The MDI Medium-l Program in Review

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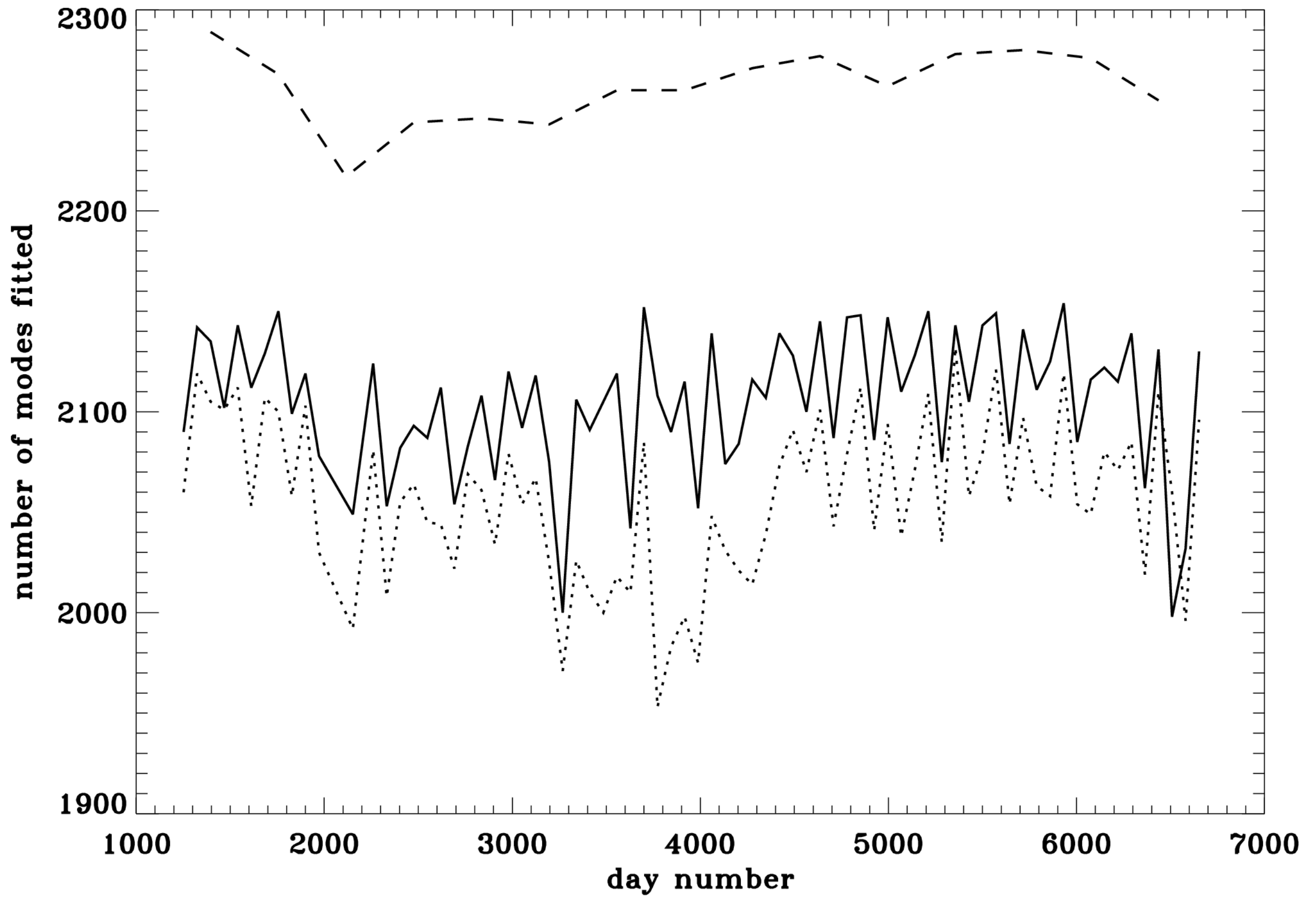
With the completion of the MDI Medium-l program in April 2011, we are now in a position to update its analysis in its entirety. Our previous work focused mainly on ten 72 day periods during the declining phase of the solar cycle, in which we applied a series of corrections and updates to the original analysis to see what effect each had on the mode parameters and systematic errors. We now extend this investigation to an analysis of the entire mission as a single timeseries spanning 5472 days, which will give us maximal signal to noise ratio and may yield expanded mode coverage. In order to see the solar cycle dependence we also analyze all the data in one year intervals, which will also shed light on the time dependence of our errors. Additionally we reanalyze all 74 of the original 72 day timeseries with and without asymmetric profiles to see if this has any effect on inversion results such as the torsional oscillation. Finally we repeat our earlier exercise for 10 periods during the rising phase of the solar cycle as a check of our previous conclusions.

Long Timeseries

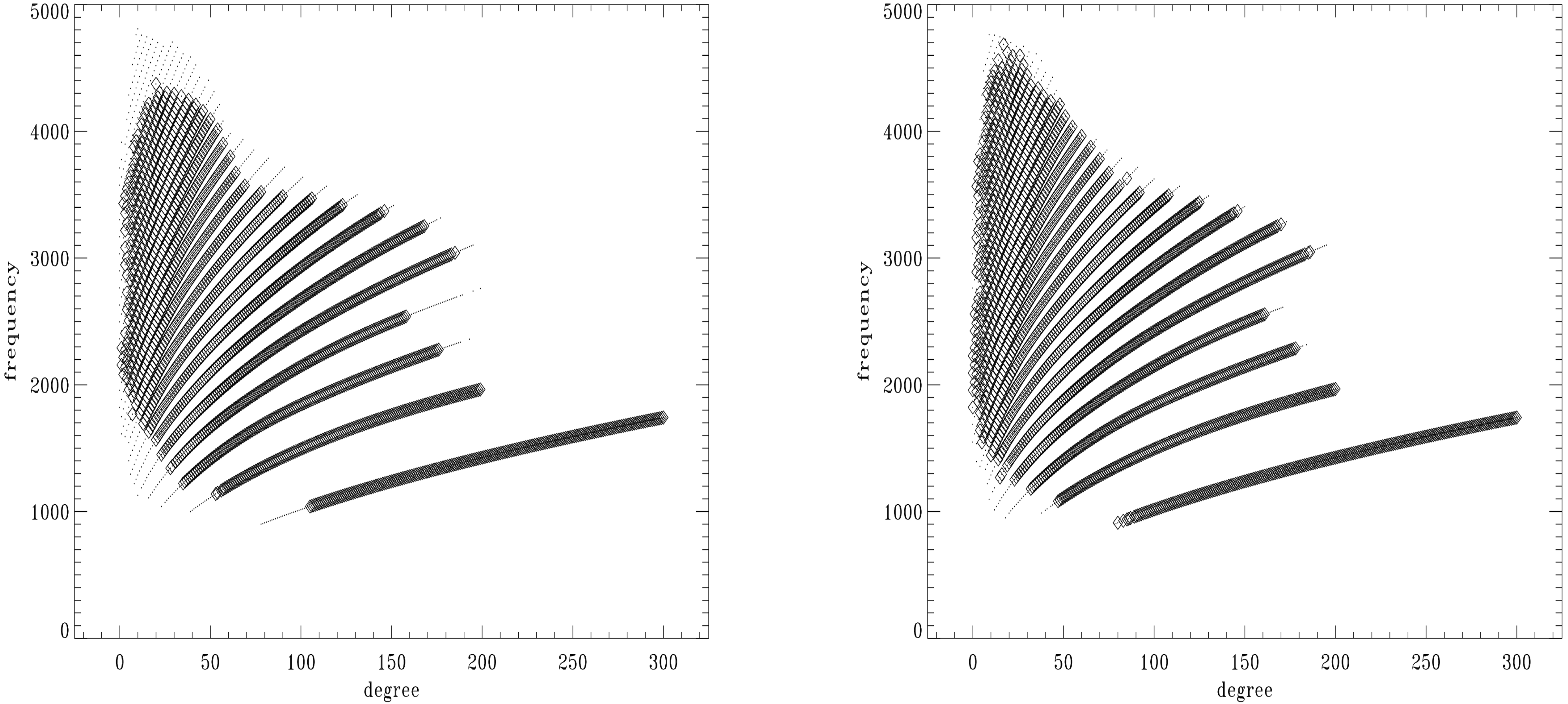
The entire mission has now been analyzed in four different ways:

- -the original analysis of the 72 day timeseries
- -using the same time periods with all corrections applied (see below) and symmetric line profiles
- -applying the same corrections to non-overlapping 360 day timeseries
- -using the original time periods with all corrections applied including asymmetric line profiles

The 5472 day timeseries have been created, but as it turns out there were unexpected technical difficulties in the peakbagging. The 360 day results, however, yielded encouraging mode coverage, as the following plots show.

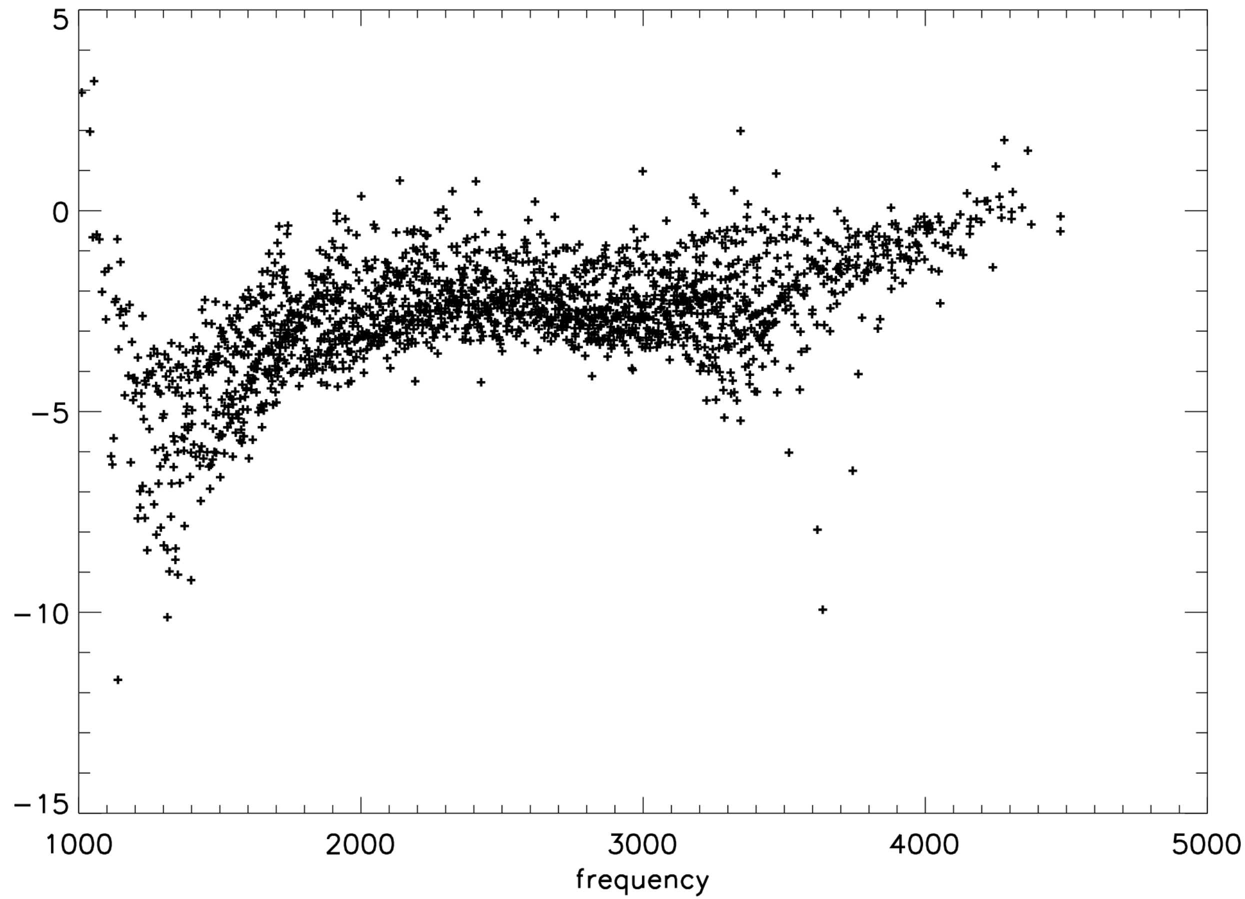


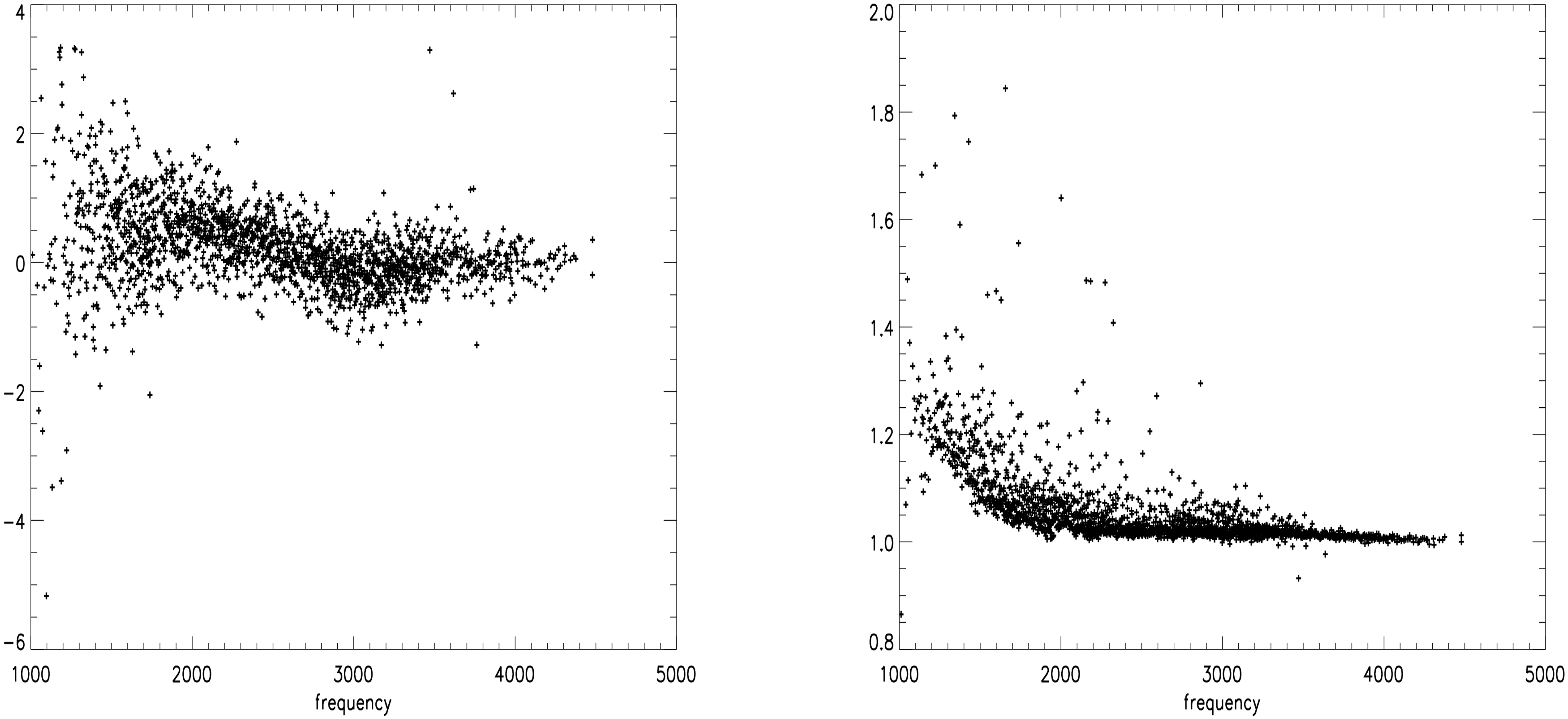
Mode coverage as a function of MDI day number. The dotted line is for the original analysis, the solid line is for the improved analysis, and the dashed line is for the 360 day timeseries. For the latter, the dip in the third year is because of the very low duty cycle (< 60%). Not shown is the mode coverage using the asymmetric line profiles, because that fitting requires automatic rejection of outliers between iterations of the peakbagging, and the mode coverage will depend on the rejection criterion.



Mode coverage for 72 day timeseries on the left, and for 360 day timsseries on the right, with the same set of corrections applied. Modes fit at least once are shown by a dot, modes fit at least 75% of the time are shown by diamonds.

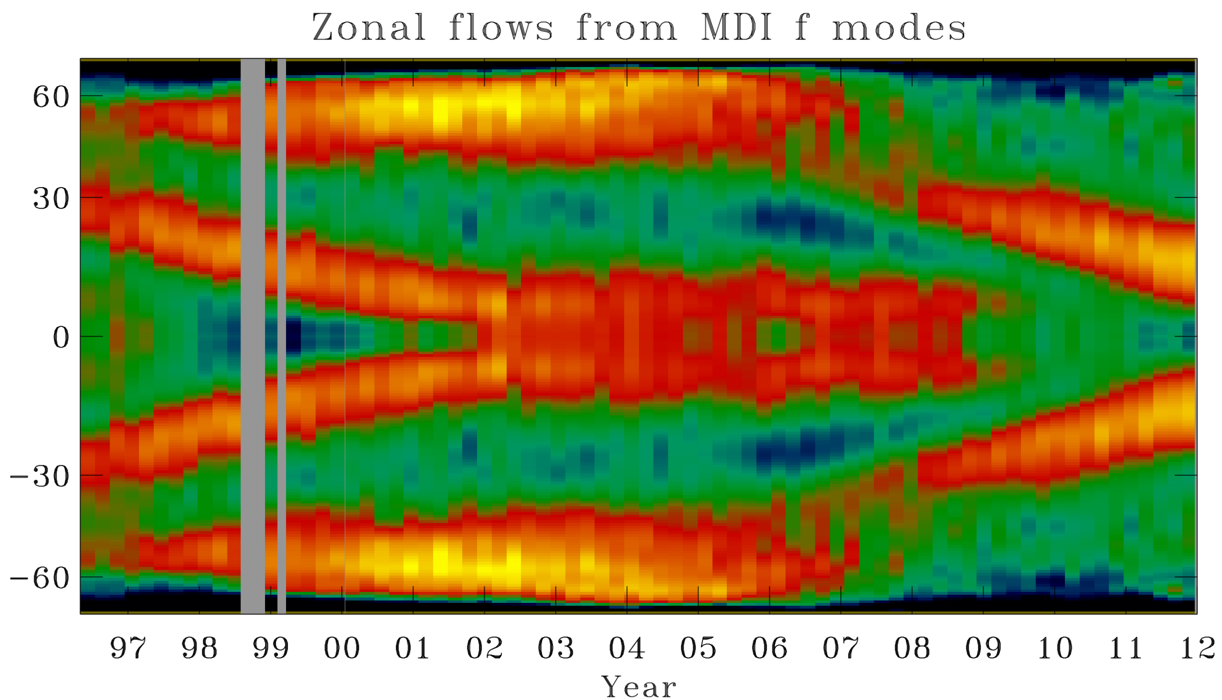
To examine the effect of the length of the timeseries on the mode parameters themselves, we took the modes that were present in all five 72 day fits covering a given 360 day interval, and took a straight average of the parameters. The most significant difference was for the widths, shown at right. Plotted are the differences in units of the standard deviation from the 360 day fits, versus frequency.





Left: frequency differences between the 360 day fits and the averaged 72 day fits, in units of standard deviation from the 360 day fit.
Right: ratio of the errors from the averaged 72 day fits to the errors from the 360 day fits. Note that the errors from a single 72 day fit would be larger by a factor of $\sqrt{5}$

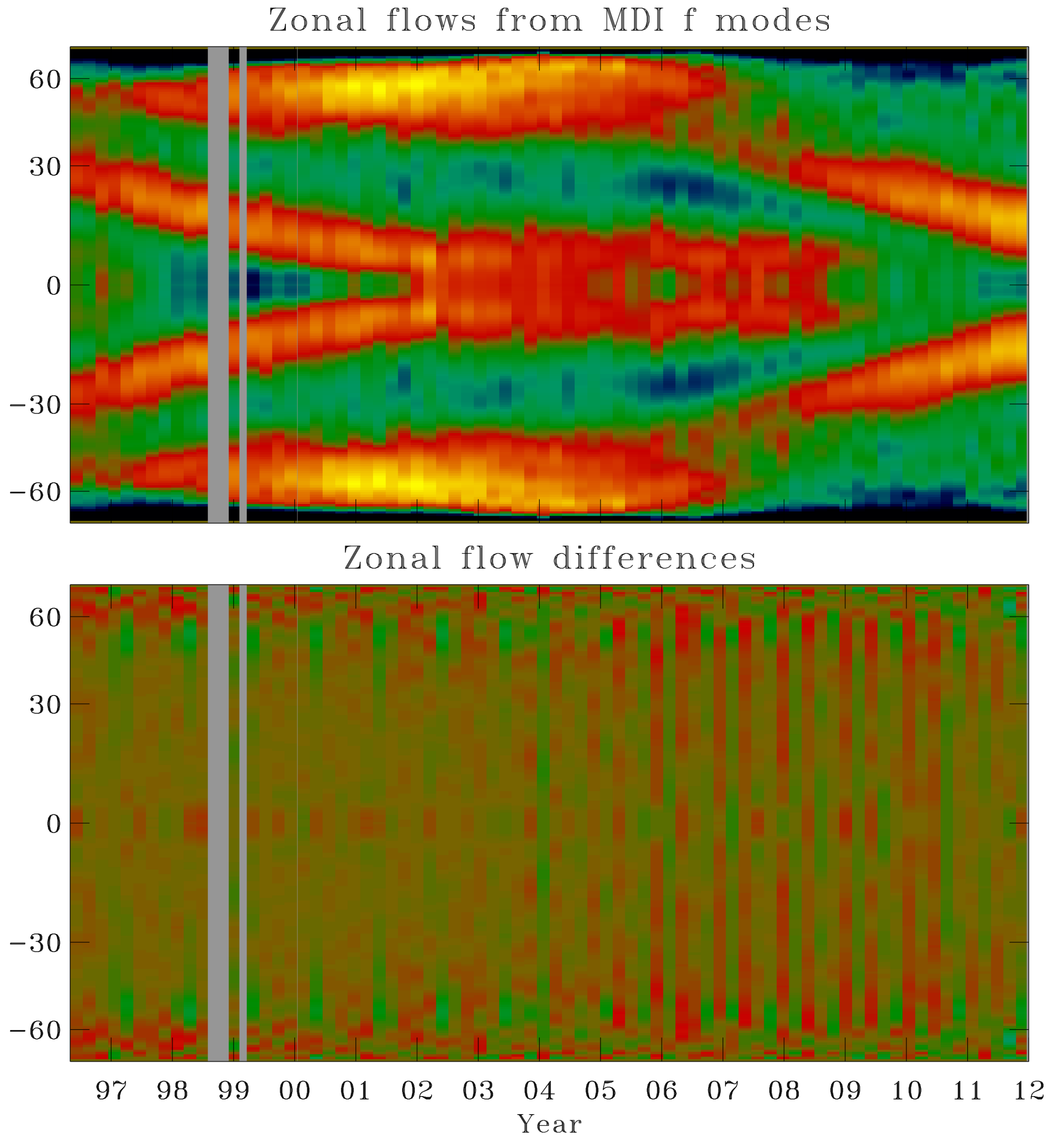
Torsional Oscillation Plots



Original analysis. The maximum range for all plots is ± 9 m/s.

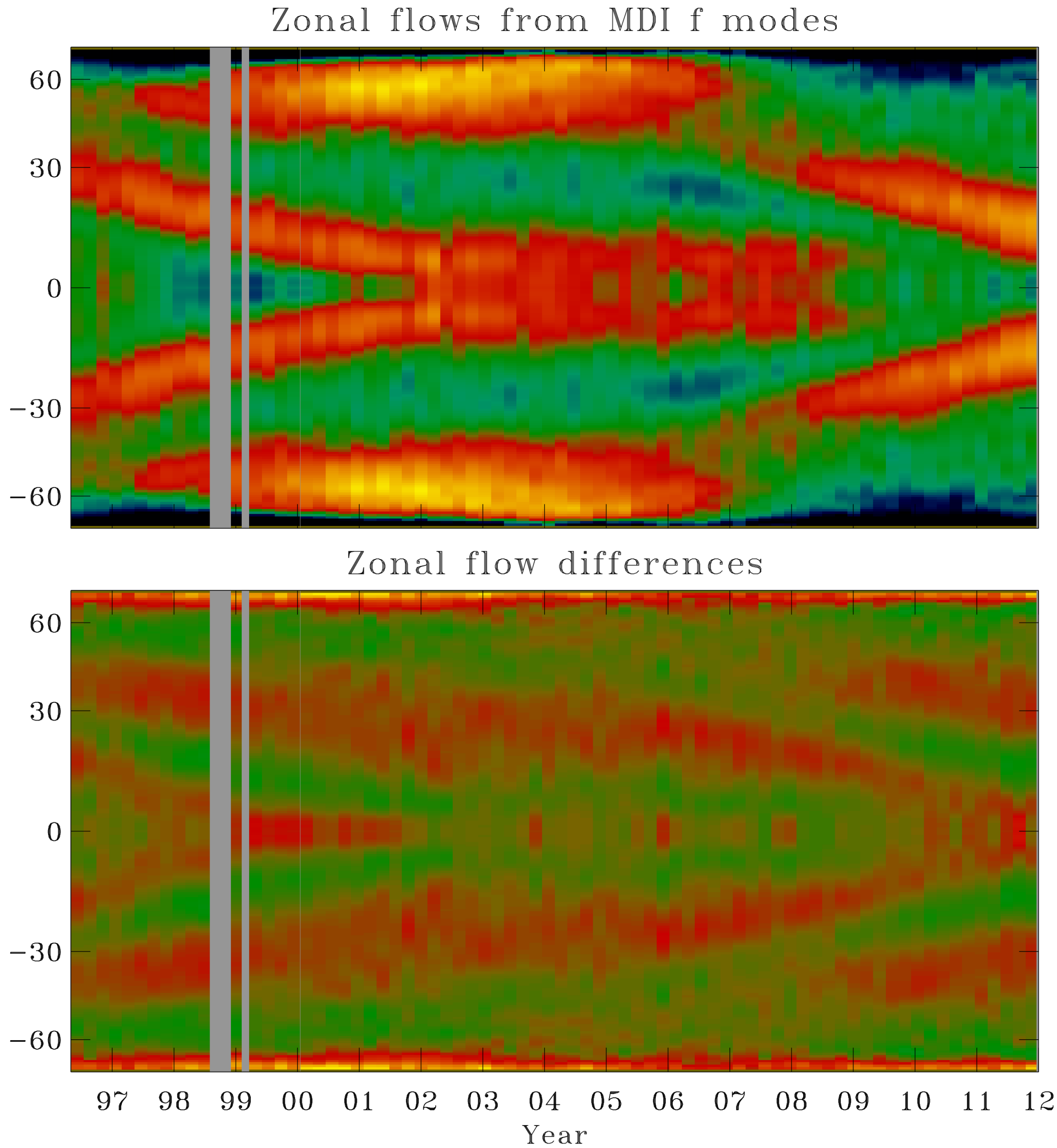
Top plot shows torsional oscillation for the improved analysis using symmetric line profiles.

Bottom plot shows the difference between the improved and original analysis.



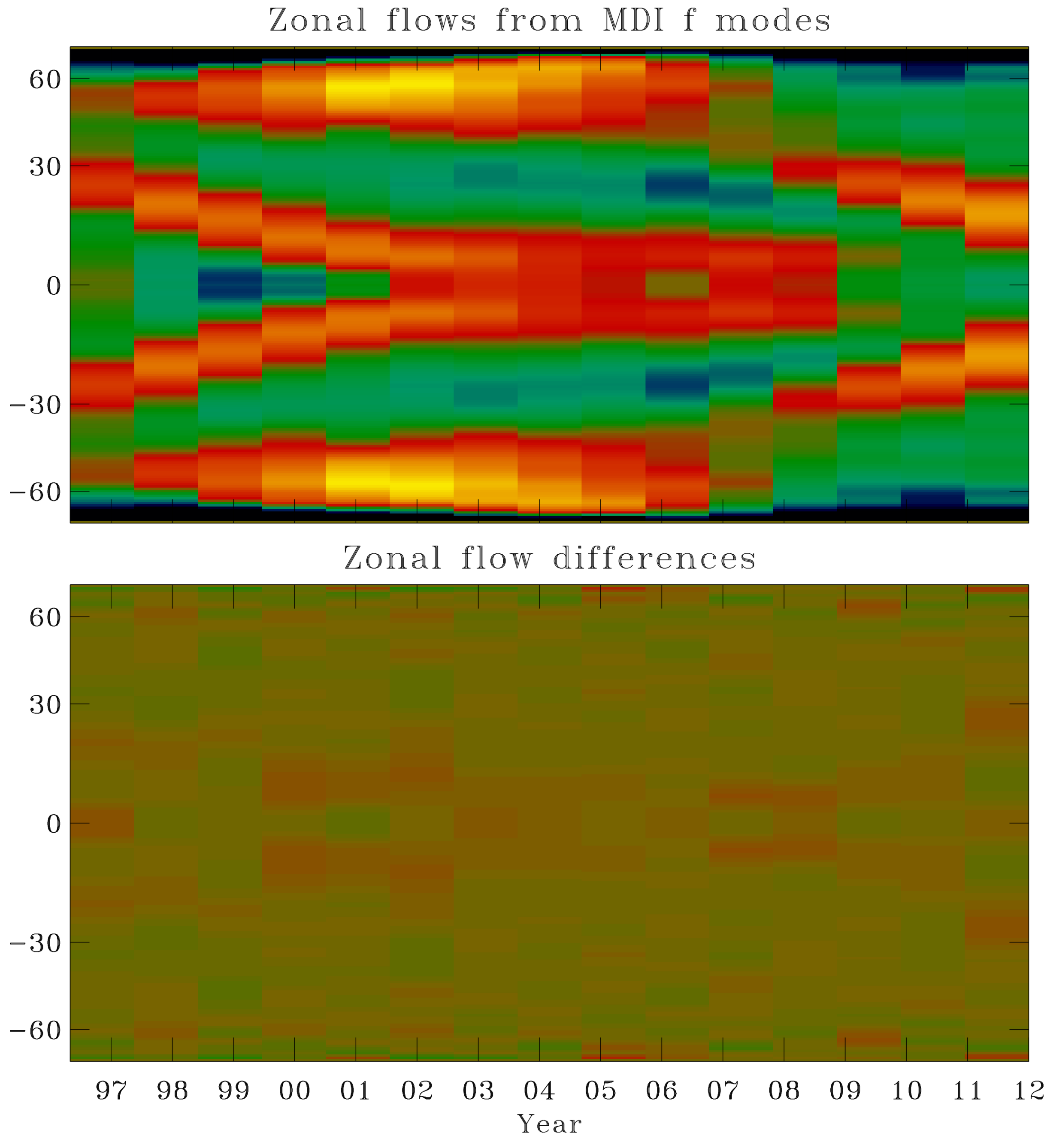
Top plot shows torsional oscillation for the improved analysis using asymmetric line profiles.

Bottom plot shows the difference between the asymmetric and symmetric fits.



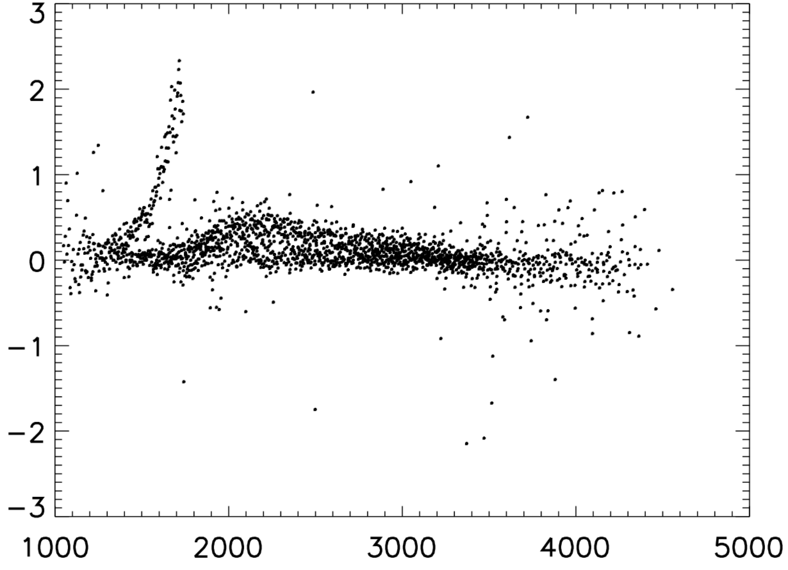
Top plot shows torsional oscillation for the 360 day timeseries.

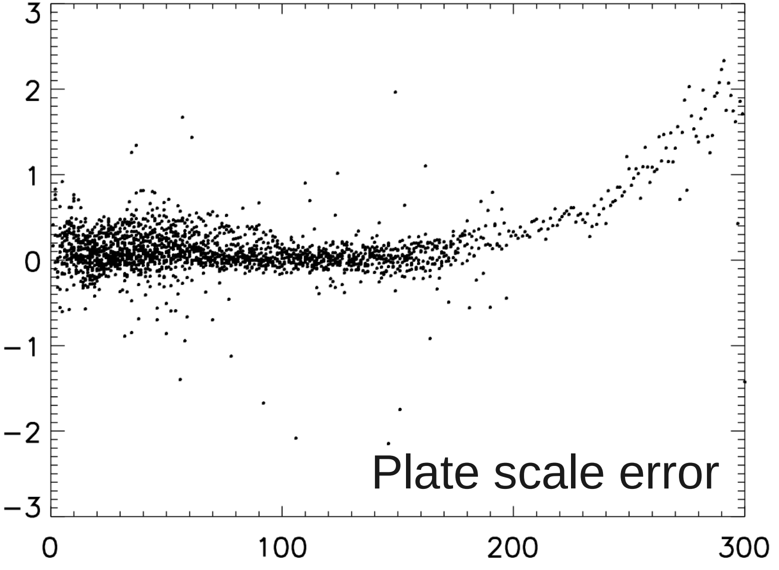
Bottom plot shows the difference between the 360 day results and the binned 72 day results.

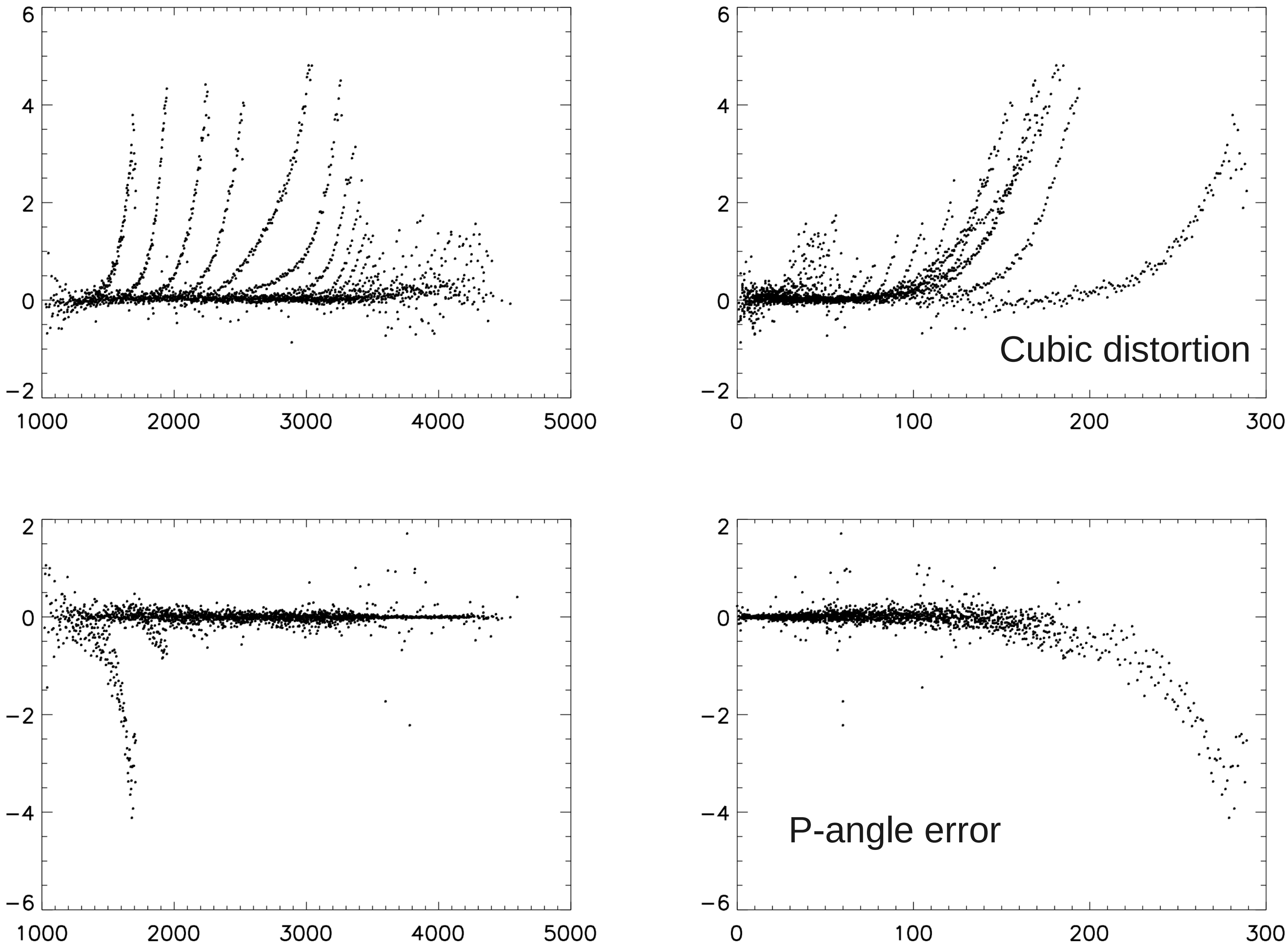


Corrections

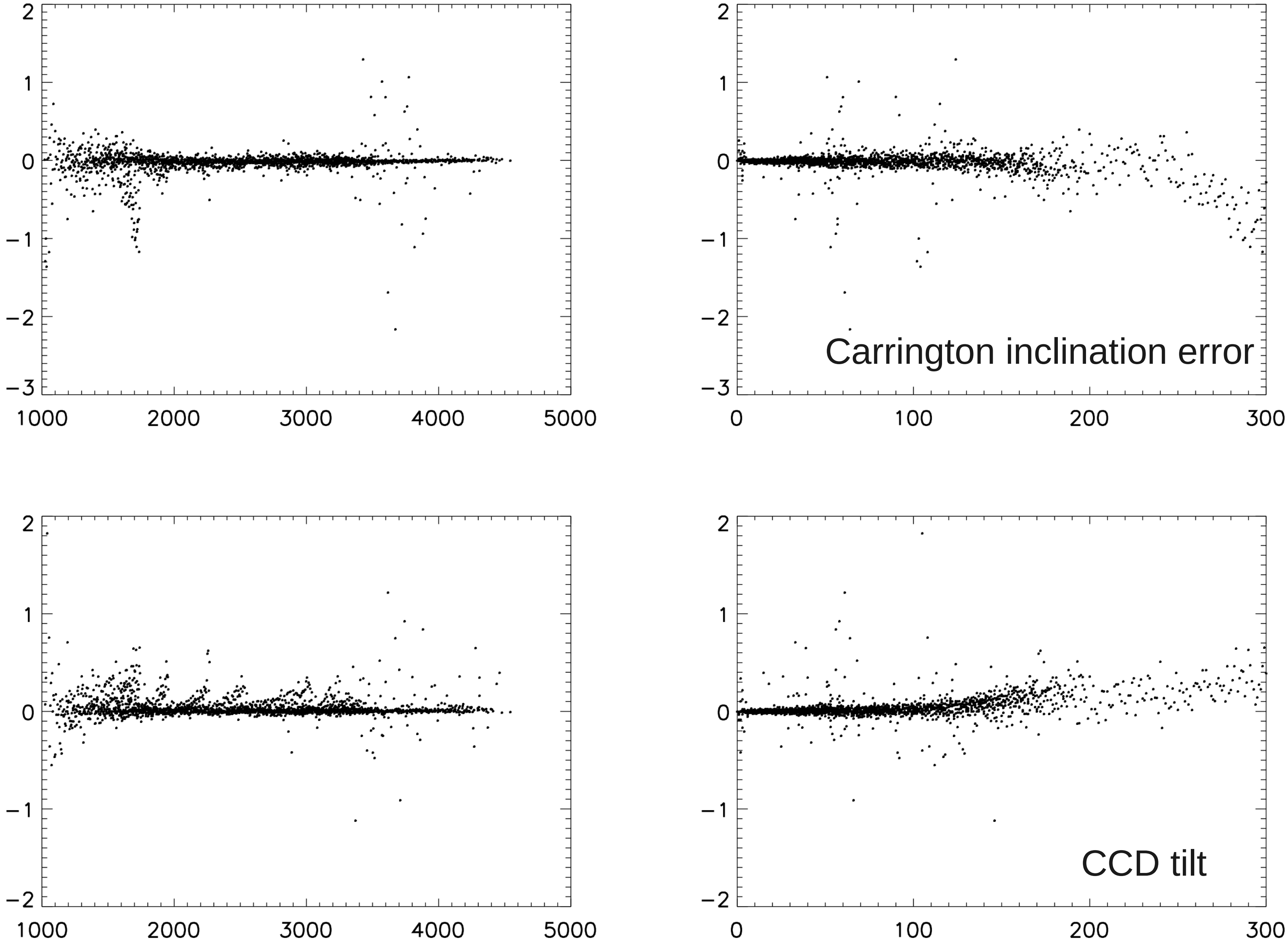
We apply 10 corrections or improvements to the calculation of the mode parameters in the following sequence: plate scale, cubic distortion, P-angle error, Carrington inclination error, CCD tilt, window function/detrending, gapfilling, horizontal displacement at the solar surface, distortion of eigenfunctions by differential rotation, and asymmetric line profiles. Each is applied to the first 10 72 day periods, and an average is found by taking the modes that were fit at least 70% of the time, fitting a second degree polynomial to each mode parameter as a function of time, and taking the average of the fit. Shown below are normalized frequency differences between each succeeding correction or improvement.

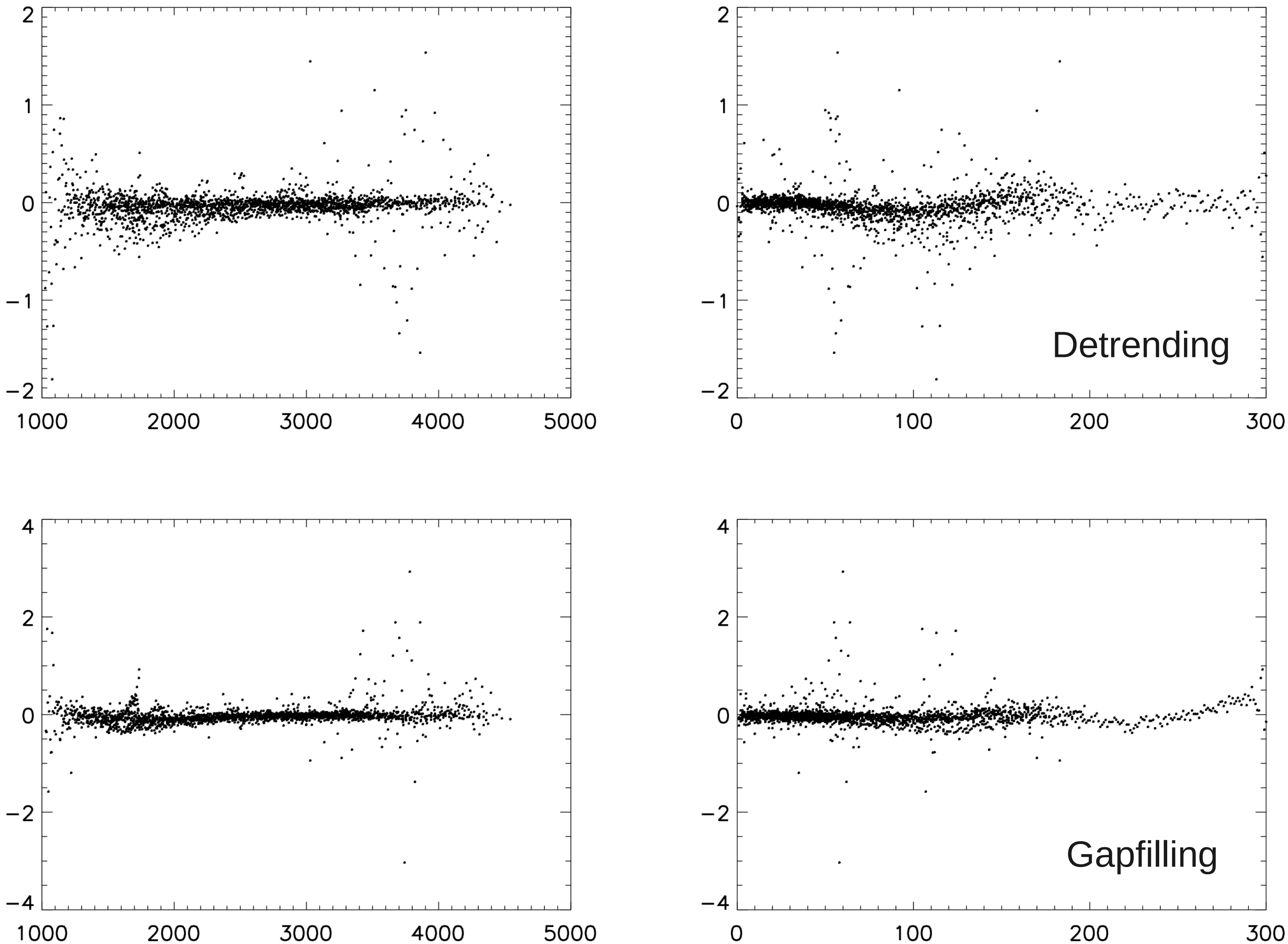




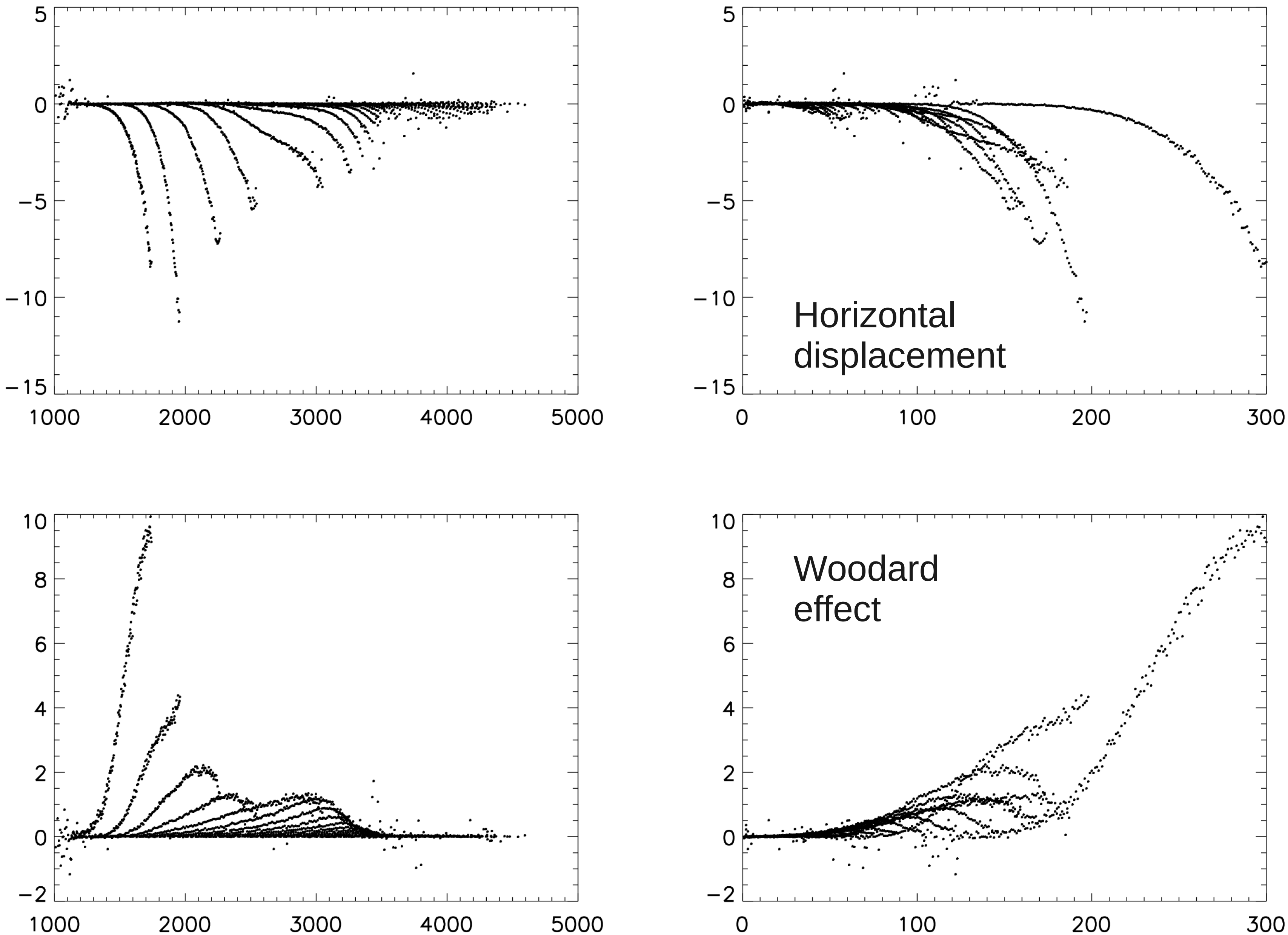


Cubic distortion
P-angle error
6
4
2
0
−2
−4
−6
1000
2000
3000
4000
5000
100
200
300

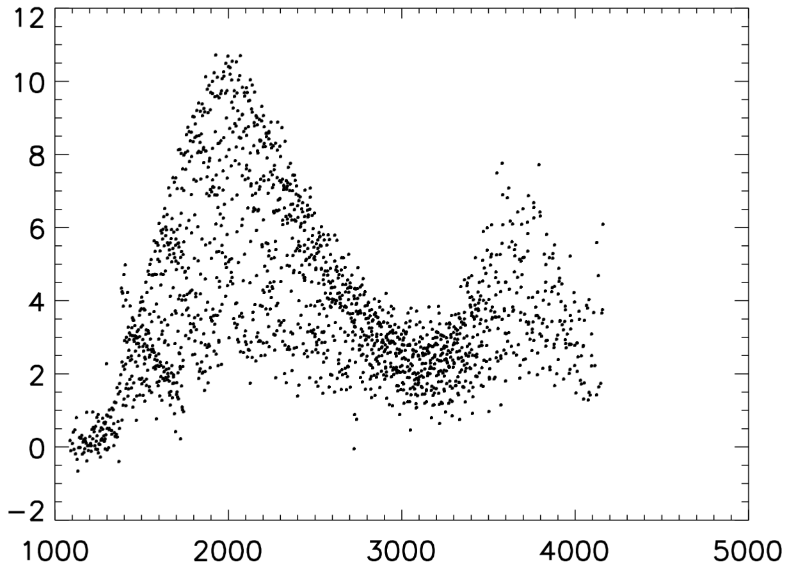

Carrington inclination error
CCD tilt
2
1
0
−1
−2
−3
1000
2000
3000
4000
5000
0
100
200
300

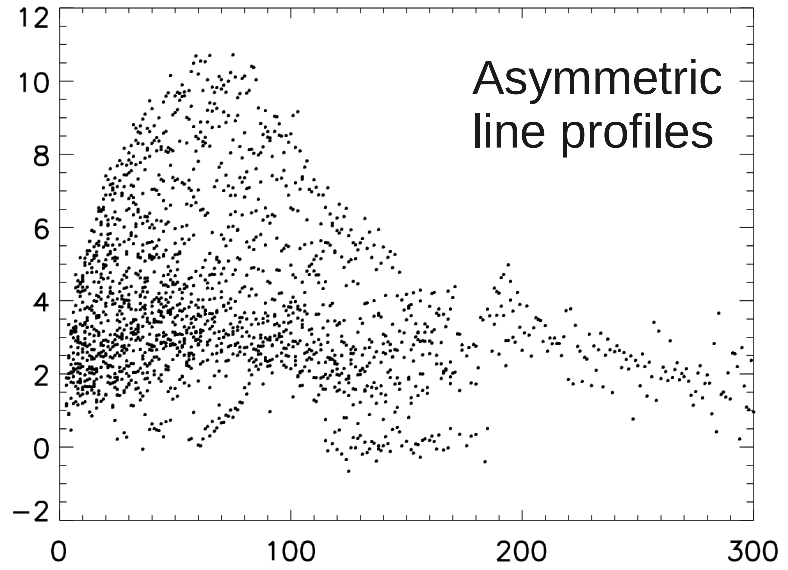


Detrending
Gapfilling



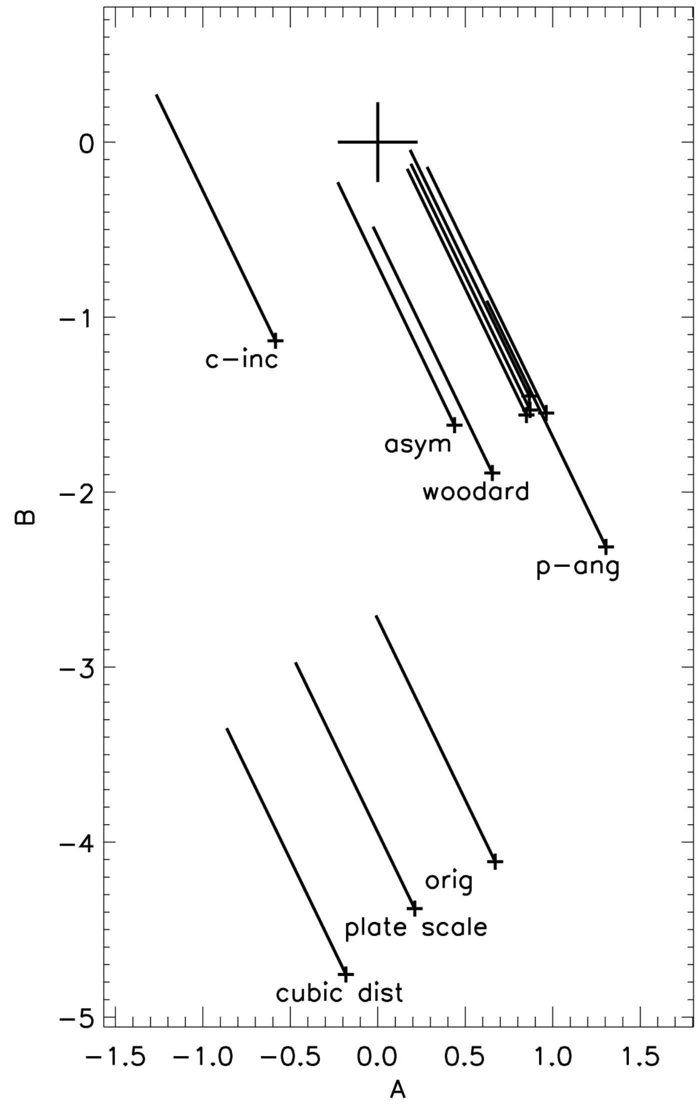
5
0
−5
−10
−15
1000
2000
3000
4000
5000
5
0
−5
−10
−15
Horizontal displacement
0
100
200
300
10
8
6
4
2
0
−2
1000
2000
3000
4000
5000
10
8
6
4
2
0
−2
Woodard effect
0
100
200
300





Frequency differences in units of standard deviation, on the left as function of frequency in microHz, on the right as a function of degree l.

One of the systematic errors we have sought to eliminate is a spurious one year periodicity in the fractional differences in the f-mode frequencies. To quantify this error, we fit a function of the form A*sin(ωt) + B*cos(ωt) + C*t + D to the f-mode frequency changes, where t is measured in days and ω=2π/365.25. This assumes the solar cycle dependence can be approximated as linear over this 720 day time period. To the right is a phase diagram showing the magnitude of the annual component for each analysis (marked with a +). We also corrected each analysis for the doppler shift of the f-mode frequencies caused by the spacecraft motion, which caused the points to shift as indicated. These results are basically consistent with what we found earlier, although now applying the doppler correction puts us much closer to the origin with all corrections applied.



Conclusions

The 360 day timeseries yielded significantly expanded mode coverage and smaller errors at low frequencies. The parameters themselves were mostly in agreement, although the widths were smaller for the longer timeseries, especially at low frequences, and there is a hint of a trend in the frequency differences.

Using asymmetric line profiles changed the amplitude of the torsional oscillation, especially around the edges of the bands. These fits also yielded less mode coverage, however, and we have not yet inverted a common mode set. In the future we hope to expand the mode coverage of the asymmetric fits by tuning mode rejection.

Applying all of the corrections one by one yielded results mostly consistent with what we found before. Some of the differences may be due to the different order in which the corrections were applied, but the decreased importance of the plate scale correction was certainly because the original plate scale used was better at the beginning of the mission. The corrections applied in the peakbagging were the most signifcant.