Reduction of Systematic Errors in MDI Measurements

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Abstract

Several types of imperfections have been identified in the MDI instrument and it has become clear that the resulting systematic errors in the results limit our ability to make inferences about the Sun. In this poster we will start by describing a couple of these problems and how we have succeeded in quantifying them. We will then apply the corresponding corrections to MDI data and show the improvements to normal mode frequencies. After that we become distracted and show some significantly more interesting results regarding supergranulation.

Introduction

Rather than addressing several systematic errors we focus on one particular example, that of the apparent annual modulation of the seismic solar radius inferred from the f-mode frequencies illustrated in Figure 1. This seismic radius is derived by noting that the f-mode frequency is, to a high degree of accuracy, given by $\omega^2 = gk$, where $g = GM/R^2$ is the surface gravity, $k = L/R$ is the wavenumber, M is the mass of the Sun, R is the solar radius, $L^2 = l(l+1)$ and l is the degree of the mode. Combining this gives $\omega^2 = GML/R^3$ from which it follows that the relative error in the solar radius, compared to that of a model is given by $\delta R/R = -2/3\delta\omega/\omega$ (at fixed l). For a more detailed and accurate description, the reader is referred to Dziembowski, Goode and Schou (2001, ApJ, 553, 897).

Two features are clearly visible in Figure 1. One is that the effective solar radius is decreasing with time, presumably related to the solar cycle. The other is that there is a variation with a one year period.

It has long been speculated that this annual variation is the result of a systematic error. In particular one might assume that the underlying systematic error has a one year period. There are two known systematic problems with a period of one year. The first is that the error in the radius of the solar images changes due to the temperature variation of the MDI instrument. However, much larger variations are introduced by the focus changes which are performed at irregular intervals and those do not appear to cause any changes in the inferred radius.

The other error is that the solar rotation elements are assumed to be those derived by Carrington (1853). It is by now

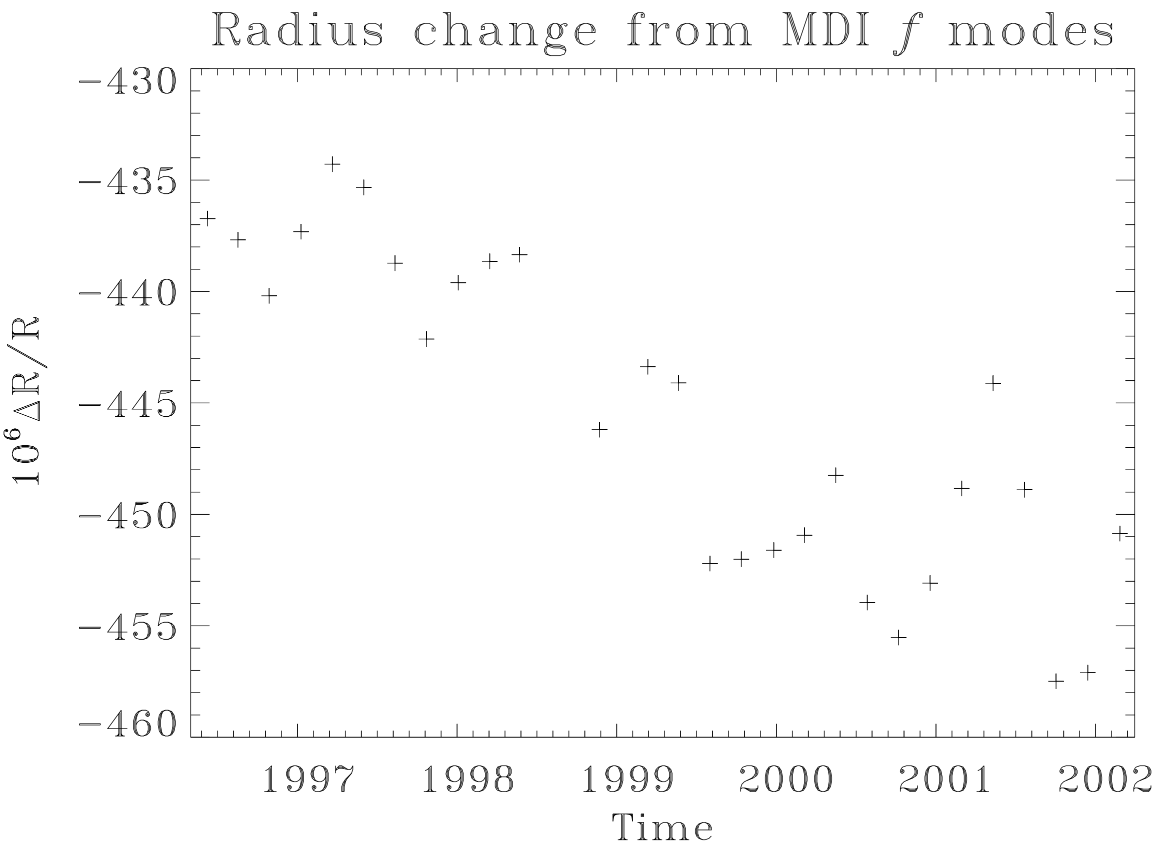

Figure 1: Seismic radius of the Sun as derived from f modes with $160 \leq l \leq 250$. Each point used 72 days of data from the MDI Medium-l program. See text for details.

well established that while the Carrington elements are remarkably good given how they were derived, they are slightly off (see eg. Giles PhD dissertation). In particular the inclination of the solar rotation axis relative to the ecliptic appears to be closer to 7.15° than to the 7.25° derived by Carrington.

One might ask why such errors would cause the frequencies to change. The reason is that the peaks for the different modes are not completely separated and that the relative power observed in different peaks depends on the geometry. Overlap between the peaks then cause the frequencies to be pulled systematically. It is worth noting that the degree of overlap between different modes increases with frequency and thus l, due to the increase in linewidth and the decrease in the separation of the modes. As might be expected from this, it is indeed observed that while the slow (solar cycle timescale) variation in the frequencies varies slowly with l, the annual component is a rapidly increasing function of l (see Antia, Basu, Pintar and Schou, ESA SP-464, 27).

Results

Figure 2 shows the results of using the corrected Carrington elements as well as correcting for the P angle error of -0.2° introduced by the misalignment of the MDI instrument on the SOHO spacecraft (Toner, private communications). As can be seen this reduces the amplitude of the annual variation somewhat. Also shown is the result obtained by correcting for the error in the radius assumed in the remapping of the MDI images.

One might draw at least two conclusions from this depressing result. One is that something else is causing the radius variations, the other is that whatever is causing the problem has a one year period. However, while the first conclusion may be correct, the second one is not. As Figure 3 shows, even a constant P angle change leads to annual variation in the frequencies. Changing the B angle alone also leads to an annual variation.

While the general mechanism for the changes can be understood in terms of the leakage matrix variations, the specifics are not yet understood. In particular it is not clear why a constant change in the P angle should lead to changes with a one year period. Similarly the change in the B angle (which is simply multiplied by a constant factor) would naively be expected to

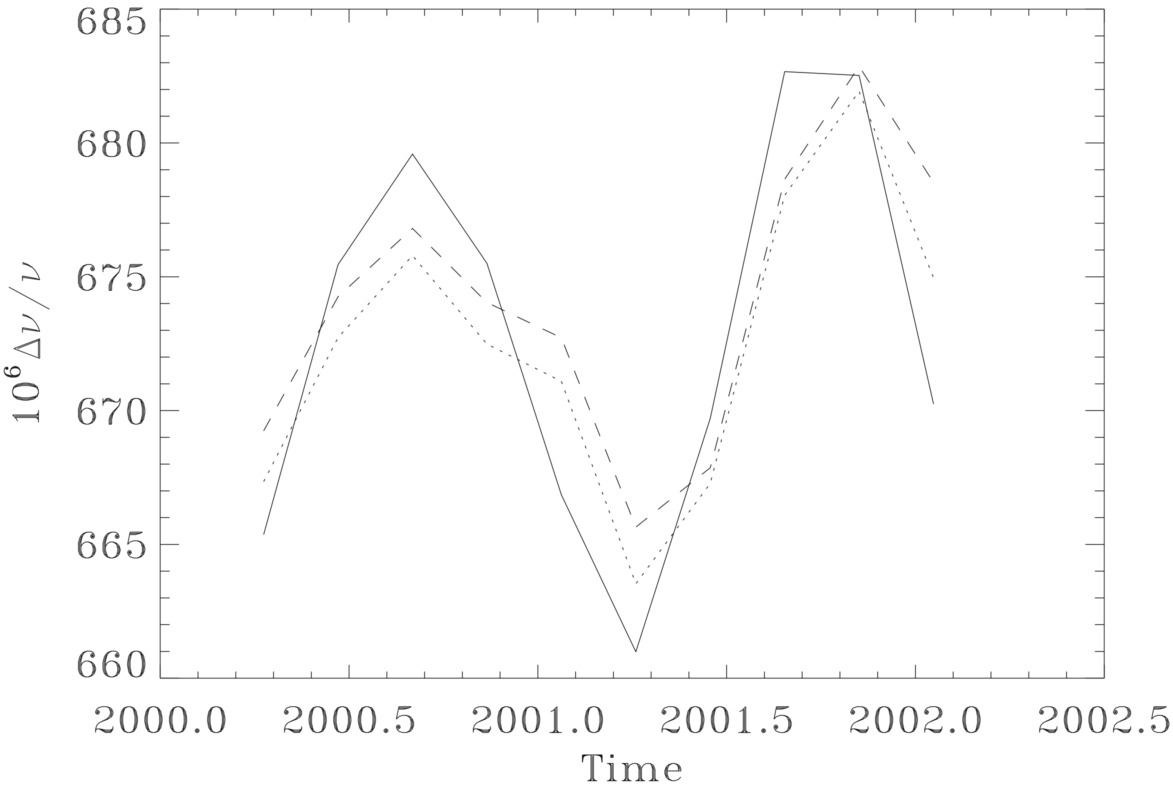

Figure 2: Mean frequency changes for ten of the 72 day time series used for Figure 1. In this case the results were averaged over $200 \leq l \leq 250$. Solid line shows the same results are shown in Figure 1. The dotted line shows results with corrected B and P angles and the dashed line the results of correction both the radius and the B and P angles.

cause a half year period (North and South on the Sun should be equivalent), but it actually causes a one year period.

So what can the remaining error be due to? Since it has been shown that even constant perturbations cause annual variations in the frequencies (presumably by interacting with something else like the B angle), it is difficult to narrow the range of possibilities. The usual candidates for problems can, of course, be dragged out. These include image distortions (unlikely since

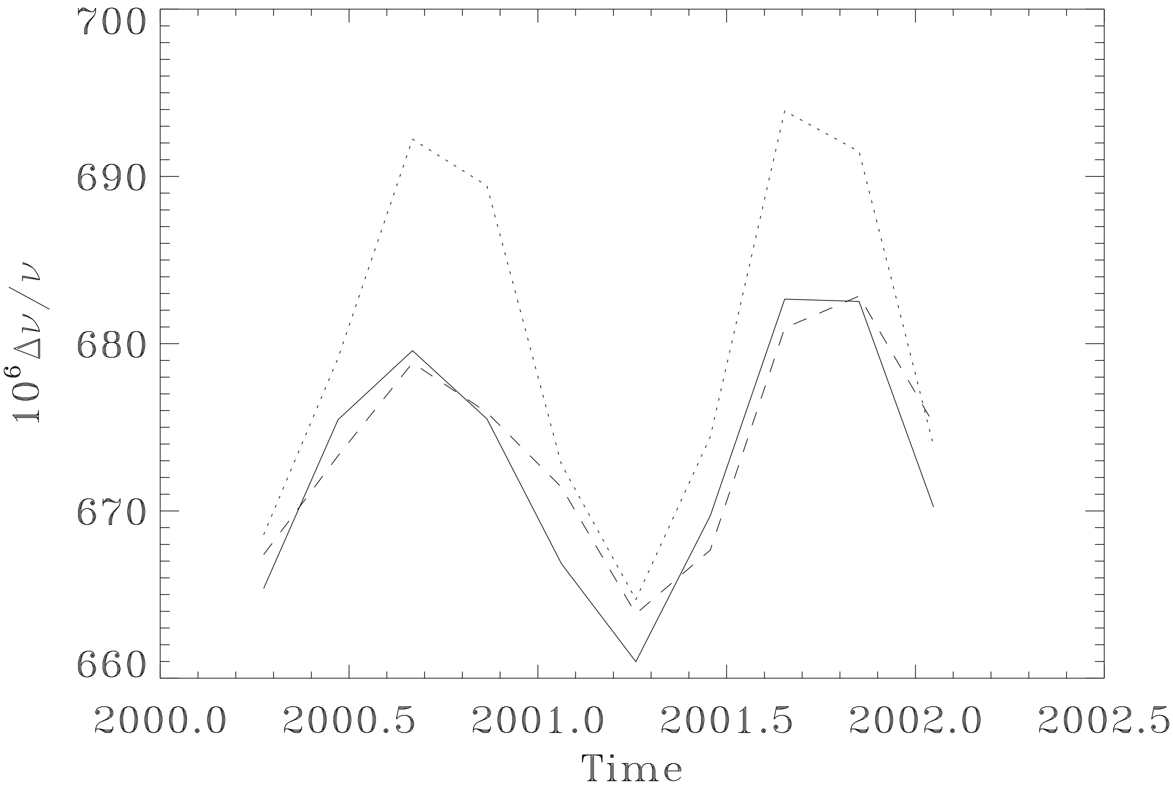

Figure 3: As Figure 2. Solid line is the original result. Dotted line is for a constant P angle error of 0.2° and dashed for a corrected B angle.

the dominant effect looks like a radius error), sensitivity errors (simple models were tried but caused little change), distortion of the eigenfunctions by the differential rotation, incorrect modeling of the horizontal displacement at the surface and assorted other skeletons from the helioseismologist's closet. Both the distortions and the horizontal displacement are easy to test, but this was not done for reasons explained at the end of the conclusion.

Of course the changes could be solar in origin. However it is hard to see why the period should be exactly one year.

Conclusion

It is clear that very small errors, such as the misalignment of MDI and the incorrect rotation elements of the Sun have to be corrected if we are to eliminate systematic errors, such as the annual variations in the f-mode radius.

It is also clear that this work is particularly tedious and boring. We therefore became distracted and started working on different subjects described in the rest of this poster.

Acknowledgements

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Supergranular Waves in Surface Doppler Shift Data

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Abstract

As shown in the note by Gizon, Duvall and Schou (GDS), supergranules appear to have wavelike properties. Here we show that this is also visible in the surface Doppler shift data previously used for supergranulation studies.

Results

The results shown here were obtained using MDI Doppler shift data from the 1996 dynamics run covering 60 days. These are the same data used for Beck and Schou (Solar Physics 2000, 193, 333, in the following BS) and for the GDS results. These data were first derotated and averaged over 1 hour intervals to remove the p-mode signals. Strips in longitude with length of $\approx 150°$ and a width of $10°$ in latitude were extracted, multiplied by a weighting function, tracked and passed through a 3 dimensional Fourier transform.

Figure 4 shows cuts in the power spectra. Note the different power level in prograde waves (lower right) and retrograde waves (upper right) in the top panel. In the bottom panel there appears to be a slight excess power in the southbound waves (upper right) relative to the northbound waves (lower right). The poor resolution in the bottom panel is due to the fact that the strips are narrow in latitude.

Figure 5 again illustrates the excess power in the southbound waves (at positive frequencies).

Figure 6 show the dispersion relation (half the distance between the peaks in the power spectra) for the waves at the equator. Note that the frequencies appear to follow a power law quite well. Points below $l \approx 30$ are likely to be quite unreliable.

Figure 6 also shows the rotation rate at the equator as derived from the average of the frequency of the peaks in the power spectra.

Finally Figure 7 shows the rotation rate and meridional flow derived from fitting the power spectra.

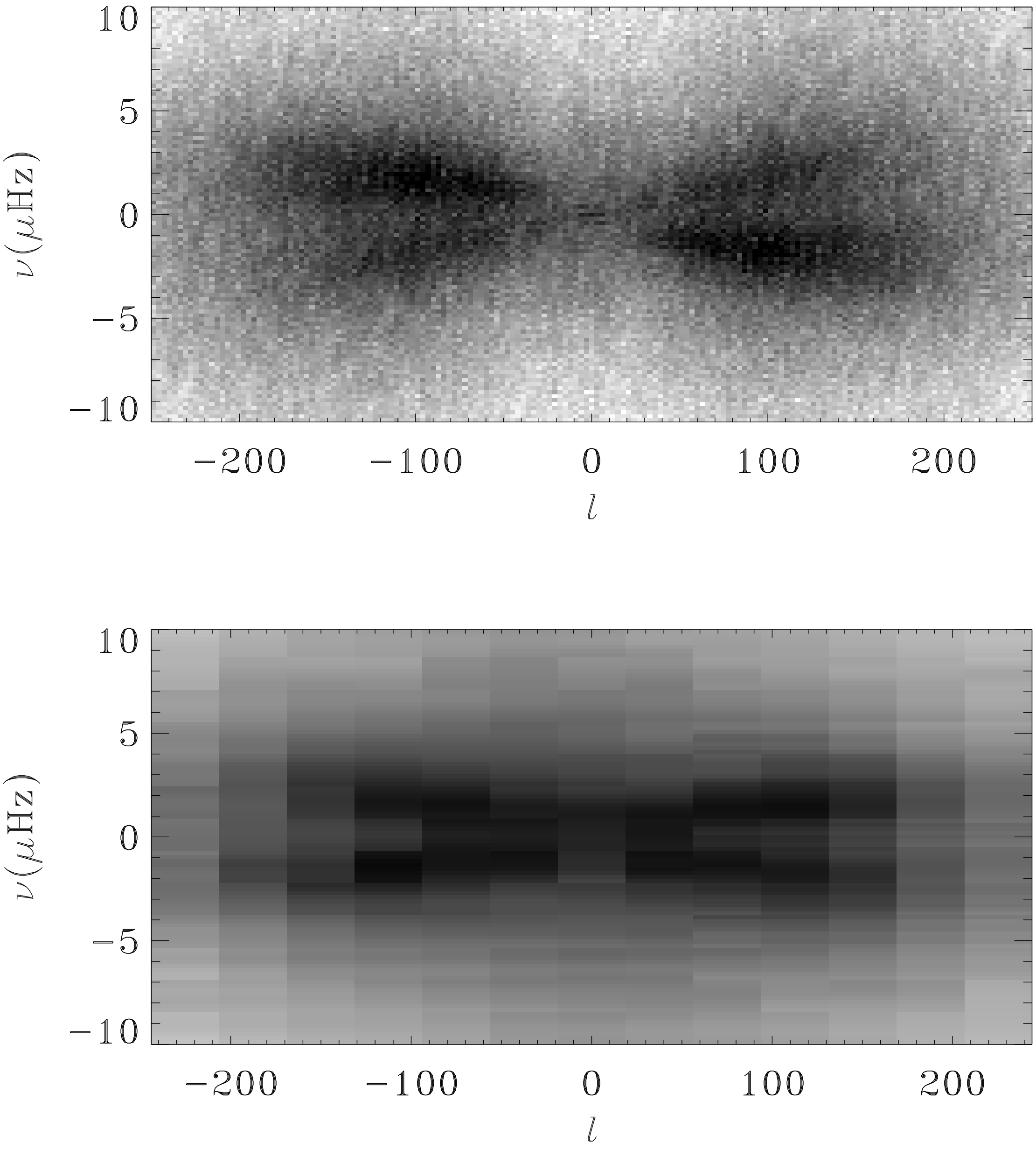

Figure 4: Top: Cut in the 3 dimensional power spectrum at the equator and around $k_y = 0$. The grayscale is logarithmic with black 300 times the power of white. The weighting function contains a sign flip at the central meridian and an apodization. Bottom: Cut at 40° latitude around $k_x = 0$. The weighting function only contains an apodization.

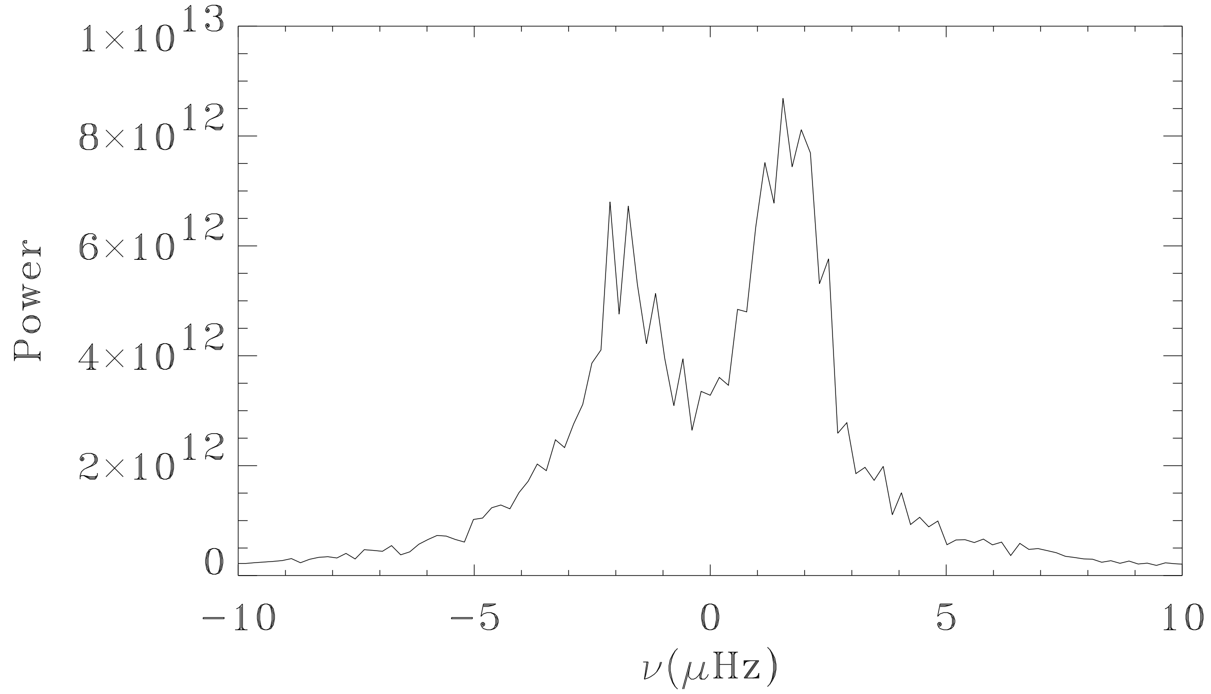

Figure 5: Cut at l=110 in the bottom panel of Figure 4.

Discussion

As can be seen the waves observed in the time distance analysis are easily visible in the raw Doppler shift data. A few points are worth noticing.

First of all these results generally confirm those in GDS.

The rotation rate shown in Figure 6 is much less l dependent that that previously derived from the same data in BS (which had a variation of the order 10nHz between l=50 and l=200). The rotation rate derived by the traditional analysis is essentially a combination of the rotation rate and the dispersion relation.

The rotation rate derived here is remarkably close to the magnetic tracer rate of Komm, Howard and Harvey (Solar Physics, 145, 1).

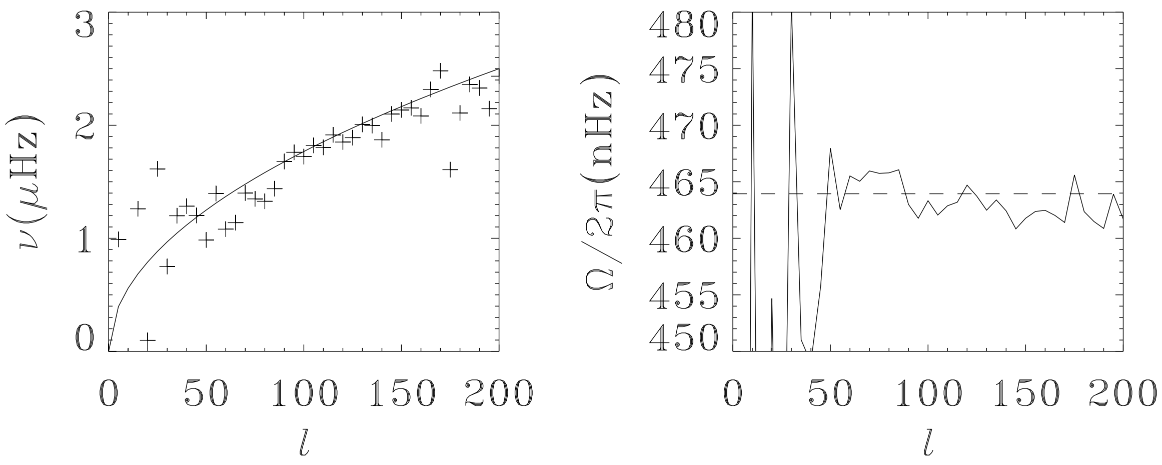

Figure 6: Left: The dispersion relation derived from the top panel of Figure 4. Also shown is $1.25(l/50)^{0.5}\mu$Hz. Right: The sidereal rotation rate derived from the same data (solid). Also shown is the equatorial rate from Komm, Howard and Harvey (Solar Physics, 145, 1).

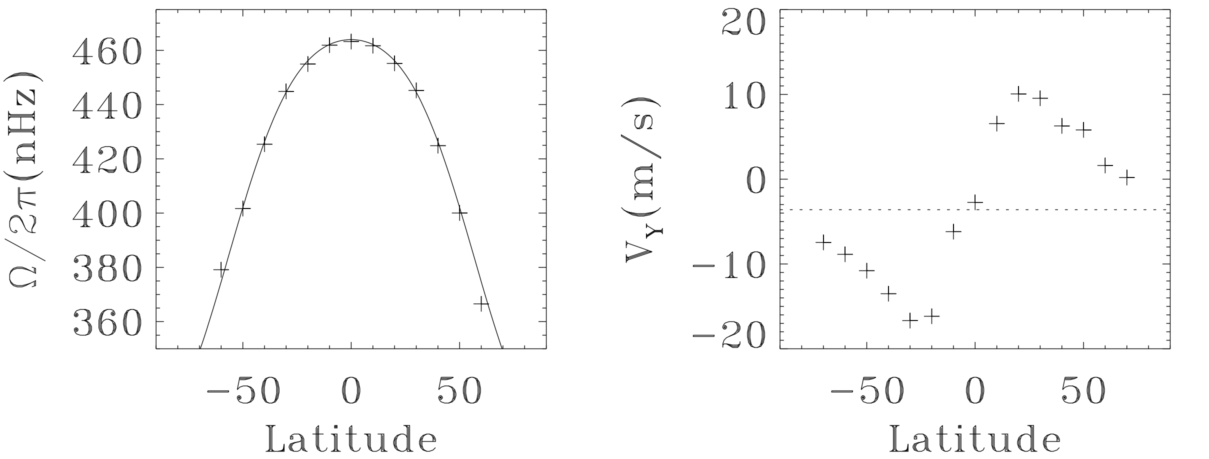

Figure 7: Left: The sidereal rotation rate as a function of latitude, averaged over $75 \leq l \leq 175$. Solid line is the Komm, Howard and Harvey rate. Right: The meridional flow, also averaged over $75 \leq l \leq 175$. Dotted line is a rough estimate of the effect of the incorrect P-angle.

The meridional flow results appear to be quite stable up to around 70 degrees latitude with a clear turnover. It is interesting to note that the meridional flow is not perfectly anti-symmetric across the equator. It turns out that this is nicely explained by the P angle error mentioned in the first part of the poster, thereby providing a convenient connection between the two parts.

When observing near the equator it is seen that there is essentially no signal in the latitude direction. Given the projection effects and that fact that waves were seen propagating in the latitude direction near the equator in GDS is strong evidence that the waves have an almost purely horizontal displacement in the direction of propagation near the surface. It, unfortunately, also means that the waves traveling in latitude are essentially unobservable in surface Doppler shift at the equator and that the longitudinally propagating waves become difficult to observe at higher latitudes. This may explain the curious rotation results at $\pm 70^\circ$ latitude and the noisy meridional flow measurements near the equator.