THE COMPARISON OF SIMULTANEOUS SOI/MDI AND MT. WILSON 60-FOOT TOWER POWER SPECTRA AND P-MODE PARAMETERS

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ABSTRACT

In this paper we will present the results of the first detailed comparison of solar p-mode parameters obtained during the 1996 Dynamics Run of the SOHO SOI/MDI Full-Disk (FD) Program with a similar set of parameters obtained from a simultaneous time series of ground-based, full-disk observations taken at the 60-Foot Solar Tower of the Mt. Wilson Observatory (MWO). Specifically, we will show a comparison of corresponding SOI/MDI and MWO power spectra and we will also compare the high-degree p-mode frequencies, frequency uncertainties, frequency splittings, widths, and power densities which we obtained by numerically fitting the peaks and ridges that are contained in the MDI and MWO power spectra.

Key words: solar oscillations; modal parameters.

1. INTRODUCTION

The observations obtained by the SOI/MDI Full-Disk Program are unprecedented both in their high quality and in their freedom from the deleterious effects of the terrestrial atmosphere. Nevertheless, some of the results which we have recently obtained from our analysis of the initial MDI Full-Disk observations differ systematically from the results of some preceding high-degree p-mode studies. (Please see our companion paper in this volume, Rhodes et al., 1998, for a more complete discussion of these differences.) Therefore, in order to determine whether or not these differences were due to possible problems with the reduction and analysis of the MDI observations, we have exploited the availability of a time series of simultaneously-observed observations which were obtained at the 60-Foot Tower to generate an independent set of MWO p-mode parameters which we have compared with our corresponding MDI results.

Beginning on May 23, 1996, the SOI/MDI experiment began its first high duty cycle run of 1024 × 1024 pixel full-disk images. The 60.75-day time series which followed has been designated as the 1996 MDI Dynamics Run. On 57 days of this Dynamics Run a second time series of simultaneous 1024 × 1024 pixel full-disk Dopplergrams was obtained at MWO. The initial high-degree p-mode parameters which we computed from the 1996 MDI power spectra are presented in Rhodes et al. (1998). From the simultaneous MWO observations we also computed 601 sets of zonal, tesseral, and sectoral power spectra which covered the degree range of 0 to 600. These sets of MWO power spectra were then analyzed to yield: 1) both modal and ridge-fit frequencies, 2) the corresponding modal and ridge-fit frequency uncertainties, 3) the widths of the peaks, and 4) the power densities of the peaks. In addition, for ℓ ≥ 1 all of the MWO power spectra were also processed to yield estimates of the so-called “n-averaged” rotational splitting coefficients for every degree between ℓ = 4 and ℓ = 600.

In this paper we will present the results of the direct comparison of the corresponding MDI and MWO p-mode parameters and we will compare our splitting coefficients with both the previously-published coefficients from the 1996 SOI/MDI Medium-ℓ Program and with the MDI high-degree splitting coefficients which we are presenting in Rhodes et al. (1998).

2. OBSERVATIONS

We have been acquiring annual time series of full-disk filtergrams with either sodium or potassium versions of the Cacciapuoti Magneto-Optical filter (MOF) at the 60-Foot Solar Tower of the MWO since the summer of 1984. In the summer of 1987 we installed a large-format (1024 × 1024 pixel) CCD camera at the 60-Foot Tower. With that camera we have been able to obtain full-disk filtergrams which are similar in spatial resolution to the filtergrams which have been obtained by the MDI experiment.

In normal operations at the 60-Foot Tower we obtain a pair of full-disk filtergrams that are taken in the op-
posite wings of the Na D lines every 60 seconds. During subsequent processing we convert each of these filtergram pairs into a full-disk Dopplergram. During early 1996 we changed the timing of our MWO CCD camera exposures so that the mid-point of the two 0.5 second exposures in each pair would coincide exactly with the mid-point of the set of six exposures which the MDI would be taking during the same minute. Hence, whenever the Sun was observable from MWO during the 1996 MDI Dynamics Run, we were able to obtain two simultaneous time series of full-disk Dopplergrams.

2.1. Generation and Fitting of Power Spectra

Initially, averages of the rotationally-induced frequency splittings were computed for the frequency range of 1800 to 4800 μHz at each nonzero degree. Next, these so-called n-averaged splittings were employed to compute an average power spectrum for each degree. As an example, the m-averaged power spectrum for \( \ell = 300 \) which we computed from the MWO observations is compared with the corresponding MDI spectrum in Figure 1. After we had computed the m-averaged MWO power spectra, we then employed the identical peak-fitting algorithm which we had employed for the fitting of the peaks in the MDI power spectra to compute an independent set of estimates of all of the \( p \)-mode parameters which were listed above.

2.2. Correction of Ridge-Fit Frequencies

We have discussed the problems inherent in the fitting of broad ridges rather than sharp, isolated peaks of observed power in Rhodes et al. (1998). In that paper we have outlined a multiple-step approach which we have employed to correct the MDI ridge-fit frequencies. Due to the overall similarity in the peaks of the MWO and MDI m-averaged power spectra, we have been able to employ the identical frequency-correction procedure on both our MDI and MWO power spectra. This technique employs a multiple-linear-regression approach; however, our new technique has been substantially revised from previously-published multiple-regression approaches in order to improve its numerical stability. With our fitting technique we have been able to fit many of the low- and intermediate-degree power spectral peaks using both a narrow fitting range and also using a much broader fitting range. The frequencies which we have computed using the narrow fitting ranges are our so-called "modal" frequencies, while the frequencies which we have obtained from the use of the wide fitting range are our so-called "ridge-fit" frequencies.

In Figure 2c of Rhodes et al. (1998) we show the \( \ell = 75, n = 4 \) multiplet along with the fit obtained using our "ridge fitting range" and the alternative fit obtained for this multiplet using our "wide fitting range." While it is not evident at the scale of this figure, the frequencies computed for the two different fits for the same multiplet are in fact slightly different. When we repeated these two types of fits for all of the cases for which we could employ both the narrow and broad fitting ranges, we obtained two different sets of frequencies. For these cases we next subtracted the two sets of frequencies on a peak-by-peak basis to obtain a set of "modal" minus "ridge-fit" frequency differences. The sets of MWO and MDI "modal" minus "ridge-fit" frequency differences are shown here in Figures 2a and 2b. The similarities of these two figures indicate that the two sets of frequency differences are caused by the same underlying causes for both the MDI and MWO power spectra.

After we had computed these frequency differences, we then employed them as the dependent variable in our multiple-regression model. In this model we used the frequency, the degree, the logarithm of the full-width at half-maximum, and the derivative of the observed power density with degree of the observed velocity-based power spectral peaks as the independent variables. We then used least-squares techniques to obtain a set of regression coefficients for this model. Next, we employed the coefficients of this regression model to compute a set of frequency corrections which we then applied to each raw, ridge-fit frequency. We show the MWO frequency corrections which resulted from these steps in Figure 3a. The corresponding MDI frequency corrections are shown here in Figure 3b. Again, the frequency corrections appear to be very similar for both the MWO and MDI spectra.

Once we had computed both sets of ridge-fit corrections, we then applied them to both the the raw, uncorrected MWO and MDI ridge-fit frequencies and, in so doing, we obtained two sets of corrected ridge-fit frequencies. The corrected high-degree frequencies which we have obtained with this method are much smoother and more internally consistent than were the frequencies which we obtained previously when we employed Korzennik's (1990) correction codes.

3. COMPARISON OF \( p \)-MODE PARAMETERS

Our initial table of MWO frequencies consists of the set of 1,866 modal frequencies which is supplemented by the set of corrected ridge-fit frequencies for the
7,813 remaining cases for which we could not obtain such a modal fit. In Figure 4a we illustrate the portion of the $\ell$-$\nu$ plane where we were able to identify MWO modal frequencies and the remainder of the plane where we could only compute the ridge-fit frequencies. In Figure 4b we show the corresponding $\ell$-$\nu$ coverage for our MDI frequency dataset.

The first comparison which we made was to look at the two sets of modal frequencies. Since there were 11 peaks in the MDI power spectra for which we were not able to obtain a converged solution in the corresponding MWO power spectra, our original total of 1,866 modal fits was reduced to a total of 1,855 common modal fits in both our MDI and MWO tables. The mean value of these two sets of modal frequency differences was equal to $-22.5$ nHz with a standard deviation of $238$ nHz. Hence, we found that our MDI and MWO modal frequencies agreed to within 0.1 of one standard deviation. Furthermore, as Figure 3b of Rhodes et al. (1998) illustrates, we found no measureable frequency dependence to these modal frequency differences. Nor was there any discernable degree dependence to these modal frequency differences. These results attest to the validity of the
averaged-spectrum method of frequency estimation and to the accuracy of both the MDI and MWO sets of observations.

In Figure 5 we compare our corrected MDI high-$\ell$ ridge-fit frequencies and our corresponding set of MWO corrected ridge-fit frequencies. The frequency dependence of the differences between these two datasets is shown in Figure 5a, while the degree dependence is shown in Figure 5b. These two plots indicate that our MWO high-degree frequencies agreed very closely with the simultaneous MDI ridge-fit frequencies.

We now compare our MDI modal frequency uncertainties with the corresponding MWO modal frequency uncertainties. In Figure 6a we show the comparison between our two sets of modal frequency uncertainties. Specifically, the ratio of the one-sigma MWO frequency uncertainty to the one-sigma MDI frequency uncertainty is plotted in Figure 6a as a function of frequency. This figure illustrates that the average ratio of these modal frequency uncertainties was very close to the ratio of the duty cycles of the two time series, which was 2.94. Since the durations of the two observing runs were almost identical, the one-sigma uncertainties for the narrow modal peaks might have been expected to scale primarily with the duty cycle of each run and this indeed appears to be the case.

The frequency dependence of the ratio of the one-sigma frequency uncertainties, but computed from the ridge-fits instead of the modal fits is shown in Figure 6b. For the ridge-fit cases the mean ratio of the MWO to MDI uncertainties, which was equal to 1.77, was smaller than was the mean ratio for the modal fits.

In Figure 7a we show the ratio of the FWHMs of the MWO modal fits to the corresponding FWHMs from the MDI modal fits. Also shown in this figure is the average of these ratios, which was equal to 1.107. This number is very close to the ratio of the durations of the MDI and MWO observing runs, which was equal to 1.07. This similarity indicates that, for the modal fits, the run with the longer duration has the narrower peaks as would be expected. In Figure 7b we show a scatterplot of the MWO FWHMs as computed from the ridge-fits versus the corresponding MDI ridge-fit FWHMs. The diagonal line in this figure shows what would be expected if the two sets of widths were identical. The nearly constant offset of the MWO FWHMs above this line indicates that the MWO ridge widths were systematically larger than the MDI ridge widths over the entire range of FWHM values.
Figure 7. a.(left) The frequency dependence of the ratio of the full-width at half-maximum (FWHM) of the MWO modal fits to the FWHM of the corresponding MDI modal fits. The horizontal line is drawn at the average value of this ratio, which was 1.107. Since the ratio of the duration of the MDI and MWO observing runs was equal to 1.07 (with the MDI run being slightly longer), the ratio of the FWHM values might be expected to scatter about that value, which is very close to the mean ratio. b.(right) Scatterplot of MWO ridge-fit FWHMs vs. MDI ridge-fit FWHM values.

Figure 8. a.(left) Frequency dependence of MWO Power Density. b.(right) Frequency dependence of MDI Power Density.

Figure 9. a.(left) The frequency dependence of the logarithm of the ratio of the MWO and MDI power densities for the modal fits. As was mentioned above, this ratio increases with increasing frequency, most likely due to the differing height-of-formation of the Na II lines used in the MOF at MWO and of the Ni I line used in the MDI. b.(right) Frequency dependence of the logarithm of the ratio of the MWO and MDI power densities from the ridge-fits.

In Figures 8a and 8b we show the frequency dependence of the MWO and MDI power densities, respectively. Both sets of observations were calibrated into radial velocities in m/sec, so that differences in the two sets of points should be indicative of actual radial velocity differences at the two different heights in the solar atmosphere where the two sets of observations were obtained. In Figure 9a we show the frequency dependence of the logarithm of the ratio of the MWO power density to the corresponding MDI power density as determined from the modal fits. In Figure 9b we show the frequency dependence of the logarithm of the same ratio, but as determined from the ridge-fits. As was evident in Figure 1 the ratio of the MWO and MDI power densities is frequency-dependent. This is also most likely due to the height differences of the sources of the observations.

3.1. Comparison of High-Frequency p- Modes

In Figure 10a we show the unbinned differences of the uncorrected MDI and MWO ridge-fit frequencies.
In Figure 10b we present the binned differences in these two sets of frequencies over the same frequency range. We do so to illustrate the systematic frequency differences which exist at high frequencies in the MDI and MWO datasets. We believe that these differences are entirely due to the difference in the height-of-formation of the photospheric Ni I line used by the MDI instrument and of the chromospheric Na II lines employed by the Magneto-Optical Filter at MWO. Furthermore, the binned frequency differences shown in this figure give clear evidence for oscillations in these frequency differences for frequencies above 6200 μHz. We believe that these oscillations may tell us something about the relative atmospheric heights of the source of the p-modes themselves and of the spectral lines used in our two instruments. While the high-frequency modes do have aliases of frequencies from above the Nyquist frequency complicating their profiles, the exact same temporal sampling was used in space and on the ground for the two sets of observations which yielded the frequency differences of Figure 10. Hence, we would have expected any alias-induced alterations of the ridge-fit frequencies to be the same for both sets of frequencies rather than being the cause of the differences shown in Figure 10.

4. HIGH-DEGREE ROTATIONAL SPLITTINGS

We also modified the rotational splitting analysis software which Korzennik (1990) developed for the 1988 MWO observations to employ the 1996 MWO unaveraged power spectra as the input spectra. We studied the degree dependence of the Legendre splitting coefficients for the modes accessible from MWO by computing a set of fifth-order a-coefficients for every degree ranging between 8 and 600. Such a single set of splitting coefficients obtained from the simple degree is known as a set of "n-averaged" splitting coefficients. While such averaged splitting coefficients are no longer the state-of-the-art for use in rotational inversion software, we showed the entire set of n-averaged splitting coefficients in Figure 10b of Rhodes et al. (1998) in order to compare them with similar n-averaged coefficients obtained from simultaneous MWO observations in Figure 10b and with the non-averaged MDI coefficients which are shown in Figure 10c.

In order to illustrate that all of the MDI and MWO high-degree splitting coefficients are in need of systematic corrections due to the profiles of the p-mode ridges, we also included in Figure 10d of Rhodes et al. (1998) the set of odd a-coefficients which we computed from the Medium-ℓ observations which were also acquired during the 1996 Dynamics Run. Also, in order to show the systematic differences between the FD coefficients and the Medium-ℓ coefficients, we included lines in the panels which show the values of the corresponding coefficients obtained from the rotation of magnetic features in the photosphere. It was clear from this comparison that the Medium-ℓ coefficients agreed reasonably well with the surface rotation rate coefficients, but that the higher-degree ridge-fit splittings were all systematically displaced away from the surface values. The change in the behavior of the a₁, a₃, and a₅ splitting coefficients between degrees of 120 and 200 is caused by the blending together of the p-mode peaks into ridges in each of the 2ℓ + 1 separate spectra which are employed in the measurement of the splittings.

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