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Characterization of High-Degree Modes using MDI, HMI and GONG data

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Abstract. We present the first characterization of high-degree modes (i.e., ℓ up to 900 or 1000), using three instruments and three epochs corresponding to the 2001, 2002 and 2010 MDI Dynamics runs. For 2001, we analyzed MDI full-disk dopplergrams, while for 2002, we analyzed MDI and GONG full-disk dopplergrams, and for 2012 we analyzed MDI, GONG and HMI full-disk dopplergrams. These dopplergrams were spatially decomposed up to ℓ = 900 or 1000, and power spectra for all degrees and all azimuthal orders were computed using a high-order multi-taper, power spectrum estimator. These spectra were then fitted for all degrees and all azimuthal orders, above ℓ = 100, and for all orders with substantial amplitude. Fitting at high degrees generates ridge characteristics, characteristics that do not correspond to the underlying mode characteristics. We used a sophisticated forward modeling to recover the best possible estimate of the underlying mode characteristics (mode frequencies, as well as linewidths, amplitudes and asymmetries). We present the first attempt to apply this method to three instruments and three epochs. The derived sets of corrected mode characteristics (frequencies, line widths, asymmetries and amplitudes) are presented and compared.

1. Introduction

The inclusion of high-degree modes (ℓ up to 1000) has the potential to better constrain the outer 4% of the solar interior. Rabello-Soares et al. (2000) have shown what additional constraints on the solar stratification can be derived when including high-degree modes, while Korzennik & Eff-Darwich (1999) have shown which improvements can be expected when deriving the solar internal rotation. Since individual modes merge into ridges at high degrees ($\ell > 300$ for f-modes, $\ell > 200$ for low order p-modes), one can only fit ridges at higher degrees. The resulting ridge characteristics ($\tilde{\nu}$, $\tilde{\Gamma}$, $\tilde{A}$, $\tilde{\alpha}$) are not the underlying mode characteristics (see Korzennik et al. 2004). Our approach is to fit ridges at high degrees and correct the ridge characteristics, using a precise and

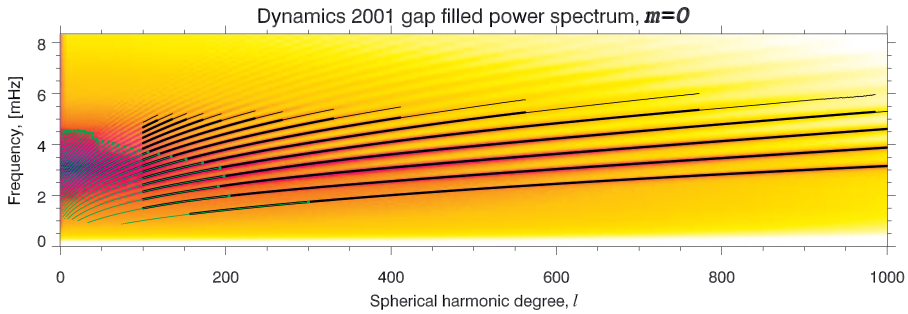

Figure 1. Gap-filled Dynamics 2001/MDI power spectrum, displayed on a logarithmic scale, for the zonal modes ($m = 0$). The dots represent the fitted ridges (black) or modes (green).

sophisticated ridge modeling procedure. We use a high-order sine multi-taper spectral estimator to smooth out the realization noise and fit ridges $100 \leq \ell \leq 1000$ or 900, using a multi-step least-squares minimization, and for all ℓ and all m.

We present the result of our analysis of six data sets acquired by 3 instruments over 3 co-eval epochs. We reduced the MDI data acquired during the 2001, 2002 and 2010 Dynamics runs (90, 98 and 67-days long each), GONG data for the co-eval 2002 and 2010 epochs, and HMI data for the co-eval 2010 epoch.

We corrected the ridge characteristics to derive mode estimates using a precise and sophisticated model of the ridge, (see Korzennik et al. 2013, and references therein). This model use the effective leakage matrix that is appropriate for each instrument.

2. Results

We first compare the mode frequencies for the overlap range between mode fitting and ridge fitting. Indeed, at low and intermediate degree modes are resolved and individually fitted (green dots in Figure 1). The high-order sine-multitaper used to estimate power spectra for our ridge fitting also merged the individual modes into a power ridge at intermediate degrees, allowing us to fit ridges down to $\ell = 100$ (black dots in Figure 1). That comparison is shown in Figure 2 and in Table 1. The figure shows the frequency differences for all six data sets, the table presents the mean and standard deviation of the differences, and of the scaled differences, i.e., differences divided by their uncertainties.

Figure 3 compares the frequencies, FWHM and asymmetries estimated for each instrument and co-eval epoch, with respect to MDI values. Table 2 presents the mean and standard deviation of the frequencies, and scaled frequencies differences. Figure 4 compares the rotational splittings estimated for each instrument and co-eval epoch.

3. Conclusions

We have successfully implemented our high degree ridge fitting and ridge-to-mode correction methodology for all three major helioseismic instruments: GONG, MDI

Table 1. Mean and standard deviation of frequency differences, and scaled frequency differences (differences divided by their uncertainties), between estimated mode frequencies derived from ridge fitting and co-eval resolved mode frequency measurements, for the $100 \le \ell \le 200$ or 300 overlapping range.

Year	Instrument	$\Delta\nu$	$\Delta\nu/\sigma_\nu$
2001	MDI	-0.220 ± 0.673	-0.880 ± 2.182
2002	MDI	-0.298 ± 0.966	-0.862 ± 2.631
	GONG	0.176 ± 0.769	0.517 ± 2.416
2010	MDI	-0.088 ± 1.087	-0.077 ± 2.766
	GONG	0.748 ± 1.186	2.751 ± 2.411
	HMI	0.269 ± 0.616	0.880 ± 2.044

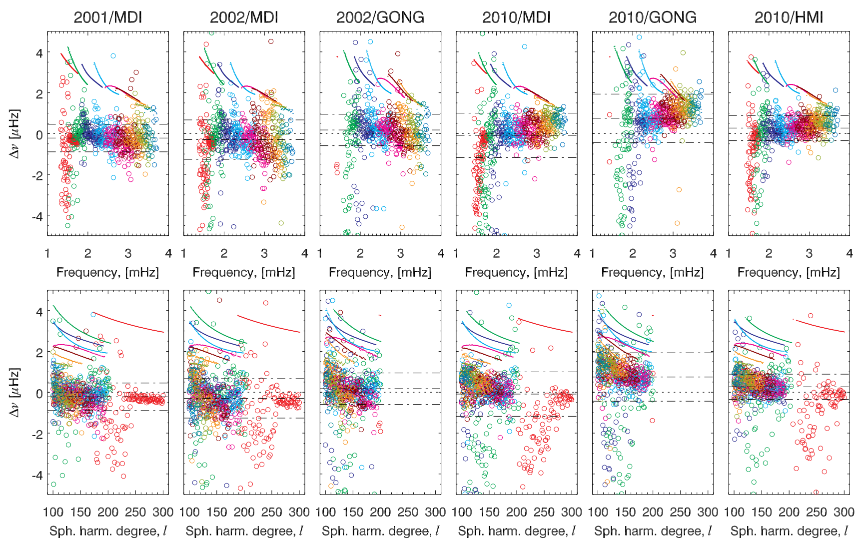

Figure 2. Differences between mode frequencies (multiplets) estimated from ridge fitting and values measured by fitting resolved modes using co-eval epochs, for the overlapping range ($100 \le \ell \le 200|300$). These differences (circles) are plotted vs frequency (top row) or spherical harmonic degree, ℓ (bottom row), the dots correspond to the ridge-to-mode corrections.

and HMI. Comparisons for the overlapping range with resolved mode fitting suggest a rather good validation of the corrected multiplets, except for one data set (2010/GONG) and for a residual trend with ℓ for the f-mode (mostly visible for 2001/MDI). Comparisons at all degrees between estimates from different instruments at co-eval epochs show residual frequency mismatch at higher degrees, especially for the 2010 epochs. Estimates of FWHM and asymmetry show good agreement. The corrected rotational splittings derived from the six data sets agree for co-eval estimates after the ridge-to-mode correction. In contrast, the uncorrected splittings differ for co-eval estimates from different instruments, indicating that our instrument-specific correction scheme is

Table 2. Mean and standard deviation of frequency differences, and scaled frequency differences, between estimated mode frequencies derived from ridge fitting for different instruments and co-eval epochs, with respect to MDI values.

Year	Instruments	$\Delta\nu$	$\Delta\nu/\sigma_\nu$
2002	GONG – MDI	−0.222 ± 0.460	−1.317 ± 1.470
2010	GONG – MDI	−0.982 ± 0.934	−4.260 ± 2.770
	HMI – MDI	−0.655 ± 1.117	−2.162 ± 1.572

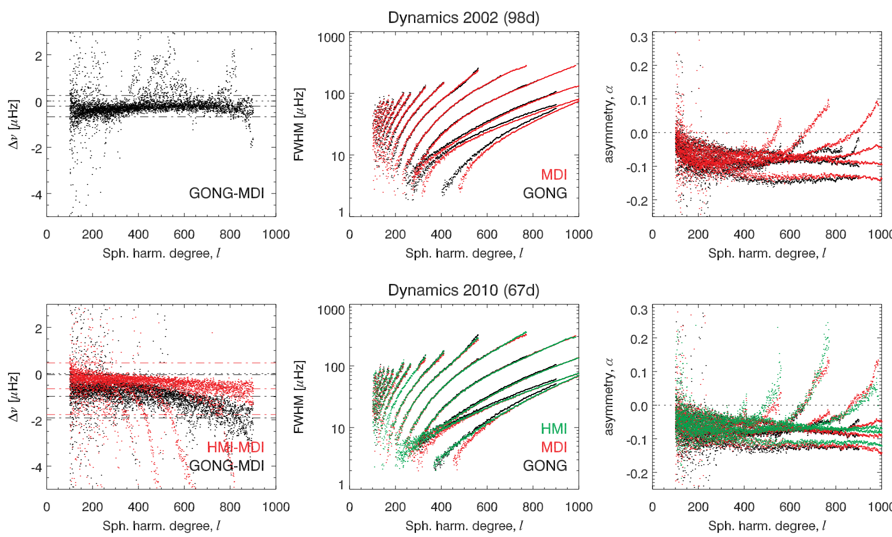

Figure 3. Comparison of frequencies, FWHM and asymmetries, estimated from ridge fitting, of co-eval observations of MDI and GONG in 2002 (top row), and MDI, GONG and HMI in 2010 (bottom row). The panels from left to right show frequency differences, FWHM and asymmetry comparisons, plotted as a function of degrees, ℓ. In contrast to the 2002 data, the 2010 frequency comparison shows a clear variation with degree, and some dependence on frequency.

properly incorporating some of the instrumental differences. Still, we see residual discrepancies at the 1.3 σ level for 2002 and at the 2 to 4 σ level for 2010. These are are likely the result of our limited knowledge of GONG's & MDI's PSFs. The co-eval 2010 data sets give us a unique opportunity to check and maybe validate MDI and GONG PSFs using the HMI observations.

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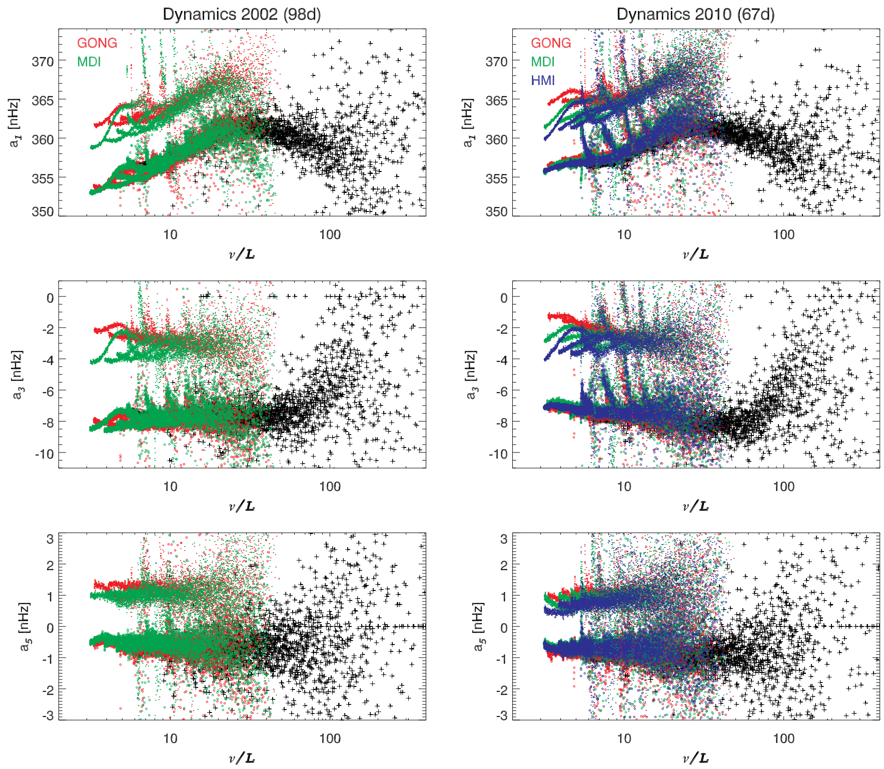

Figure 4. Comparison of Clebsch-Gordan rotational frequency splitting coefficients, plotted as a function of the ratio ν/L, with the rows corresponding to the first three even coefficients. Panels on the left compare 2002 results (GONG and MDI), panels on the right compare 2010 results (GONG, MDI and HMI). In each panel, the colored dots are the coefficients corresponding to the ridge frequencies, while the colored circles are the values corresponding to the mode frequency estimates, i.e., after applying the ridge to mode correction scheme. The black crosses are the values derived from fitting resolved modes (for co-eval epochs).

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