Applying speckle-masking to spectra

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Abstract. We have applied the technique of speckle masking to spectra. The observation of elongated solar structures avoids the problem of missing information in one-dimensional spectra. Image motion perpendicular to the slit was diminished by a one-dimensional image stabilization system. The remaining influence of the earth's atmosphere was removed by a modified speckle-masking algorithm, adapted to the single spatial dimension occurring in the spectra. The reconstructed spectra achieve the diffraction limit of the telescope and the spectrograph.

The first application of this technique to observations of spicules and penumbral filaments reveals more details and also yield line profiles which differ from those before reconstruction. The Hα emission in spicules shows line-of-sight velocities two times larger than in the unprocessed spectra. The non-magnetic line Fe 709.03 nm shows penumbral line widths, reflecting mostly the line asymmetry from the Evershed effect, which are tightly correlated to the continuum intensity fluctuations. Our reconstruction increases the coherence between both from 0.6 to 0.8.

1. Introduction

The investigation of the solar fine-structure is usually hindered by influences from the earth's atmosphere, i.e. image motion, image degradation, and blurring. The first effect can be largely eliminated by image stabilization and short exposure times. The other two effects can be removed by numerical methods such as speckle masking (Weigelt, 1977; von der Lühe, 1993). The resulting two-dimensional images achieve the limiting resolution of the telescope used (e.g. de Boer, 1995; Denker, 1998).

The understanding of the solar fine-structure, however, often requires spectral information which is difficult to extract from two-dimensional images. A first step toward a spectral analysis at very high spatial resolution is multi-color photometry of the spectral continuum from numerically reconstructed images, which allows a determination of the temperature via the Planck law (Tritschler, Schmidt and Knölker, 1997; Sütterlin and Wiehr, 1998; Sütterlin *et al.*, 1999). However, other parameters such as velocity, magnetic field, gas pressure, turbulence, require spectrally resolved line profiles which can either be achieved by classical spectroscopy or with a scanning Fabry-Pérot interferometer (e.g. Krieg *et al.*, 1999).

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In classical long-slit spectra, very high spatial resolution is difficult to achieve since image motion temporarily moves the structures away from the spectrograph slit. In addition, the application of speckle techniques suffers from long exposure times and from the single spatial direction which yields only few locations for a determination of the Fourier phase angles. Here, we present a method which avoids these restrictions, and give the first results of our new technique.

2. Method

The degradation of a solar image has, in general, two sources: light from the corresponding location on the solar disk is lost and light from other solar locations is added. The elimination of such an image degradion requires the knowledge of both locations, those where the scattered light originates from and those where the lost light is spread to. Spectra contain only a single spatial dimension and therefore lack information about the total two-dimensional surroundings.

A successful solution was found by Keller and Johannesson (1995). They used a combination of speckle deconvolution and a rapidly scanning spectrograph. In addition to the spectra, simultaneous slit-jaw images were taken. Applying the Knox-Thompson method to the sequence of slit jaw images, they derived the point spread function which was finally applied to the spectrogram.

We pursue another way, the direct reconstruction of the spatial coordinate in spectra. The image reconstruction method of speckle masking uses the Fourier representation of the image. Here, the phase relation between different wavenumbers at a given lag are used to compute the phase of the true image in the Fourier domain (Knox and Thompson, 1974). In case of an image with spatial variations mainly in one dimension, the Fourier transform has contributions only along the corresponding single direction and is zero elsewhere. The standard procedure of speckle masking can then be confined to that single dimension.

In order to be free of the other spatial dimension, the width of the spectrograph slit should not exceed the spatial resolution limit of the telescope. In that case, however, a reasonable count rate in the spectra would require exposure times which are too long to assure frozen wavefronts. A broader slit may be accepted, if only solar structures are observed which extend along one direction more than in the other. If the spectrograph slit intersects their long axis perpendicularly, we may assume that spatial variations over the slit width are negligible. Examples of such 'quasi one-dimensional' objects are spicules and penumbral filaments.

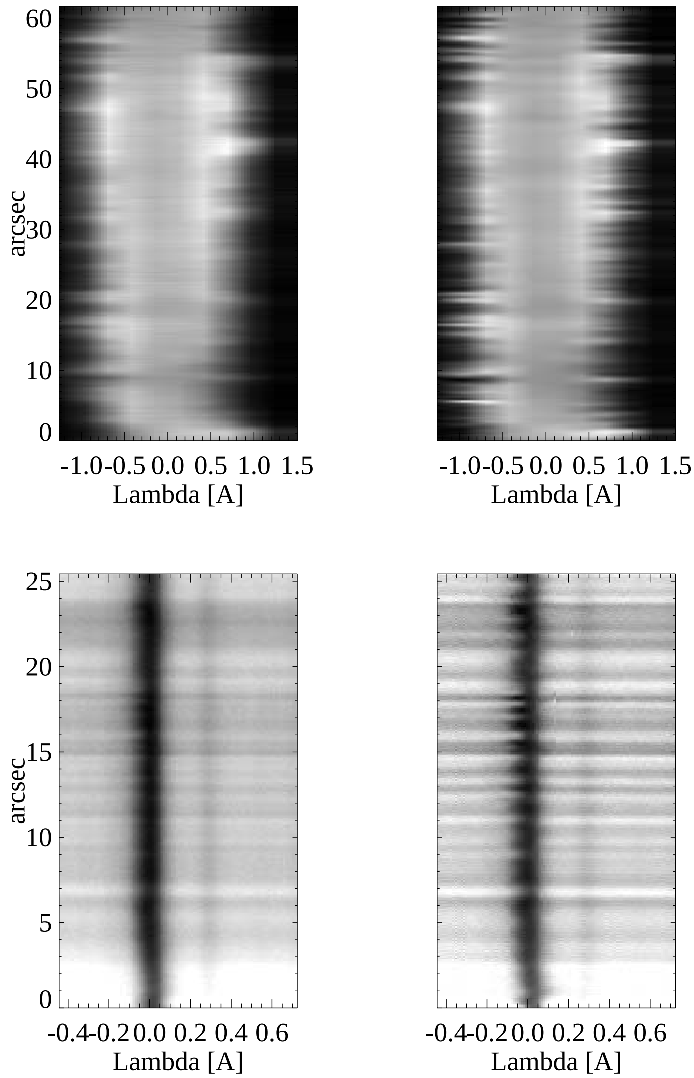

Figure 1. Spectra of Hα in spicules (upper panel) and Fe I 709.03 nm in a penumbra at $\theta \sim 70^\circ$ (g=0, lower panel); best spectrum of the burst (right-side); speckle reconstructed (left-side)

3. Observations

On 22 May 1997, we observed the Hα emission in spicules above the limb with the evacuated Gregory Coudé Telescope on Tenerife. A 0.75 arcsec spectrograph slit was oriented perpendicular to the spicules.

This slit width corresponds to 500 km and is small compared to the typical spicule length and does therefore not limit the achievable spatial resolution in the spectra, as it would be the case for fine-structures which are not elongated. The image scale of 8.2 arcsec/mm at the Gregory telescope corresponds to 0.16 arcsec/pixel on the CCD at the spectrograph output.

A one-dimensional image stabilizer driven by the solar limb in the white-light slit-jaw image (cf., Sütterlin *et al.*, 1997) was used to reduce the image motion component perpendicular to the spectrograph slit to about 0.3 arcsec. Observing spicules at a location where the solar limb is oriented parallel to the slit, avoids the use of the Coudé image derotator which would diminish intensity, contrast, and total modulation transfer function.

A second observing campaign was carried out on June 29, 1998, targeting the non-magnetic line Fe I 709.03 nm in a sunspot penumbra at ($\sim$ 70°W ; 30°N) using the Vacuum Tower Telescope (VTT) on Tenerife and the same slit width of 0.75 arcsec. Here, the penumbral structures were monitored on the spectrograph slit by means of the correlation tracker system of the VTT which reduces seeing to about 0.2 arcsec (Schmidt and Kentischer, 1995). The image scale at the VTT spectrograph is 4.8 arcsec/mm corresponding to 0.18 arcsec/pixel on the CCD.

As for speckle observations of two-dimensional images, the data were taken as 'bursts', i.e. short exposures of 35 ms in a rapid sequence of about 3 frames per second. The exposure time is a compromise between the request of frozen wavefronts and sufficient counts for an acceptable signal-to-noise ratio. The limiting factor for the total number of images is the time needed to record the whole burst of images which should be short as compared to evolutionary changes of the solar structures under study. Our bursts of 60 frames correspond to a time span of 20 seconds.

4. Data reduction

After standard image processing of dark and flatfield corrections, the spectra of each burst were spatially aligned to compensate for image motion and telescope jitter. To estimate the Fried parameter, r_0, using the spectral ratio method (von der Lühe, 1984), the spectra were compressed in wavelength for a better signal-to-noise ratio. The small amount of data in our one-dimensional case allows to use the full rather than the truncated speckle masking bi-spectrum. The derived r_0 value

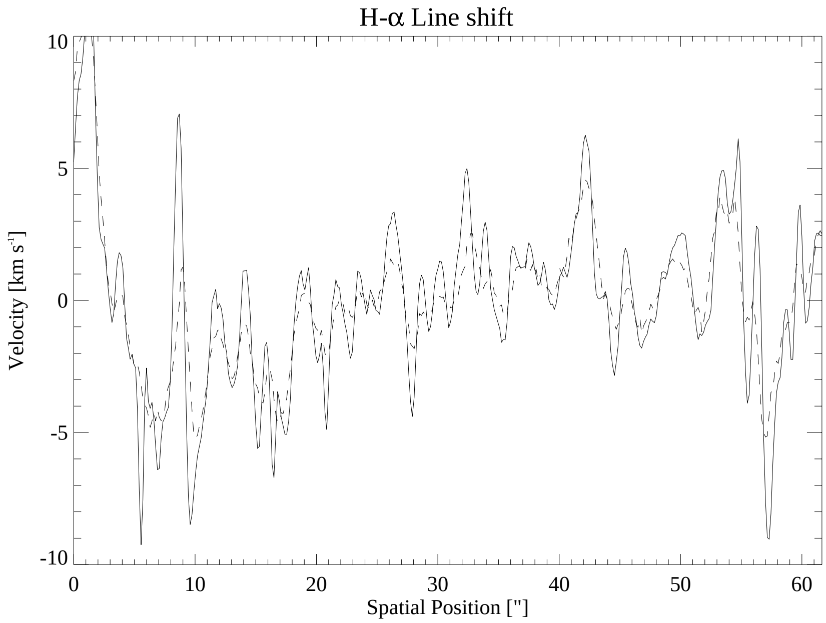

Figure 2. Spatial variation along the slit direction of the Doppler shift of the Hα emission in spicules before (dotted) and after (full line) image reconstruction by speckle masking

and hence the corresponding speckle transfer function (STF) were used for all wavelength positions in the spectrum.

In a second step, the spectra were divided into spatial subspectra, adapted to the typical size of iso planar seeing patches. Within each subspectrum, every wavelength point was reconstructed independently. The Fourier phases can be computed from the speckle masking bispectrum

$$F_\lambda^3(k,l) = \langle F_\lambda(k) \cdot F_\lambda(l) \cdot F_\lambda^*(k+l) \rangle$$

by a recursive process (F_λ being the Fourier transform of the spatial intensity signal at wavelength λ). Together with the Fourier amplitudes determined by the method of Labeyrie (1970), this gives the real intensity signal $f_\lambda(x)$.

In a last step, the reconstructed one-dimensional intensity slices for each wavelength position were connected, thus forming the spectrum within one iso planar patch. Finally, the different subspectra were connected to obtain the complete spatial extension of the reconstructed spectrum.

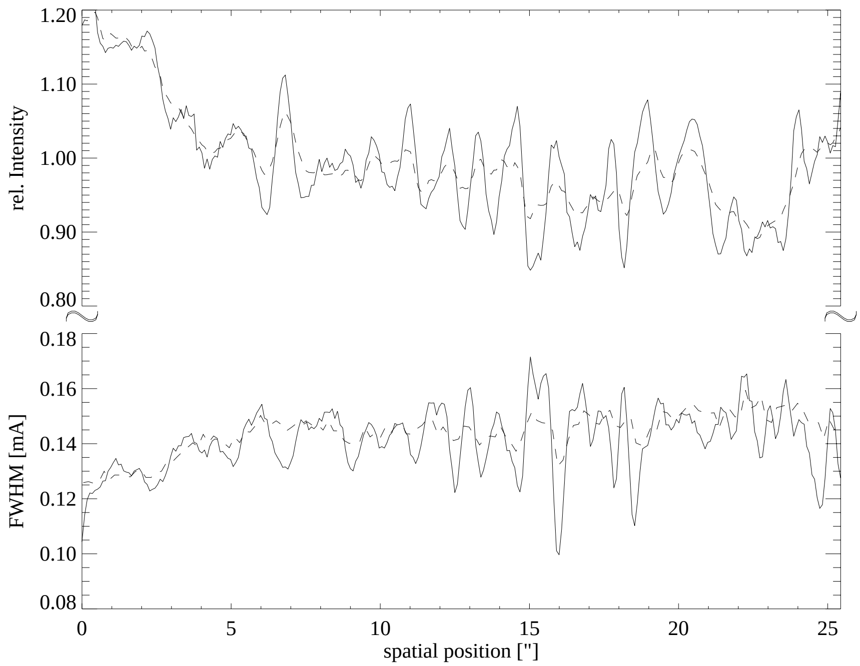

Figure 3. Spatial variation of continuum intensity (upper), and line width FWHM (lower panel) of Fe 709.03 nm along the spatial slit direction through a center-side penumbra near $\vartheta = 70^o$ before (dotted) and after (full lines) image reconstruction by speckle masking. The FWHM is a measure for the line-asymmetry from the Evershed effect

5. First results

The influence of the reconstruction process on the spectra of spicules and of sunspot penumbral structures is shown in Figure 1. The removal of atmospheric image degradation not only yields enhanced contrasts but also fine-structure not visible even in the best unprocessed spectrum of the burst. The most important result, however, is the remarkable influence of the reconstruction procedure on the line profiles. The Doppler shifts in spicules (Figure 2) and also in the penumbra are enhanced by about a factor of two. Interestingly, the spatial locations of the velocity extrema do not fully coincide in the processed and in the unprocessed spectra.

Similar as the Doppler shifts, also the line widths (FWHM) are modified by speckle masking. The mean spatial coherence of FWHM and continuum intensity increases from 0.6 before reconstruction to 0.8 (Figure 4). Since outside the disk center the widths of non-magnetic lines in penumbrae are a measure for the profile asymmetry from the

Figure 4. Phase relation and coherence between the spatial variations of continuum intensity and the line-asymmetry from the Evershed effect (FWHM) of Fe 709.03 nm (cf., Fig.3); dashes in the lower panel: coherence before image reconstruction by speckle masking, full line: after that.

Evershed effect (cf., Wiehr, 1999), our result supports the finding by Wiehr and Degenhardt (1992) that the tight correlation between the Evershed effect and dark penumbral structures increases with the spatial resolution achieved. This fact strongly supports that the Evershed effect (and very probably also the photospheric magnetic field) abruptly cease where the penumbral structures end, in agreement with numerous observations at lower spatial resolutions (cf., references in Wiehr 1999) and in contrast to Börner and Kneer (1992).

In the domain 21 to 26 Mm^{-1} (300 to 240 km), the cross-correlation coefficient increases even from 0.2 to 0.65, whereas its maximum at 29 to 38 Mm^{-1} (220 to 165 km) is almost unaffected by the reconstruction (cf., Figure 4). It remains unclear why these widths ranges show a particular sensitivity of the cross-correlation to the reconstruction process.

6. Conclusion

We have shown that speckle masking reconstruction of spectra not only enhances the contrast along the spatial direction. Instead, fine-structures are revealed which are not seen in the unprocessed spectra. This information is hidden in the light lost from the solar structure under study and in the light added from other solar locations in the slit direction. Our one-dimensional speckle masking procedure reconstructs that hidden spectral information. As long as one restricts oneself to lengthy solar structures and uses an image stabilizer, the application of speckle masking to spectra achieves a spatial resolution near the diffraction limit of the telescope, permitting the investigation of sub-arcsec solar structures. An interesting application of our method would be the study of fine-structure of the penumbral magnetic field.

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