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ONE-DIMENSIONAL SPECTROSCOPY OF THE SOLAR PHOTOSPHERE

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Abstract. Data from a time series of spectrograms were used to study correlative relationships between intensity and velocity in the solar photosphere. The variations along the slit of the line parameters from two Fe lines lying in the visible range of the spectrum were used. The formation height difference of these lines is over 300 km. The temporal variations of the correlation coefficients were studied, they showed a strong influence of the 5 min-oscillations. A shorter period of the oscillations was found for the higher photosphere, whereas the amplitude of the oscillations is there larger.

Key words: Sun: photosphere - Sun: granulation

1. Introduction

A common method to investigate the photospheric structure is the calculation of correlations between characteristic quantities, such as intensity and velocity, in different photospheric heights. A good correlation between continuum intensity and velocity, which decreases with increasing line formation height, was found by Mattig *et al.* (1969), Canfield & Mehltretter (1973), Hanslmeier *et al.* (1990), Komm *et al.* (1990) and Nesis *et al.* (1993). Gadun *et al.* (2000) predicted this result with their model and could confirm it by comparison with observations. They also predicted a decreasing anticorrelation between residual intensity and velocity in the higher photosphere, their observations confirmed this. Canfield & Mehltretter (1973) also found an inverted correlation of these parameters in the high photosphere. Hanslmeier *et al.* (1990) and Hanslmeier *et al.* (2000) studied correlations between velocities depending on the formation height difference. They still found a good correlation even at differences over 300 km.

2. The Data

The data consisted of time series of spectrograms recorded on April 28^{th} 2000 with the German Vacuum Tower Telescope (VTT) at the Observatorio del Teide (Izaña, Tenerife). The recordings were carried out from 09:26:36 to 09:41:36 UT, the target was almost in the center of the solar disc in the quiet atmosphere near AR 8976. The Adaptive Optics (AO) system of the NSO/SP was allocated on loan for a test deployment at the VTT. The slit width of the Echelle spectrograph was 100 μm equivalent to 0.5". The slit was oriented perpendicularly to the horizon. The exposure time was 1 s and the spectra were separated by 3 s. Spatial and spectral samplings were 0.125"/pixel and 2.4096 mÅ/pixel, respectively. The slit-jaw image system was used to record the exact position of the spectrograph slit on the solar disc.

All spectra were then photometrically reduced using the precise reduction procedure of Wöhl *et al.* (2002). High frequency noise was removed by Gaussian filtering (Gray, 1976), the center-to-limb darkening was removed, and the spectra were normalized. The spectral line parameters were then calculated, such as the continuum intensity, the residual intensity and the Doppler velocity.

Several Fe lines in the visible range of the spectrum were chosen, here the Fe II line at 4993.358 Å and the nearby Fe I line at 4994.129 Å are used. Some estimated line formation heights and the line's equivalent widths are collected in Table **I**. The parameters given are the effective heights of line formation for the line central depth H_d calculated with the depression contribution function and the geometrical height H_τ at line center optical depth $\tau_{\lambda 0} = \tau_{\lambda 0}^{\mathrm{C+L}} = 1.0$ (C...continuum, L...line). They were obtained using two different atmospheric models: with the MACKKL model (Maltby *et al.*, 1986) and with a 1-D model which was obtained by spatial and temporal averaging of the 2-D models (e.g. Gadun *et al.*, 1999; Gadun *et al.*, 2000). 2-D models do not consider the chromospheric growth of temperature though, so they can produce wrong formation heights for some lines.

	Fe II	Fe I
Eq. width / mÅ	39	105
H_d (MAC)	165.9	475.8
H_τ (MAC)	108.9	472.2
H_d (2-D)	127.1	392.2
H_τ (2-D)	77.2	449.5

Table I: Estimated line formation heights in km obtained with two models.

3. Results

The data used here do not consist of the actual two-dimensional spectrograms, but of the one-dimensional variations of the various line parameters along the slit. The line parameters continuum intensity I_c, residual intensity I_r and Doppler velocity v are investigated. The velocity is given in km/s, negative values for upflows and positive values for downflows are used. The index 1 corresponds to the Fe II line and the index 2 to the Fe I line, respectively. For the next sections, 950 values in spatial (∼120" on the disc) and 300 in temporal direction (15 min) are used.

3.1. Temporal variation of correlation coefficients

The main idea was to study the temporal changes of the correlation between different line parameters. Therefore, the correlation coefficients of the parameter variations have been calculated for each spectrum and were then aligned along the time axis.

Figure 1 shows temporal variations of the correlation between the residual intensities (solid line) and the velocities (dotted line), respectively. Although the lines are formed in atmospheric layers separated by more than 300 km, both correlations are quite good and fluctuate about a mean value of 0.6. Both correlations fluctuate due to the 5 min-oscillations, the amplitude of the velocity correlation is larger. The maxima of the I_r-correlation do not always occur at the same times as the maxima of the velocity correlation.

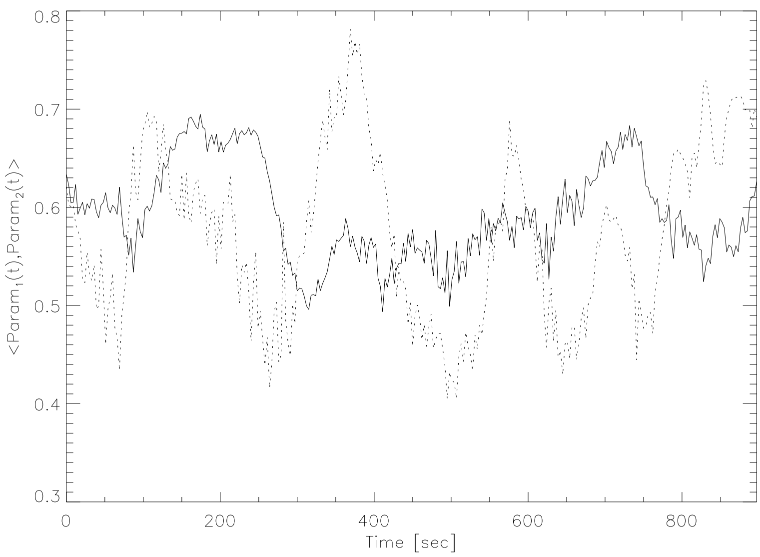

Figure 1: The temporal variation of the correlation between I_{r1} and I_{r2} (solid), and between v_1 and v_2 (dotted).

The temporal variation of the correlation between I_c and velocity is displayed in Figure 2. The correlation for the Fe II line (solid) is negative and shows quite large fluctuations about a mean value of -0.6. The same correlation for the Fe I line (dotted) shows similar variations with time, though the mean correlation coefficient is much lower. The large fluctuations in Figure 2 are due to the 5 min-oscillations. The

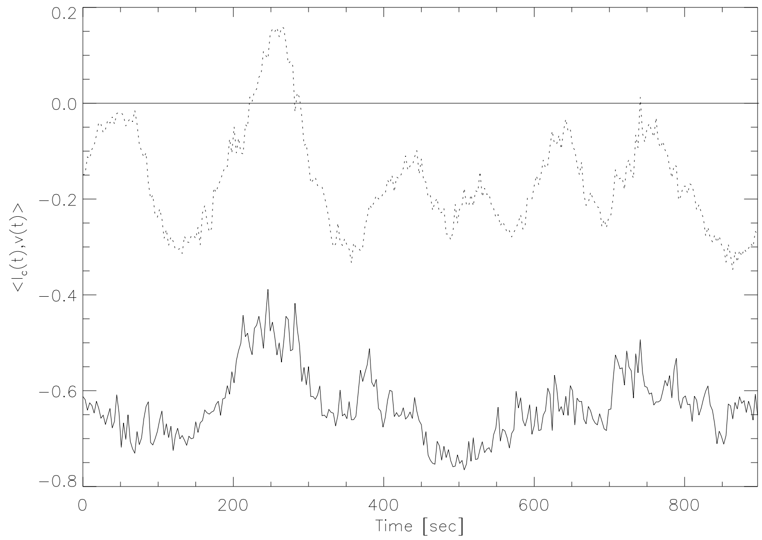

Figure 2: The temporal variation of the correlation between I_c and v.

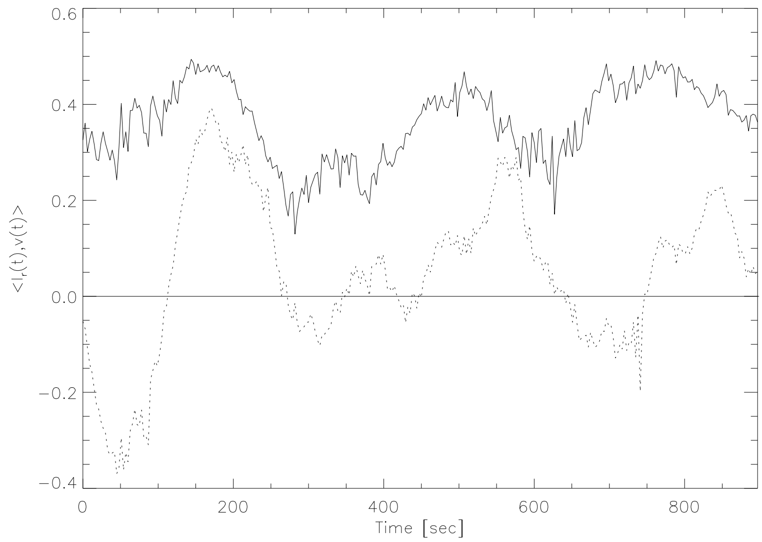

Figure 3: The temporal variation of the correlation between I_r and v.

Fe I line shows oscillations with shorter periods, because the frequency changes from the photosphere to the chromosphere.

The correlation between I_r and respective velocity show a similar temporal behavior (Figure 3). For the Fe II line (solid), there is a low correlation, the coefficient fluctuates around 0.35. For the Fe I line (dotted), the coefficient fluctuates around zero, the curve's minima are negative. Again, the influence of the 5 min-oscillations is clearly visible.

3.2. Mean correlation coefficients

Table **II** shows the averaged correlation coefficients over all 300 spectra. As can be seen from the previous figures, these mean values are not capable of representing the real physical situation. The correlation between line parameters can fluctuate strongly with amplitudes of over 0.4 during a time series. The strong influence which the 5 min-oscillations have on the correlation coefficients has to be taken into account.

$< I_c, v_1 >$	-0.63 ± 0.07
$< I_c, v_2 >$	-0.16 ± 0.11
$< I_{r1}, v_1 >$	0.36 ± 0.08
$< I_{r2}, v_2 >$	0.05 ± 0.16
$< I_{r1}, I_{r2} >$	0.59 ± 0.05
$< v_1, v_2 >$	0.57 ± 0.09

Table II: Mean correlation coefficients with standard deviations. Large uncertainties are found for the correlations of the Fe I line indicating larger amplitudes of the temporal fluctuations.

4. Discussion

The resulting mean correlation coefficients correspond well to the findings in literature. The correlation between I_c and velocity is good for the low to mid-photosphere and decreases with height. This decrease shows that the intensity fluctuations (and therefore the temperature fluctuations) become less coupled with height, in the upper photosphere the material is not necessarily ascending above the bright granules. The good, but not perfect correlation in the lower photosphere indicates the asymmetry of the the granular flow (Nesis *et al.*, 1993). They found that the intensity maxima do not coincide with the velocity maxima. The good correlation of about 0.6 which decreases with height was also found by Mattig *et al.* (1969), Canfield & Mehltretter (1973), Hanslmeier *et al.* (1990) and Komm *et al.* (1990), to name a few. Gadun *et al.* (2000) compared theoretically derived correlations with data from observations. Their model predicts a decrease of the correlation between I_c and velocity with height, which is also confirmed by their observations. The correlation between I_r and velocity is predicted to be positive in the low photosphere, decrease steeply with height and become negative in the mid-photosphere, and then show decreasing anticorrelation in the upper regions. Their observations confirmed the decrease of anticorrelation in higher regions, which is also found in here. Hanslmeier *et al.* (1990) calculated correlations between the line center velocities depending on the height difference. For height differences larger than 300 km, they found values of about 0.65, which is in accordance with the results presented in here. Hanslmeier *et al.* (2000) again studied the correlation between velocities of different lines. They found a linear decrease with increasing height difference. Their largest height difference is 250 km, and the correlation is still about 0.76. For I_r, they also found a high value of 0.7 at this height difference.

5. Conclusions

It was possible to show the influence of the 5-min oscillations on the correlations between line parameters. A shortened period of the oscillations was found for the higher forming line, as well as a larger amplitude of the fluctuation of the correlation coefficient. The averaged values of the correlation coefficients over 15 minutes are in accordance to previous findings: a good correlation between I_c and velocity for the low to mid-photosphere decreasing with height and a low anticorrelation between I_r and velocity, also decreasing with height. A good correlation is also found between the two velocities, and for the two residual intensities a similar value was found.

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