Variations in Global Mode Analysis

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Abstract

As with any data analysis, the standard MDI medium-l analysis pipeline is based on approximations and somewhat arbitrary choices in the processing. It is furthermore known that the results of the standard analysis contain systematic errors, most notably a bump in the normalized residuals of the a-coefficients around 3.4 mHz, an annual variation in f-mode frequencies, and possibly a polar jet in the rotation inversions. Our previous work has explored how these errors are affected by making various corrections to the analysis. In this poster we extend our study to include a comparison of the results of full disk data to those of the binned data we have previously used. We go on to explore how several choices made in the analysis, such as the amount of zero padding and the width of the fitting interval, affect the mode parameters and the magnitude of the systematic errors.

The Data & Analysis

The MDI instrument is capable of producing images of the Sun with a resolution of 1024x1024 at a cadence of one minute. However, due to telemetry constraints, these images are usually smoothed by a Gaussian, cropped at 90% of the solar radius, and sampled every 5x5 pixels. Dopplergrams obtained in this way are called vector weighted and are the usual input for the MDI medium-l program. Every year for some months, however, there is telemetry available to send down the full disk images in addition to the lower resolution ones. These are the dynamics runs. The full disk images can be run through the pipeline in almost exactly the same way as the vector weighted images. But not only is the spatial resolution higher, the data goes closer to the limb. Specifically, vector weighted images are usually apodized with a cosine curve from a fractional image radius of 0.83 to 0.87, while the full disk images are usually apodized in the same way from 0.90 to 0.95.

For this work, the remapping for the spherical harmonic decomposition uses updated values for the P-angle and Carrington inclination and makes corrections for the plate scale of the instrument, cubic distortion and CCD tilt. The resulting timeseries are then detrended and gapfilled, and all of our peakbagging takes into account the Woodard effect and horizontal displacement.

In addition, we try several variations of our peakbagging method. The first is zero padding, that is, appending a chunk of zeros to the end of the timeseries before performing the Fourier transform. We artificially extend the length of the timeseries in this way by factors of 2, 3 and 4, which increases the the frequency resolution of the Fourier transform by the same factor. We also try using different fitting intervals. The standard pipeline uses an interval of 5 linewidths, and we try using 7.5, 10, and 15 linewidths. This is partly motivated by discrepancies with the GONG project, which uses a much wider fitting interval. Specifically, we expect that using different fitting intervals may affect the systematic error we see in the normalized residuals of a-coefficients after a rotation inversion.

We use the following obvious abbreviations to label these variations: pad2, pad3, pad4, fi75, fi10, fi15. The default analysis will be labeled by gf (short for gap-filled).

Results

For each variation, we reanalyzed two years of data. To summarize the effect of each variation, we took the average over the two years by taking the modes that were fit at least 70% of the time and fitting a second-order polynomial to each parameter. We then took the average of the fit. Figures 1 & 2 show the difference between two variations divided by the error in the fit, for the modes that they had in common (fit in 70% of both). That is, each y-axis is in units of standard deviation. None of the variations made significant changes to mode frequencies. Zero padding had only a small effect on mode amplitudes. The number of modes fit for each variation is shown in the table below:

Label	# Modes
gf	2040
fi75	1903
fi10	1745
fi15	1108
pad2	2067
pad3	2055
pad4	2026

We did not fit pad4 above l=280 because of technical problems with the code. Also, the lack of mode convergence as the fitting interval is increased is not understood. Both issues require futher investigation.

Figure 1. differences in amplitude and linewidth as a function of (l+1/2)/ν for different fitting intervals.

Figure 2. Differences in linewidth and amplitude for different amounts of zero padding. Top panels show pad4 minus default. The same plot for pad3 and pad2 are visually similar to these. However, the bottom panels shows pad4 minus pad2, indicating that the two analyses differ significantly for (l+1/2)/ν around 0.11 and for linewidths less than 0.15.

Effect on Systematic Errors

The top panel in Figure 3 shows a plot of the change in seismic radius of the Sun derived from f-mode frequencies. The annual component can clearly be seen. To explore this phenomenon, in the case of each variation we fit a function of the form $f(t) = A\sin(\omega t) + B\cos(\omega t) + Ct + D$ to the fractional change in average f-mode frequency corrected for Doppler shift due to spacecraft motion, with t measured in days and $\omega = 2\pi/365.25$. This assumes that the solar cycle dependence can be represented by a straight line over this interval (see Figure 3). The table below and Figure 3 demonstrate that the only variation that made substantial changes to this fit was fi10. We were unable to use fi15 for this part of the investigation because we were unable to fit any f-modes for it.

Label	Magnitude	Residual
gf	1.9056861	0.43263142
pad2	1.8796518	0.35998310
pad3	1.8752539	0.34398811
pad4	1.8687606	0.34025307
fi75	1.8228774	0.39910758
fi10	1.3411684	0.97724273

The magnitude is given by $\mathrm{sqrt}(A^2 + B^2)$.

Another systematic error in the analysis can be seen in the bump in the normalized residuals of the odd a-coefficients. Zero padding had negligible effect on the bump. Changing the fitting interval, however, drastically altered the behavior of the normalized residuals (see Figure 4). This would seem to indicate that our model is not a good fit to the data.

Finally, we examine the actual rotation profile that results from a full two dimensional RLS inversion of each analysis (see Figure 5). The zero padding did not make significant changes to the profile, and fi15 is not shown because its rotation profile is likely skewed by the lack of modes. The feature that is believed to be spurious is the jet at high latitudes.

Figure 3. Effect on the annual component. Top panel is for the original analysis, with vertical lines marking the two years over which we repeated our analysis. Bottom two panels show the fit to these two years as a solid line. Diamonds are data points.

Figure 4. Normalized residuals of a_1 and a_3, with Gaussian fit shown as a solid line, for various fitting intervals.

Figure 5. Rotation profiles for various analyses. From the top of each plot, the solid lines represent 0, 15, and 30 degrees latitude. Dash-dot is 45 degrees, dashes are 60 degrees, and dots are 75 degrees.

Dynamics Runs

For this work we analyzed the first ten dynamics runs, described in the following table.

Year	Start Day	# Days	Duty Cycle	Start Date	End Date
1996	1238	63	0.97594	1996.05.23	1996.07.25
1997	1563	93	0.98201	1997.04.13	1997.07.15
1998	1834	92	0.97257	1998.01.09	1998.04.11
1999	2262	77	0.97298	1999.03.13	1999.05.29
2000	2703	45	0.99999	2000.05.27	2000.07.11
2001	2980	90	0.96575	2001.02.28	2001.05.29
2002	3368	72	0.97215	2002.03.23	2002.06.03
2003	3942	38	0.94256	2003.10.18	2003.11.25
2004	4202	65	0.95750	2004.07.04	2004.09.07
2005	4558	67	0.98398	2005.06.25	2005.08.31

Note that the timeseries end on the last minute of the day before the given end date. Also, substantial data is available before the given start dates in 2002 and 2003, but was not used because of its poor duty cycle. Future studies will include this data.

To examine the effect of using the full disk data versus the vector weighted data, we reanalyzed these ten periods in two different ways. First, we used the same full disk data but used the same apodization that is used for the lower resolution data. Second, we performed our regular analysis on these periods. In both cases we used a common window function as input to the gap-filling. This is necessary because the full disk data usually has a lower duty cycle than the vector weighted, and we wanted to eliminate this variable from our comparison. The results are shown in Figure 6. Left panels show the difference between the regular full disk analysis and the same using the tighter apodization. Right panels show the difference between using full disk and vector weighted data with the same apodization. In other words, the left panels show the effect of the apodization, and the right panels show the effect of the spatial resolution. The sense of subtraction is such that the sum of the two sides gives the difference between the regular full disk analysis and the regular vector weighted analysis.

Using full disk data had only a small effect on mode frequencies (as compared the the regular analysis). In addition to affecting the amplitudes, it also had a significant effect on the linewidths. Although not shown in the interest of brevity, the apodization had the greater effect on this parameter as well. Also, the variation from year to year was present, but not as drastic as for the amplitudes.

We also examined the effect of apodization and spatial resolution on some of the systematic errors. See Figures 7 & 8. As in Figure 6, it seems that the apodization has the greatest effect. One should bear in mind, however, that the plots in Figures 6, 7, and 8 do not represent averages, as do our earlier plots.

Figure 6. Differences in amplitude as a function of $(l+1/2)/\nu$ for the first ten dynamics runs. Left panels show the effect of apodization, right panels show the effect of spatial resolution (see text).

Figure 7. Normalized residuals of a_3 as a function of frequency for the 2001 dynamics run, with Gaussian fit shown as a solid line. The magnitude of the fit in the three plots is 0.26, 1.79 and 2.49.

Figure 8. Rotation profiles for the 2001 dynamics run. The different curves are as in Figure 5.