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High frequency waves in the solar atmosphere?

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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 ($P \leq 70$ 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 CO^{5}BOLD). 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

1. High frequency waves in the solar atmosphere?

In the present study we compare Mg b_2 and Na D_1 Dopplergram time series with results from two 3-D simulations. The observations were obtained with the narrowband filter (NFI) on Hinode. The Mg b_2 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 D_1 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 CO^{5}BOLD code (Wedemeyer et al. 2004; Straus et al. 2008). They give access to both the actual

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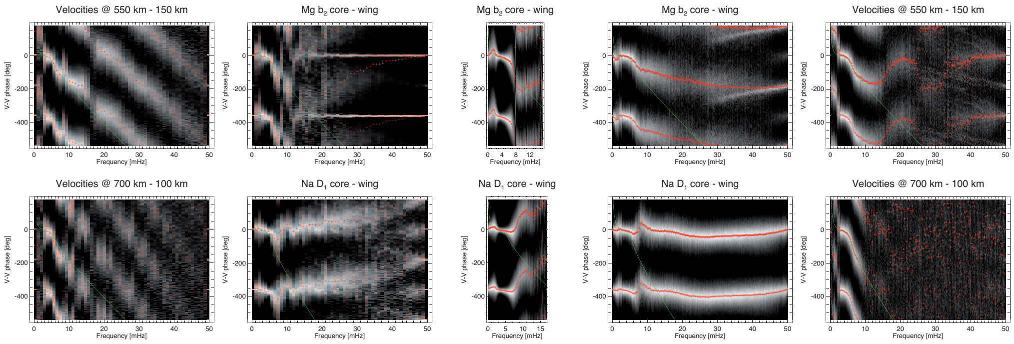

Fig. 1. Comparison between observations and simulations of the Mg b_2 (upper row) and Na D_1 (lower row) lines: The two smaller panels at the center display the spatially averaged phase difference scatter plots obtained from observations with Hinode/NFI. The deviation from the expected behavior of linear 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.

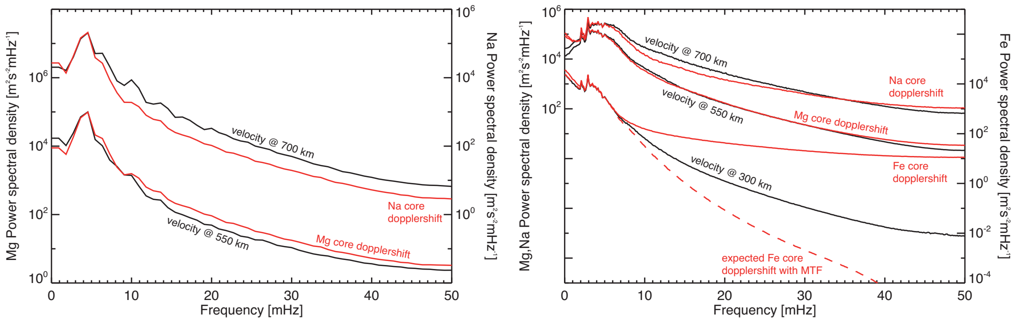

Fig. 2. Power spectra of the simulated Hinode/NFI signals and of the actual velocities at corresponding heights in the simulations. The Oslo-Stagger code results are shown in the left panel, the CO^{5}BOLD model results are on the right. The expected MTF for Fe 6301 is taken from Fleck et al. (2008). 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.

velocities at given heights in the atmosphere as well as "observed" Doppler shifts in simulated line profiles. The Oslo-Stagger simulation 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

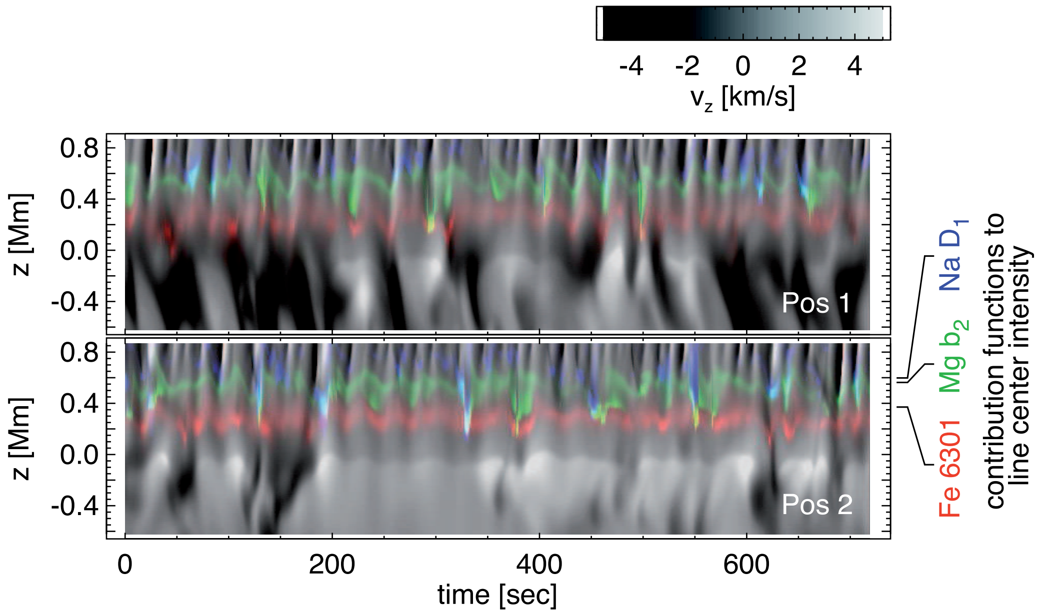

Fig. 3. $z-t$ slices of the CO^5BOLD simulation with contribution functions of Fe 6301 (red), Mg b_2 (green), and Na D_1 (blue). Note the rapid and significant height variations of the contribution functions.

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^5BOLD 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^5BOLD cube indeed suggests wave reflection near the upper boundary and at the steepening shock fronts in the chromospheric layers. This aspect of the CO^5BOLD simulations requires further investigations.

Turning to the phase differences between the simulated Doppler shifts (inner panels of Fig. 1), they are — in both simulations — markedly different from those of the corresponding actual atmospheric velocities. Up to 10 mHz they are similar to the observed spectra. This suggests that the unexpected shape of the observed phase difference spectra at high frequencies is caused by line formation effects of the Dopplergram signal rather than by unexpected propagation properties of high frequency sound waves. One is tempted to attribute this to the suppression of high-frequency waves by the atmospheric MTF due to the extended width of the velocity response functions (cf. Keil & Marmolino 1986).

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 falloff 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 magni-

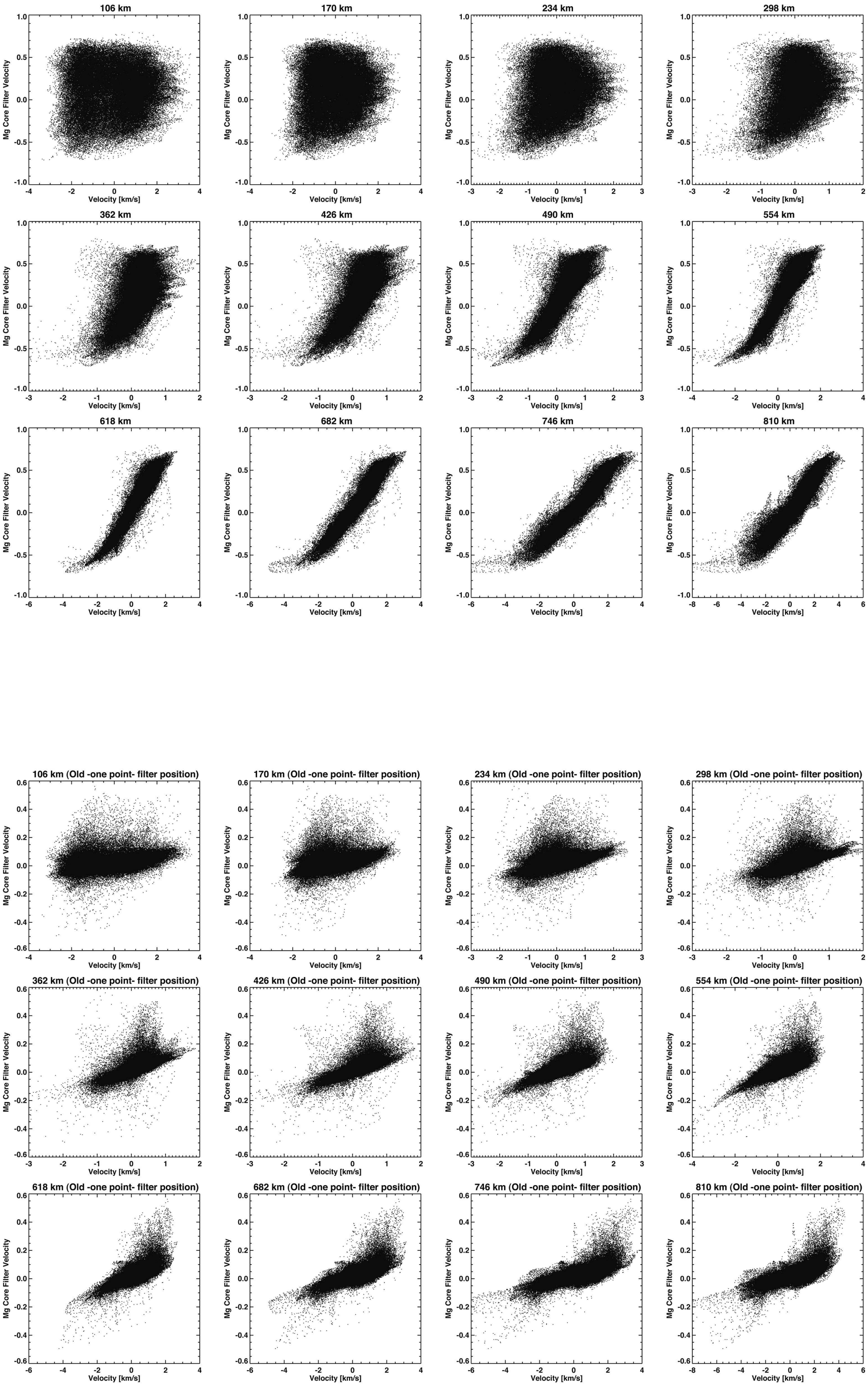

Fig. 4. Scatter plots of simulated Mg "core" Dopplergram signals versus actual velocities of the Oslo-Stagger model at various heights. The upper set of panels shows results for the filter settings of the four-point measurement used in this work, with the "core" measurements taken at at ±68 mÅ from line 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.

tude at 50 mHz (Fleck et al. 2008). The reason for this becomes clear upon inspection of the contribution functions, which shows rapid and 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 b_2 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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