Abstract. The present study addresses the following questions: How representative of the actual velocities in the solar atmosphere are the Doppler shifts of spectral lines? How reliable is the velocity signal derived from narrowband filtergrams? How well defined is the height of the measured Doppler signal? Why do phase difference spectra always pull to 0° phase lag at high frequencies? Can we actually observe high frequency waves (P ≤ 70 s)? What is the atmospheric MTF of high frequency waves? How reliably can we determine the energy flux of high frequency waves? We address these questions by comparing observations obtained with Hinode/NFI with results from two 3D numerical simulations (Oslo Stagger and CO5BOLD). Our results suggest that the observed high frequency Doppler velocity signal is caused by rapid height variations of the velocity response function in an atmosphere with strong velocity gradients and cannot be interpreted as evidence of propagating high frequency acoustic waves. Estimates of the energy flux of high frequency waves should be treated with caution, in particular those that apply atmospheric MTF corrections.

Key words. Waves – Line: formation – Sun: chromosphere – Sun: oscillations – Sun: photosphere

In the present study we compare Mg b2 and Na D1 Dopplergram time series with results from two 3-D simulations. The observations were obtained with the narrowband filter (NFI) on Hinode. The Mg b2 series was obtained on 2009/01/11. It is about 2 hours long and has a cycle time of 32 s. Each cycle comprises 4 filtergrams, taken at ±68 mÅ (“core”) and ±188 mÅ (“wing”) from the line center position, respectively. The Na D1 series was obtained on 2009/01/07, with same duration and cycle time and wavelength offsets of ±80 mÅ and ±168 mÅ, respectively. After coalignment and interpolation to a common time frame, velocity proxies have been calculated by $S_v = (R - B)/(R + B)$, where R and B denotes the measured red and blue wing (core) intensities.

The two simulations we use were computed with the Oslo-Stagger code (Hansteen et al. 2007) and the CO5BOLD code (Wedemeyer et al. 2004; Straus et al. 2008). They give access to both the actual velocities at given heights in the atmosphere as well as “observed” Doppler shifts in simulated line profiles. The Oslo-Stagger simulation
Fig. 1. Comparison between observations and simulations of the Mg $b_2$ (upper row) and Na $D_1$ (lower row) lines: The two smaller panels at the center display the spatially averaged phase difference scatter plots obtained from observations with Hinode/NFI. The deviation from the expected behavior of linear sound waves (green line) is evident. The outermost panels on either side show phase difference spectra between actual velocities (heights indicated in diagrams), with the Oslo-Stagger model on the left and CO$^5$BOLD model on the right. The inner panels show the phase difference between core and wing Doppler shifts from the simulations.

Fig. 2. Power spectra of the simulated Hinode/NFI signals and of the actual velocities at corresponding heights in the simulations. The Oslo-Stagger code results are shown in the left panel, the CO$^5$BOLD model results are on the right. The expected MTF for Fe 6301 is taken from Fleck et al. (2008). Surprisingly, none of the power spectra of the simulated observations shows such a behavior. Instead, the “observed” power is comparable to or higher than the power of the actual velocities.

covers 20 minutes of solar time and extends from the subphotospheric convection zone up to the corona. In this simulation, the Mg $b_2$ and Na $D_1$ lines have been calculated in 1D NLTE. The CO$^5$BOLD simulation covers 2 hours of solar time and has the upper boundary at approximately 900 km above the base of the photosphere. The line profiles of the Fe 6301, Mg $b_2$, and Na $D_1$ lines have been calculated in LTE. For this simulation we also have the full contribution functions to the emergent intensity at the minimum of the line profiles in each spatial point and for each time step. Furthermore, the velocity response function has been calculated for each spatial point for the first snapshot of the time series. The resulting estimates of the average formation heights are 150 km and 550 km for the wing and core Doppler shifts in the Mg $b_2$ line, and 100 km and 700 km for the wing and core signals in the Na $D_1$ line, respectively.

The phase difference spectra of the actual velocities in the Oslo-Stagger simulations show the expected behavior of linear wave theory (Souffrin 1966), with a linear phase increase up to the Nyquist frequency (Fig. 1).
The corresponding CO\textsuperscript{5}BOLD spectra show good agreement up to about 10 mHz. At higher frequencies, they do not follow the expected behavior but reveal several ±180° phase jumps, suggesting wave interference. Inspection of time-lapse sequences of x-z cuts of the CO\textsuperscript{5}BOLD cube indeed suggests wave reflection near the upper boundary and at the steepening shock fronts in the chromospheric layers. This aspect of the CO\textsuperscript{5}BOLD simulations requires further investigations.

To check this hypothesis we compared power spectra of the simulated Doppler shifts with those of the actual velocities at the target heights in the simulations (Fig. 2). As the Dopplergram signals have not been calibrated, we normalized them to the total power of the actual velocities in the frequency range from 3 to 6 mHz. Surprisingly, the power spectra of the Doppler shifts do not reveal the expected steep fall off at high frequencies. Instead, the power at high frequencies is comparable to the power of the actual velocities. In the case of the Mg core Doppler shift the power at high frequencies is even higher than that of the actual velocities. This discrepancy is most evident in the case of the Fe 6301 line, for which the high-frequency power of the Doppler shifts is orders of magnitude higher than the power of the actual velocities, although the expected MTF should reduce the power by 3 orders of magnitude at 50 mHz (Fleck et al. 2008). The reason for this becomes clear upon inspection of the contribution functions, which shows rapid and
Fig. 4. Scatter plots of simulated Mg “core” Dopplergram signals versus actual velocities of the Oslo-Stagger model at various heights. The upper set of panels shows results for the filter settings of the four-point measurement used in this work, with the “core” measurements taken at ±68 mÅ from line center. The lower panels show corresponding results for the “old” two-point settings at ±113 mÅ from the line core. The latter setting clearly yields inferior velocity measurements, as it mixes photospheric and chromospheric signals.
considerable height variations (Fig. 3). It appears that the observed high frequency Doppler signal is not due to propagating high frequency acoustic waves, but due to fast and significant height variations of the velocity response function in a dynamic atmosphere with strong vertical velocity gradients.

Scatter plots of “observed” “core” Doppler shifts versus actual velocities show a good correlation at chromospheric heights (upper panel of Fig. 4), suggesting that the dominant velocity component can be measured reasonably well with simple Dopplergrams and that the Mg “core” signal measured at ±68 mÅ from line center is indeed a useful measure of the velocities in the lower chromosphere. A previous set up of NFI for two-point measurements in Mg b2 at ±113 mÅ from the line core (i.e. close to the knee between the Doppler core and the damping wings) shows a bifurcated distribution with much reduced correlation (see lower panels in Fig. 4). At that filter position, the measured intensities are a complex mixture of photospheric and chromospheric signal. Work is in progress to better calibrate the NFI Dopplergrams and to determine the optimum filter position.

We conclude that previous claims of the detection of high frequency waves ($P \leq 70$ s) need to be re-evaluated. The observed power density at high frequencies seems to be caused by line formation effects in a dynamic atmosphere and cannot be interpreted as evidence of propagating high frequency acoustic waves. Therefore, estimates of the energy flux of high frequency acoustic waves should be treated with caution, in particular those that apply atmospheric MTF corrections. On the other hand, narrowband filtergrams provide a reasonable measure of the strong and dominant 3- and 5-min oscillations if the filter position is chosen well (i.e. far from the knee between the Doppler core and the Lorentzian damping wings).

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