COMPARISON OF LOCAL FREQUENCY SHIFTS BETWEEN MDI VELOCITY AND INTENSITY DATA

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ABSTRACT

We analyze the frequencies of high–degree *p* modes using velocity and intensity data from MDI. The study is carried out with the local helioseismic technique of ring diagrams. The resultant power spectra at several different positions on the solar disk are fitted with symmetric and asymmetric profiles to find the center–to–limb variation (CLV). Using symmetric profiles in the anaylsis produces significant differences in frequency between velocity and intensity with the differences increasing from disk center to the limb. The use of asymmetric peak profiles reduces these differences and in the 3 mHz band the frequencies agree reasonably well with each other.

Key words: Sun: Oscillations, Sun: Interior.

1. INTRODUCTION

Comparing power spectra obtained in Doppler velocity, total spectral intensity, and modulation from Global Oscillation Network Group (GONG), Harvey *et al.* [1] found different central frequencies. Toutain *et al.* [2] also report systematic differences between mode frequencies measured in intensity and in velocity power spectra. It is further shown in [3] that the use of Lorentzian profiles as a model of low-degree *p*–mode lines leads to systematic differences in the determination of mode frequencies between intensity and velocity observations. Comparing GONG+ prototype spectra of velocity and intensity, it was shown in [4] that the frequency dependence of the frequency shift is negligible below the acoustic cutoff frequency around 5.3 mHz and substantial above the cutoff. This supported the conclusions given in [1]. This work was extended to many other locations in [5] and the analysis suggested that the frequency shifts between velocity and intensity is a function of location on the disk and is higher near the disk center than near the limb. Since the apparent frequency shift between an oscillation observed in velocity and intensity can not be a property of the mode, it must arise from the excitation mechanism. However, it is known that the peaks are not symmetric [6], and that the sense of the asymmetry is reversed between velocity and intensity. Peaks in the velocity power spectra have negative asymmetry (more power towrads lower frequencies) while the intensity spectrum shows a positive asymmetry. The effects of including the asymmetry of the peak profiles on the fitted solar oscillation frequencies for low and intermediate degrees were studied in [7]. They found that the use of asymmetric peak profiles improves the fit to observed spectra and the frequencies are increased as compared to those obtained when symmetric profiles are used. The analysis was extended to high–degree modes and other observables in [8]. Analyzing the power spectra at the disk center through the ring diagram techniques, the study showed that the frequencies obtained by fitting asymmetric peak profiles to different spectra agree reasonably well with each other, while the use of symmetric profiles gives significant differences between frequency computed using intensity and velocity or line-depth spectra. Here, we extend the investigations to many different positions on the solar disk to find the variation from the disk center to limb. To compare the results, we fit the spectra using both symmetric and asymmetric peak profiles.

2. DATA

The data consist of velocity and intensity images obtained from the Michelson Doppler Imager (MDI) instrument onboard SOHO for the period May 19 – 28, 1997 when solar activity was near minimum. We have used spectra from the disk center and at different longitudes from 15° to 45° at an interval of 7.5°. Each region of 15° × 15° was extracted, remapped onto a grid of 128 × 128 pixels, and tracked for 1664 minutes. A 3D FFT [9] was used to obtain the power as a function of (ν, k_x, k_y). In order to enhance the signal, the power spectra of each 1664 minutes interval are averaged together before the fitting procedure is applied.

To bring out the peaks in the power spectra, we take the azimuthal average around the rings. The resultant and rescaled spectra for ℓ of 675 at four different locations

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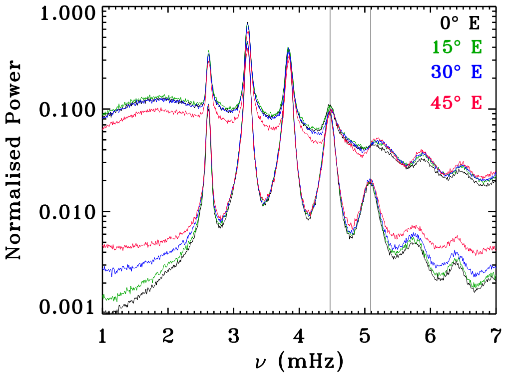

Figure 1. Azimuthally–averaged velocity (lower curves) and intensity (upper curves) power spectra for ℓ of 675 at four different positions on the solar disk. The locations are color coded and are shown in the right top corner.

are shown in Figure 1. It is quiet apparent that the spectra are asymmetric. At low frequency, the asymmetry agrees with the known results; velocity has negative asymmetry *i.e.* more power on lower frequency side. The peaks in the intensity spectrum show positive asymmetry. There is also an indication that the asymmetry of velocity power spectra is reversed at higher frequencies. Thus, it is natural to expect that the determination of the frequencies would be improved if the asymmetry is included in the fitted peak profile.

Figure 1 also shows a shift in frequency between the two power spectra above the cutoff frequency which is consistent with those in [4, 10]. There is a hint that the central frequencies in velocity and intensity are different even below the cutoff as marked by the solid lines. Although the spectra are not corrected for projection, the velocity power is higher near the disk center and decreases towards the limb in agreement with the predominately radial nature of the oscillatory velocity field. Note that the normalization of the spectra to have equal maxima results in an apparent reversal of the CLV of the relative velocity power at low and high frequencies.

2.1. Fitting Methods

To extract mode parameters, the power spectrum is fitted with two different profiles. The symmetric profile model [11] considers the peaks in the power spectra to be Lorentzian and fits for n–values from 0 to 6 and k values corresponding to ℓ of about 180–1200:

$$P(k_x, k_y, \omega) = \frac{A}{(\omega - \omega_0 + k_x U_x + k_y U_y)^2 + \Gamma^2} + \frac{b}{k^3} \tag{1}$$

where P is the oscillation power for a wave with a temporal frequency ω and the total wavenumber $k = k_x^2 + k_y^2$.

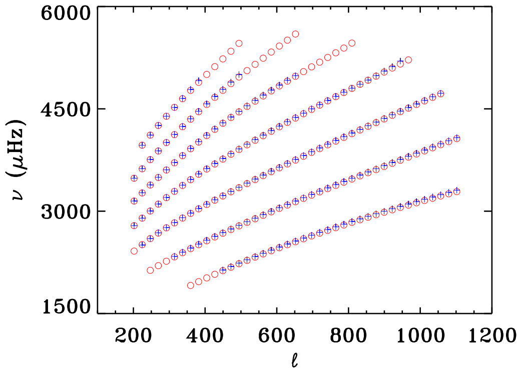

Figure 2. The $\ell - \nu$ diagram constructed from the fitted parameters for velocity (circles) and intensity (pluses) spectra at disk centre. The parameters are obtained from the symmetric model.

Six fitting parameters are used to specify the profile: two Doppler shifts ($k_x U_x$ and $k_y U_y$) for waves propagating in the zonal and meridional directions, the background power b, the mode's central frequency ω_0, the mode width Γ, and the amplitude A.

To apply the model with asymmetric peak profiles, we take the azimuthal average of each spectra to obtain 2D spectra in $k - \omega$. These are fitted with the model of [12]:

$$P(k, \omega) = \frac{e^{A_0}[(1 + Sx)^2 + S^2]}{1 + x^2} + e^{b_1}[1 + b_2(1 - \frac{\omega}{\omega_c})], \tag{2}$$

where $x = (\omega - \omega_c)/\Gamma$, $\exp(A_0)$ is the amplitude of the peak and Γ is the half-width. The six parameters, A_0, ω_0, Γ, S, b_1, and b_2 are determined by fitting the spectra using a maximum likelihood approach. The parameters S controls the asymmetry in the peaks, and the form of asymmetry is the same as that used in [13]. Other parameters have the same meaning as in the case of the symmetric model.

3. RESULTS

Figure 2 shows a characteristic $\ell - \nu$ diagram obtained from the fits to both velocity and intensity power spectra at disk center. It is clear that fewer modes are fitted in the intensity spectra compared to velocity spectra. This is also true when the asymmetric model is used. Comparing the modes obtained from the symmetric and asymmetric formula, we find that more modes are fitted when the symmetric profile is used but in the case of the asymmetric model, the modes are densely spaced in ℓ.

Figure 3 shows the asymmetry parameter, S, estimated from spectra at disk center and 45° longitude. It is clear that this parameter is negative for most modes in velocity,

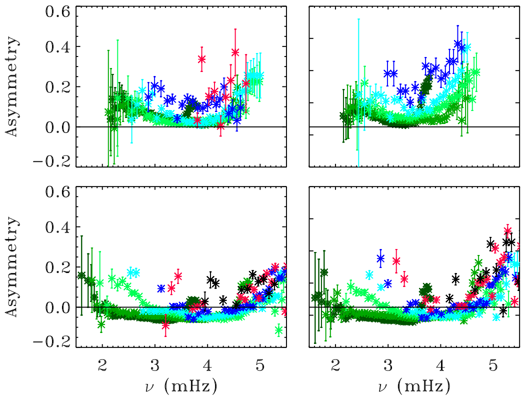

Figure 3. Asymmetry parameter, S, obtained from fits to different 2D spectra for intensity (top panel) and velocity (bottom panel). The left and right panel in each figure refers to the disk center and to longitude of 45° respectively. The color indicates different radial orders.

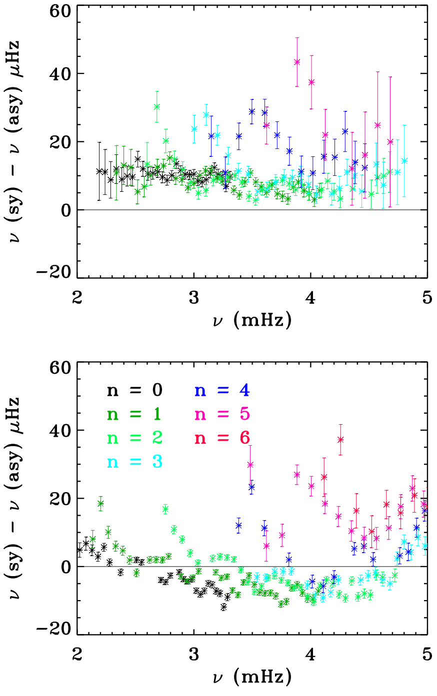

Figure 4. Differences in frequency at disk center obtained using symmetric and asymmetric peak profiles. The top panel shows differences in intensity while the bottom panel shows the differences in velocity. The color represents different radial orders and are marked in the bottom panel.

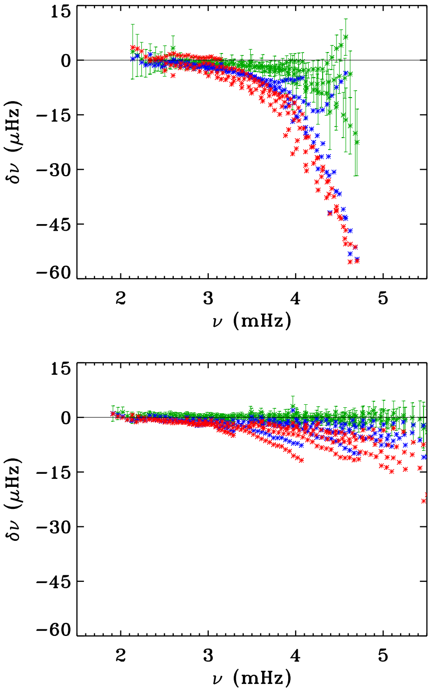

Figure 5. Frequency differences between intensity (upper panel) and velocity (bottom panel) modes at three different longitudes (green: 15°, blue: 30°, and red: 45°) with respect to disk center. The modes are fitted using symmetric model profile. The error bars only for 15° longitude are shown for clarity.

while it is positive for most modes in intensity spectra. There is also some variation with frequency. At high and low frequencies, the asymmetry associated with velocity appears to be positive confirming the results deduced from Figure 1. It is also possible that the form of asymmetry used in the model does not adequately represent the real profiles. More work is needed to understand this behaviour.

Figure 4 shows the differences in frequency obtained from symmetric and asymmetric fits to intensity and velocity spectra at disk center. There is a considerable difference between the two fits reaching about 45 μHz for modes with $n = 5$ and 6. Since the shift essentially gives the error introduced by assuming the peak profiles to be symmetric, we expect opposite shifts for intensity and velocity as in [8]. Our result for intensity agrees with this interpretation, and we find that the frequency shift is always positive for intensity spectra at all locations. However, the shifts for velocity shows both positive and negative values at all locations. Specifically, low frequency *f*–modes and most of the $n \geq 4$ modes shows positive values. We speculate that this may be related to the asymmetry parameter.

Figure 5 shows the frequency differences between modes

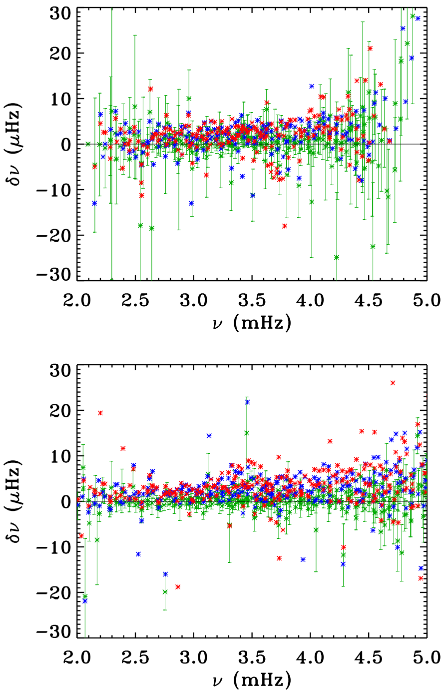

Figure 6. Same as Figure 5 but for asymmetric profiles.

at different locations with respect to disk center when the fits are carried out using symmetric profiles. The difference increases with distance from the disk center and suggests that the shift is a function of the location on the solar disk. Large variations are seen for the high–order radial modes, approaching ≈ 50 μHz for intensity spectra at a longitude of 45°. But it is to be noted that the projection effect is not corrected, which could contribute to the frequency differences. We also note that the frequency differences among velocity modes at different locations are smaller compared to the intensity modes. The differences are significantly reduced when asymmetric profiles are used for fitting (Figure 6) and it does not depend on the location on the disk. Instead, the difference, which shows both positive and negative values, appears to be a function of the frequency alone.

Figure 7 shows the frequency differences between modes obtained from the intensity and velocity using symmetric profiles at four different positions on the disk. Ideally, one expects the frequency to be independent of the observables, however, there appears to be significant differences. The shifts are all positive implying a higher frequency for the intensity. As before, the differences are found to be a function of location on the disk, increasing from the disk center towards the limb. Since the variation in frequency obtained from intensity spectra at different disk locations shows larger changes compared to velocity spectra, we speculate that the frequency shift between velocity and intensity mostly arise from the intensity when Lorentzian profiles are used to fit the spectra.

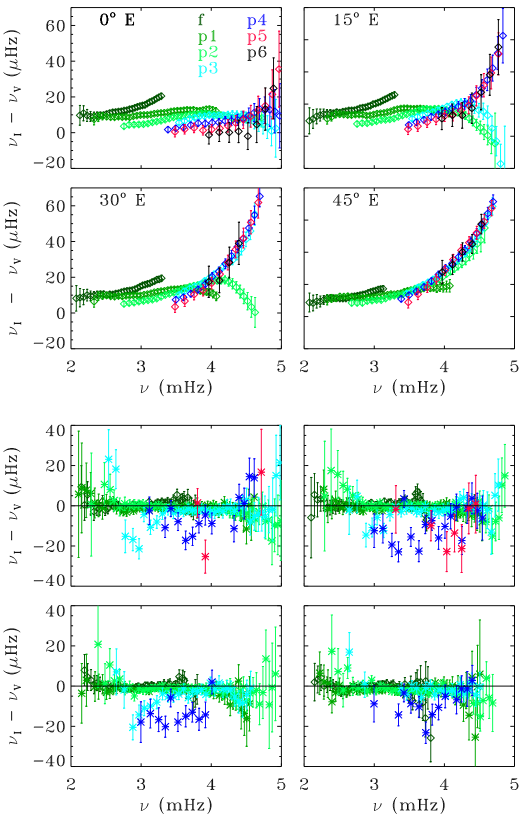

Figure 7. Frequency differences between velocity and intensity modes fitted using symmetric (top four panels) and asymmetric (bottom four panels) profiles at four different longitudes on the solar disk. The locations are marked in the top panel and has the same meaning for the bottom panel. The color indicates different radial orders and is marked in the first panel.

The use of asymmetric profiles reduces the frequency differences between intensity and velocity (bottom four panels in Figure 7). In the 3 mHz band, the shifts are within the error estimates, and is consistent with no change. However, there are systematic differences at the low and high ends of the frequency range. It is possible that the assumed form of asymmetry does not adequately represent the real profiles at these frequency ranges. A similar result for disk center was noted in [8] and it was argued that the assumed profiles does not adequately describe the velocity spectra where the signal to noise ratio is rather high.

4. CONCLUSIONS

The power spectra obtained from velocity and intensity images show a distinct asymmetry in peak profiles. The azimuthally averaged 2D power spectra show an apparent frequency shift of the central frequency observed in velocity and intensity below the cutoff frequency of 5.3 mHz. This was confirmed by fitting Lorentzian profiles to the 3D power spectra. But, since the spectra are known to be asymmetric, we fit the 2D spectra with an asymmetric model profile. The known asymmetry is recovered; we find that intensity has a positive asymmetry for all modes while most of the modes in velocity has the negative asymmetry. A few modes, especially at the low and high ends of the frequency range, show positive asymmetry which confirms the trend seen in the actual 2D power spectra. The frequencies obtained from velocity and intensity spectra by fitting asymmetric peak profiles agree reasonably well in the 3 mHz band, but a small difference is noticed at the the low and high ends of the frequency range. This probably arises from the inaccurate description of the asymmetry profile.

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