spatial frequencies in the reconstructed images (Uitenbroek, Tritschler, & Rimmele 2007).

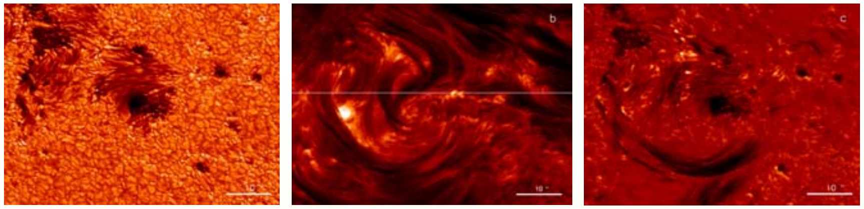

Figure 6. Active region NOAA 10875 at μ = 0.59 observed with the upgraded Göttingen Fabry-Pérot interferometer. (a) Speckle reconstructed broadband image at 6300 Å. The spatial resolution is better than 0.3″ and the FOV is about 63″ × 47″. (b) Reconstructed narrowband image in Hα line center (spatial resolution better than 0.3″. (c) Reconstructed narrowband image at Hα − 1 Å off line center (Sánchez-Andrade Nuño, Puschmann, & Kneer 2007).

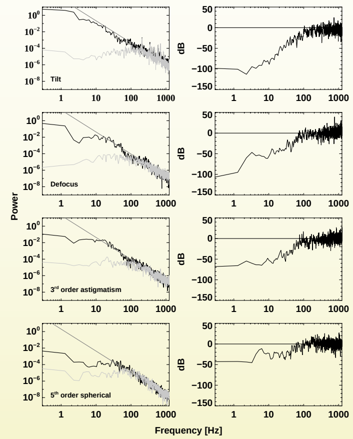

Figure 7. (*left*) Temporal power spectra of selected Zernike coefficients comparing open- (black) and closed-loop data (gray). Overplotted is also a power-law fit with an exponent of −8/3. (*right*) Ratio of open- and closed loop power spectra used in determining the zero cross-over frequency (Denker *et al.* 2007b).

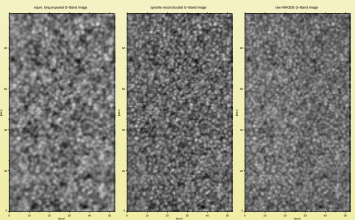

Figure 8. (*left*) Equivalent of a long exposed (200 ms) image in the Fraunhofer G-Band (430.5 nm) and (*middle*) corresponding speckle reconstruction (Wöger & von der Lühe 2007). The data was observed using the DST high-order AO system. (*right*) Raw G-Band image of the HINODE satellite operated by ISAS/JAXA of the same region.

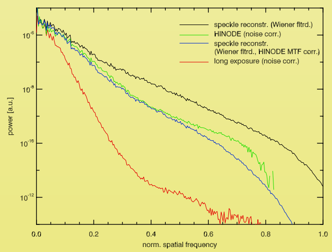

Figure 9. Spatial power spectra of the data displayed in Figure 8. The spatial frequency axis is normalized to the diffraction limit of the HINODE satellite. The spatial power spectrum of the long exposure (*red*) shows the effect of the atmospheric tubulence – the high frequency content in the data is lost in noise. The power spectrum of the speckle reconstruction shows the best estimate of the "true" object, which is free of instrumental effects (MTF). When applying the MTF of HINODE's pupil with a central obscuration of 34.4% in radius (*blue*), the power spectrum fits very well with that of HINODE.

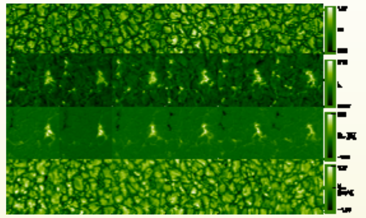

Figure 10. Time sequence of an area with network boundary magnetic fields of opposite polarity. From top to bottom: Broadband intensity BB, line centre intensity I_{lc}, magnetic flux density B_{eff} and velocity V_{cog} at 6 different time steps (Δt = 4 min 32 s and FOV: 11″ × 11″). Under the high spatial resolution achieved (< 0.3″) granules appear eroded. Intergranular lanes show a complex structure, indicating cool areas related to strong downflows sometimes located in the vicinity of magnetic features. Network boundary magnetic fields reveal strong dynamics in interaction with granular convection, changing their fine structure at time scales < 17 s. During the entire sequence the flux densities reach values of up to 800 G (Puschmann, Kneer, & Domínguez Cerdeña 2007).

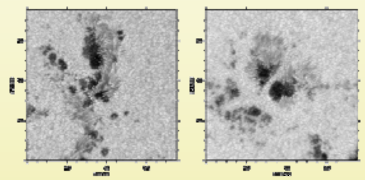

Figure 11. The reconstructions show two areas of the large and complex decaying active region NOAA 10808 observed with the 65 cm reflector at Big Bear Solar Observatory. The active region produced several M- to X-class flares during its disk passage.

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Acknowledgements. This work was supported by NSF under grants ATM 00-86999, ATM 02-36945, IIS ITR 03-24816 and AST MRI 00-79482, by NASA under grant NAG 5-12782, and by DFG under grant KN 152/29. BSAN acknowledges support by the International Max Planck Research School. The National Solar Observatory is operated by the Association of Universities for Research in Astronomy under a cooperative agreement with the National Science Foundation, for the benefit of the astronomical community.

NJIT NSO National Solar Observatory Institut für Astrophysik Göttingen INAF AIP