Multi-spectral study of acoustic mode parameters and sub-surface flows

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Abstract. Simultaneous measurements at different wavelengths offer the prospect of studying the sensitivity of helioseismic inferences to the choice of observing height both in quiet-Sun and magnetically active regions. In this context, we use observations from space-borne measurements from the Solar Dynamics Observatory and ground-based Global Oscillation Network Group to analyze high-degree acoustic mode parameters and sub-surface flows obtained with different observables. We also quantify differences and interpret results in the framework of the formation height in solar atmosphere.

1. Introduction

The helioseismic study at multi wavelength is important in order to obtain precise information about the excitation and damping of the oscillations. While this information can be used as a path to understand the transfer of energy through the solar interior and atmosphere, it is also useful as a tool to improve the fitting of the oscillation spectrum [1]. Here we study the sensitivity of helioseismic inferences to the choice of observing height and observables, and to clarify the effects of observing-line-related systematic errors. Since the physics of the solar oscillations cannot depend on the observed physical variable, here we test this assumption for high-degree modes obtained with measurements at different heights in the solar atmosphere. We also investigate whether there is any effect of observing height on the sub-surface flows.

2. Analysis and Results

We use multi-spectral data from two sources; the space-borne *Solar Dynamics Observatory (SDO)* and the ground-based Global Oscillation Network Group (GONG). The Helioseismic and Magnetic Imager (HMI) on board *SDO* provides simultaneous full-disk Doppler (HMI V) and continuum intensity (HMI Ic) observations with a resolution of 0.5 arcsec/pixel and a uniform cadence of 45 sec in spectral line Fe I 6173 Å. The Atmospheric Imaging Assembly (AIA) also onboard *SDO* provides continuum intensity measurements from 1700 Å and 1600 Å passbands with 0.6 arcsec/pixel resolution and the uniform cadence of 24 sec. The full-disk Doppler measurements from GONG (GONG V) have a resolution of 2.5 arcsec/pixel and a uniform cadence of 60 seconds in spectral line Ni I 6768 Å. These observables are formed at different

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Journal of Physics: Conference Series **440** (2013) 012012 doi:10.1088/1742-6596/440/1/012012

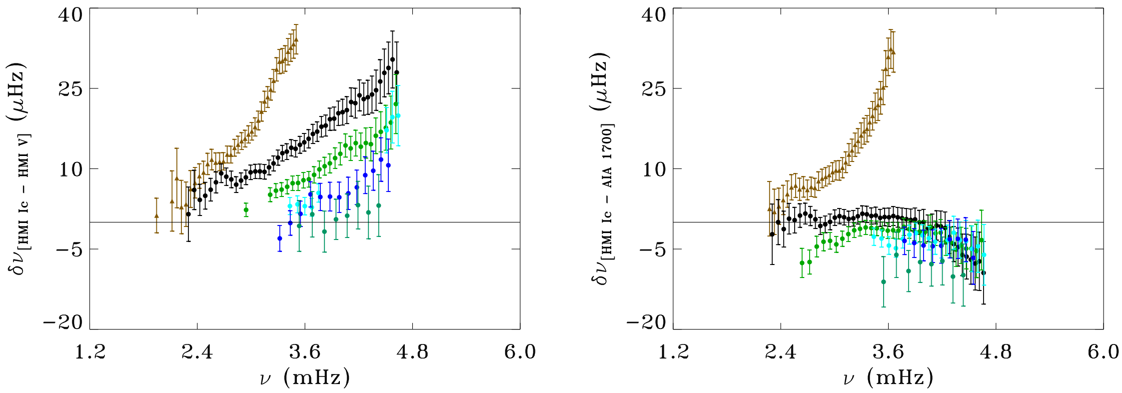

Figure 1. The frequency dependence of the difference between frequencies obtained using the symmetric profile model: (left) for HMI Ic and HMI V, and (right) HMI Ic and AIA 1700. Different colors are for different n ridges in the ℓ-ν diagram.

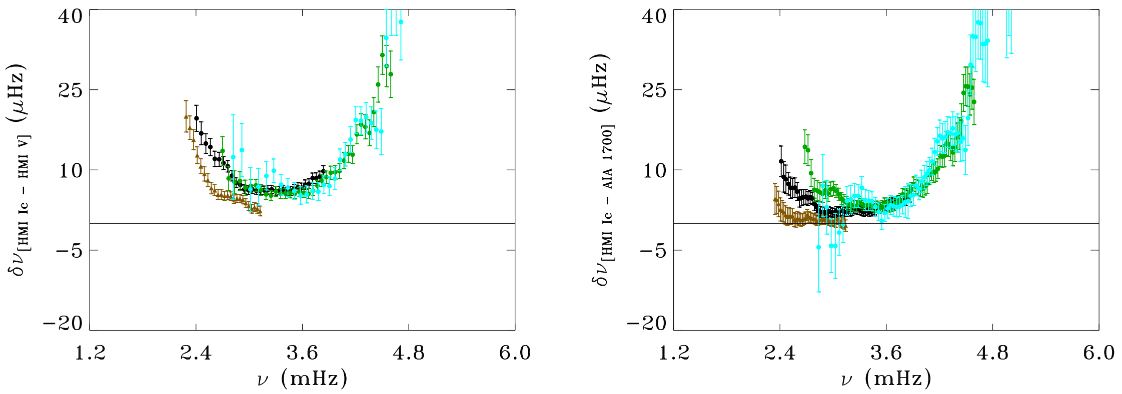

Figure 2. Similar to Figure 1 but for the asymmetric profile model.

heights in the solar atmosphere. While the HMI Ic, HMI V and GONG V measurements are taken at around 20 km, 100 km, 200 km respectively, the AIA 1700 and 1600 bands are centered at 360 km and 480 km respectively.

In order to assess the observing height related effects on high-degree mode parameters and sub-surface flows, we use simultaneous observations during a quiet period (June 24-25, 2010) and apply the technique of ring diagrams [2]. The regions of $15^{\circ} \times 15^{\circ}$ for each observable are analyzed where these are remapped and tracked for 1664 minutes. A 3-dimensional FFT is subsequently applied to obtain power spectra which are fitted to symmetric [3] and asymmetric profile models [4] to estimate mode parameters. Finally, the fitted velocities are inverted using RLS method to infer the depth dependence of horizontal velocity vectors.

In Figure 1, we show the frequency difference, $\delta\nu$, between modes obtained with the symmetric profile model. It is observed that frequencies from different observables do not agree with each other and also the difference increases with increasing frequency. This difference could be as large as 40 μHz or even more around 5 mHz. We notice the $\delta\nu$ between HMI V and HMI Ic is much more apparent as compared to two continuum measurements. We also find that the frequencies for two Doppler mesurements, e.g. HMI V and and GONG V, are comparable to each other. Frequency differences for modes fitted with the asymmetric profile model are plotted in Figure 2. For comparison, we have shown values for same type of observables as in Figure 1. In this case, $\delta\nu$ is significantly reduced, particularly for the HMI V and HMI Ic in the 3 mHz

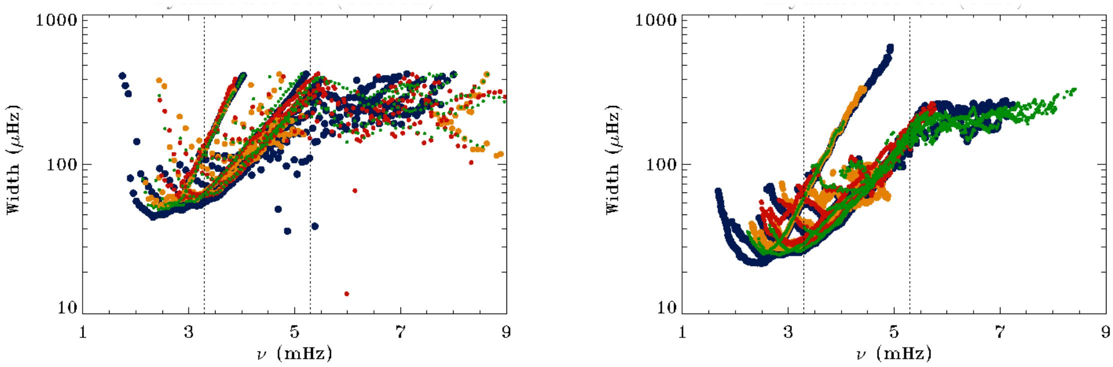

Figure 3. Half width of the fitted modes for SDO observables: HMI Ic (yellow), HMI V (blue), AIA 1700 (green) and AIA 1600 (red). The left panel shows values obtained with the symmetric profile model while the right panel is for the asymmetric profile model.

band. However, $\delta\nu$ tends to increase sharply on lower and higher ends of the spectra. It seems that the model used to define asymmetry in peaks is most suitable for the 3 mHz band and does not properly describe the asymmetry in a broader range of frequencies. We plan to revise the model to include asymmetry at frequencies below and above 3 mHz band.

In an earlier study, using data from GONG and Magneto-Optical filters at Two Heights (MOTH), the frequency differences were found relatively small as compared to the present study [5]. Note that the previous study considers only one type of observable, i.e. Doppler measurements, at different heights while present analysis is based on both Doppler and continuum measurements. In a different study, Tripathy et al. used Doppler and continuum measurements from the Michelson Doppler Imager (MDI) on board *Solar and Heliospheric Observatory (SOHO)* and found $\delta\nu$ for the asymmetric profile model are comparable to our analysis [6]. However, frequency differences in symmetric profile model are not as large as we obtain in the present study. We anticipate that different symmetric profile models used in both studies led to inconsistent results. A more detailed study is underway to understand the difference in frequencies in two symmetric profile models and will be published elsewhere.

In Figure 3, we further show the width of the fitted modes obtained using both fitting methods. It is noted that the width increases with frequency for all observables and appears to reach a constant value of about 200 μHz at high frequencies ($\nu > 6$ mHz). It is consistent with previous studies where similar results were found for a single observable [7,8]. We see a large scatter for modes fitted with the symmetric profile while values obtained with the asymmetric profile model for all observables are comparable. Since life time of the acoustic modes cannot depend on the type of the observable, our results clearly indicate that the symmetric profile does not adequately represent the true nature of peaks in power spectra, hence it is important to include proper asymmetry in mode fitting while dealing with different types of observables.

We also investigate the sensitivity of inferred subsurface flows to the choice of spectral line. Figure 4 exhibits the variation of zonal (V_x) and meridional (V_y) components of the horizontal flow with depth at the disk center for all three observables shown in Figures 1 and 2. While profiles for V_y in all cases show similar variations, there is a noticeable difference in profiles for V_x. Since different modes have different sensitivity to the averaging kernels and affect velocity profiles, we interpret this difference as resulted from the mode sets used in the inversion. In addition, the inaccurate dettermination of the asymmetry in different observables would also affect the inverted velocities. In order to check these assumptions, we analyze simultaneous Doppler measurements from GONG and HMI and the inversion is carried out only for those modes which are common in both data sets. Figures 5 and 6 show depth dependence of V_x and

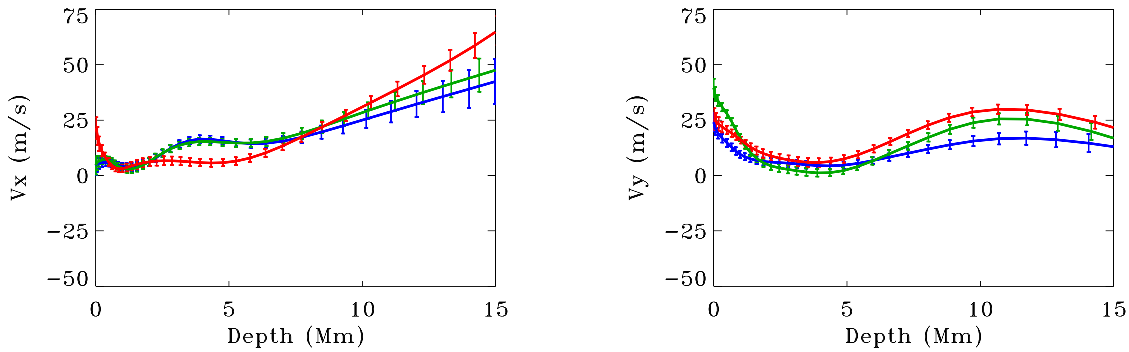

Figure 4. Variation of zonal (V_x) and meridional (V_y) components of the horizontal flow obtained for HMI V (red), HMI Ic (green) and AIA 1700 (blue) at the disk center.

V_y for several regions along the central meridian and the equator, respectively. It is evident that the inference of sub-surface flow is not much affected by the line formation height in the solar atmosphere when common modes are inverted for the same type of observable. We also notice that the agreement starts decreasing around 45° away from the disk center which could be attributed to the foreshortening as both data sets have different spatial resolution. This is consistent with earlier findings where similar flows were found for Doppler measurements in Ni and K spectral lines [9].

3. Summary

Our analysis shows that the estimated frequency for a particular mode is different for different observables. The use of symmetric profile model leads to a larger discrepancy while the asymmetric profile model reduces the difference significantly near 3 mHz. This implies that the model used to describe asymmetry in peaks is most suitable for the 3 mHz band, but needs to be revisited for a broader range of frequencies. It is clearly evident that the proper asymmetry should be included while fitting modes in different types of observables. We plan to perform a

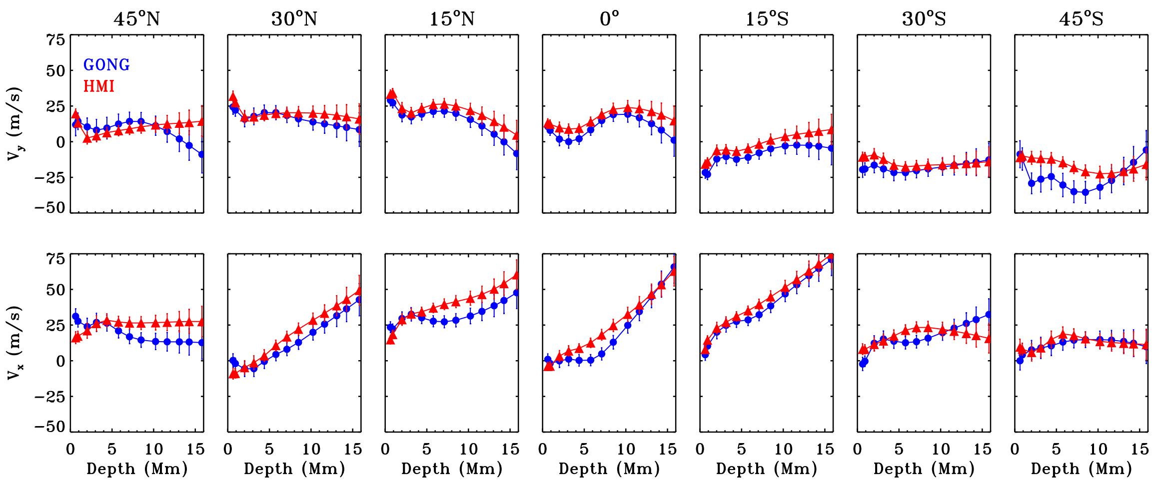

Figure 5. Variation of zonal (V_x) and meridional (V_y) components of the horizontal flow obtained using GONG (blue circles) and HMI (red triangles) Dopplergrams at different latitudes along the central meridian.

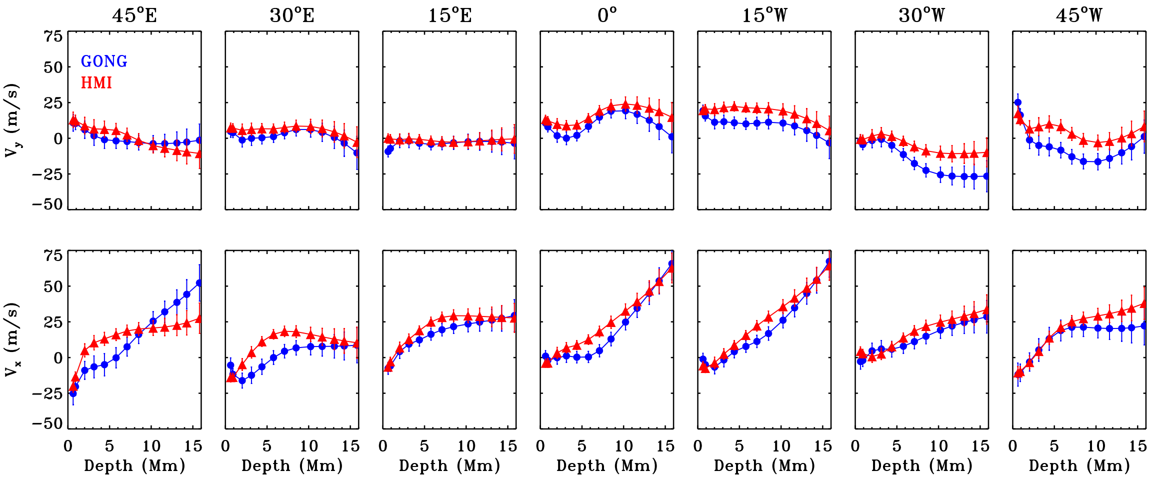

Figure 6. Same as Figure 5 but at different longitudes along the equator.

cross-spectral fitting to further improve the estimates of mode parameters. We also find that the simultaneous observations do not show any significant change in zonal and meridional flows with the choice of spectral line.

Acknowledgments

This work utilizes GONG data obtained by the NSO Integrated Synoptic Program (NISP), managed by the National Solar Observatory, which is operated by AURA, Inc. under a cooperative agreement with the National Science Foundation. The data were acquired by instruments operated by the Big Bear Solar Observatory, High Altitude Observatory, Learmonth Solar Observatory, Udaipur Solar Observatory, Instituto de Astrofisica de Canarias, and Cerro Tololo Interamerican Observatory. SDO data courtesy of SDO (NASA) and the HMI and AIA consortium. This work is partially supported by NASA grant NNH12AT11I.

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