OSCILLATION SPECTRA OF LINE DEPTH, INTENSITY AND VELOCITY FROM RADIATIVE TRANSFER CALCULATIONS

R. Wachter¹, M. Haberreiter¹, and A. G. Kosovichev²

¹Physikalisch Meteorologisches Observatorium Davos, Dorfstrasse 33, 7260 Davos Dorf, Switzerland
²W. W. Hansen Experimental Physics Laboratory, Stanford University, Stanford, CA 94305-4085, USA

ABSTRACT

Theoretical spectra for solar oscillations, as they are observed by the MDI instrument, have been calculated by modifying a model of the solar interior according to the oscillations of temperature, pressure, density, and velocity, and calculating the detailed radiative transfer for the Ni I absorption line at 6768 Å with the radiative transfer code COSI. Using the filter functions from the MDI instrument, MDI velocity, intensity, and line depth spectra are modelled. We investigate the intrinsic mode peak asymmetry of velocity, continuum intensity, and line depth spectra. We compare this to the recent results of Georgobiani et al. (2003) who found positive asymmetry for resonance peaks of high-ℓ modes in intensity. Furthermore, we look at the mutual phases of the different quantities, and we show that the decay in power with increasing frequency is most pronounced in velocity and least pronounced in line depth spectra. This is a possible explanation for the high pseudo-mode visibility in line depth spectra.

Key words: Sun: oscillations, radiative transfer.

1. MDI OBSERVATIONS

The MDI (see Scherrer et al. (1995) for a detailed description) consists of two tunable Michelson interferometers and a Lyot filter, which realize successively five narrow-banded filters $F_0 \ldots F_4$ with a separation of 75 mÅ. These filters cover the observed Doppler shift of the Ni I $\lambda$ 6768 absorption line. The filter profiles and the absorption line are displayed in Figure 1.

From the function $\alpha$

\[ \alpha_+ = \frac{(F_1 - F_3) + (F_2 - F_4)}{(F_1 - F_3)}, \]
\[ \alpha_- = \frac{(F_1 - F_3) + (F_2 - F_4)}{(F_1 - F_3)} \]

(\(\alpha = \alpha_+\) for a positive numerator, \(\alpha = \alpha_-\) for a negative numerator), the line-of-sight velocity is obtained by a nearly linear calibration function. This $MDI$-$Doppler$-velocity is defined to be positive for inward directed flows. $MDI$-$line$-$depth$ is obtained by:

\[ I_{ld} = \sqrt{2} \left( (F_1 - F_3)^2 + (F_2 - F_4)^2 \right). \]

The $MDI$-$continuum$-$intensity$ is given by:

\[ I_{cont} = 2F_0 + (F_1 + F_2 + F_3 + F_4)/4 + I_{ld}/2. \]

2. RADIATIVE TRANSFER CALCULATIONS

An oscillation spectrum has been calculated as a solution of the nonadiabatic boundary value problem (Unno et al., 1989) which accounts for the radiative energy flux in the diffusion approximation. The spectrum was brought to the time domain by an inverse Fourier transform. We calculated a spectrum of angular degree \(l = 22\) excited by a dipole source located 100 km below the base of the photosphere.
The line profile of Ni I λ 6768 was calculated for each time point with the radiative transfer code COSI (see Haberreiter & Schmutz (2003) for a description). Generally, COSI solves the radiative transport in spherical symmetry and non-local thermodynamic equilibrium (non-LTE); the present calculations, however, were carried out in LTE due to the considerable reduction of computing time. We solved the radiative transport at disk center for each time point by applying the oscillations of velocity, density and temperature on the equilibrium model atmosphere of Provost, Berthoumieu, & Morel (2000). After integration with the filter functions, equations (1), (2), and (3) provide a time series for MDI-Doppler-velocity, MDI-line-depth, and MDI-continuum-intensity, respectively.

Furthermore, we derive quantities called real-continuum-intensity from the continuum in the neighborhood of the absorption line, and real-line-depth, defined as continuum minus minimum intensity.

3. VELOCITY SPECTRUM

![Figure 2. Input velocity at the observation height (black line) and MDI-Doppler-velocity from radiative transfer calculations (red line). The peaks represent the modes \(l = 22, n = 8, 9, 10\).](image)

For validation of the method, we compare the velocity obtained from radiative transfer calculations with the input velocity. We find the best correspondence at an observation height of 180 km above the solar radius defined by \(\tau_{\text{Rosseland}} = 2/3\). Figure 3 shows that the agreement of the power spectrum is very good in the p-mode range. For very low frequencies, the spectra from the radiative transfer calculations have a high level of numerical noise.

4. ASYMMETRY OF MODE PEAKS

![Figure 3. The peaks represent the modes \(l = 22, n = 8, 9, 10\) (from left to right). Luminosity power spectrum at constant geometrical observation height (black line). Additionally, the MDI-continuum-intensity spectrum (red line), and the real-continuum-intensity spectrum (green line) is displayed. Both correspond to observation at constant optical depth.](image)

Georgobiani, Stein & Nordlund (2003) performed 3D-simulations of the upper convection zone and found positive peak asymmetry for high-\(l\) modes observed in continuum intensity. This is an effect of the oscillating observation height due to opacity perturbations. If continuum intensity is observed at constant geometrical depth, the asymmetry of the resonance peaks remains negative. Because spectra obtained by radiative transfer calculations always refer to an observation height corresponding to constant optical depth \(\tau \approx 1\), we can investigate this effect on medium-\(l\) p-modes by comparing calculated spectra at constant geometrical depth with spectra at constant optical depth.

Figure 3 compares the luminosity spectra at constant geometrical depth with the real-continuum-intensity spectra and the MDI-continuum-intensity spectra, which both refer to constant optical depth. We could not find substantially different asymmetry in spectra observed at constant geometrical depth and constant optical depth. The differing results might indicate a difference between medium-\(l\) modes and high-\(l\) modes. However, our approach is very different from the approach of Georgobiani, Stein & Nordlund (2003), so that a direct comparison is difficult.

![Figure 4. Compare the intrinsic mode peak asymmetry of MDI-Doppler-velocity, MDI-continuum-intensity, and real-line-depth. In the first two orders of magnitude in power, which are important for making fits, the profiles are roughly the same.](image)

Fig. 5 shows that observed resonance peaks have an asymmetry of opposite sense in continuum intensity and velocity. The observed asymmetry in velocity can be explained by effects of the localized source (see Wachtler & Kosovichev, these proceedings). The observed asymmetry in intensity, however, is different from the asymmetry displayed in Fig 4, and can therefore only be explained by the contribution of a correlated noise component. The observed asymmetry in line depth spectra is similar to the calculated asymmetry displayed in Fig. 4. This indicates a small contribution of correlated noise for line depth spectra.
Figure 5. Power and cross spectra of intensity (left) and velocity (right) for the $l = 22$, $n = 8$ mode from full disk MDI data. The power spectra are normalized to their maxima. The observational resonance frequency is indicated by the vertical dashed line.

Figure 4. Intrinsic line asymmetry of mode peaks in MDI-continuum-intensity (black line), MDI-Doppler-velocity (green line), and real-line-depth (red line). The peaks represent the modes $l = 22$, $n = 8, 9, 10$ (from left to right). For a unknown reason, the power spectra for MDI-line-depth have a very high level of numerical noise. Therefore, calculated line depth spectra are represented by so-called real-line-depth spectra.

5. HIGH PSEUDO-MODE VISIBILITY IN LINE DEPTH SPECTRA

The left panel of Figure 6 shows that pseudo-modes in line depth are visible up to rather high frequencies. Pseudo-modes are less visible in intensity spectra, and least pronounced in velocity spectra. Nigam (1999) has shown that correlated noise is able to both amplify and shift the pseudo-mode power peaks. If cooling events preceding the excitation process are responsible for the mode correlated noise, substantial correlated noise is not expected in differential signals like line depth and Doppler velocity. Furthermore, pseudo-mode power peaks occur at the same frequencies for velocity and line depth spectra, whereas they are slightly shifted for velocity spectra. This is an indication that the contribution of correlated noise is similarly low in velocity and line depth spectra, but higher in spectra of continuum intensity.

The right panel of Figure 6 shows that for a source of

6. CONCLUSION

Radiative transfer calculations provide accurate models for solar oscillation spectra. Our calculations do not account for the random phases of the modes, and neglect all effects from the horizontal variation of the atmosphere. These calculations should therefore be regarded as a first approach towards a more accurate description.

With our approach, we can confirm the intrinsic negative peak asymmetry for all spectra (Doppler velocity, continuum intensity, and line depth). This indicates that correlated noise is indeed responsible for the observed peak asymmetry reversal in continuum intensity. Furthermore, our calculations suggest that the high pseudo-mode visibility in line depth spectra might be a subtle effect of line formation in the solar atmosphere by radiative transport.

ACKNOWLEDGMENTS

SOHO is a mission of international collaboration between ESA and NASA. This research is supported by Swiss National Science Foundation grant number 20-65134.01 and 200020-101848/1, and by the SOI/SOHO NASA contract NAG5-10483 to Stanford University.
Figure 6. Left panel: Pseudo-modes of a \( l = 22 \) spectrum from 61 days of full-disk MDI data, observed in line depth (red line), intensity (black line), and velocity (green line). Right panel: Power spectra for real-line-depth (red line), MDI-continuum-intensity (black line), and MDI-Doppler-velocity (green line) for a source of frequency-independent strength. The spectra are normalized to their maxima.

REFERENCES


