Splittings of MDI low-degree p modes

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ABSTRACT

We use a MDI 180-bin time series of 679 days to build l=1 and 2 m-ν diagrams and an integrated velocity spectrum. From both spectra we derive sidereal splittings and show a good agreement. Nevertheless, for l=1 the splitting determination from the 1-pixel time series seems to be slightly overestimated compare to what we get from m-ν diagram fitting. Cutting the time series in two pieces, we also show that the first and second-half of the time series lead to splittings in good agreement though for m-ν diagrams the second half give splitting higher by 20 and 10 nHz for l=1 and 2, respectively. We also demonstrate that taking into account the asymmetry in the p-mode line shape doesn't change the splittings significantly.

Key words: p-modes; splitting.

1. INTRODUCTION

It is well-known that splittings of low-degree solar p modes are numbers which are difficult to measure accurately because they are small and weakly constrained when fitted. From the beginning of the eighties up to now the mean splitting measured over the 5-minute range has decreased by a factor of 2. From roughly 1 μHz with the first attempts to about 0.45 μHz with the most recent estimations (Chaplin et al., 1996; Appourchaux et al., 1997, Lazrek et al., 1997; Gizon et al., 1997). Toutain and Kosovichev, 1994 have shown with the IPHIR data that constraining the splittings can drastically change the value of the mean splitting. This problem arises especially when fitting integrated spectra because of the overlaping of the m-components in a same multiplet. For that reason, the low-order p modes (below 2 mHz) are supposed to give better splittings because they have smaller linewidths. Nevertheless inversion of the solar core rotation requests a set of low-degree p-mode splittings as large as possible. It is therefore important to also measure the splittings for modes between 2 and 4 mHz as accurately as possible. With SOHO we have access to imaged helioseismic data of long duration and high quality. In this paper we use a 180-bin time series of 679 days from MDI (Scherrer et al., 1995; Hoeksema et al., 1998) to measure the splitting of low-degree p-modes for l=1 and 2 and n=8-28. We apply optimal masks to the time series to get cleaned m-ν diagram for l=1 and 2. From the 180-bin time series we also produce an integrated velocity signal in order to compare the splitting determination using resolved and integrated spectra. Finally we discuss the influence the line-shape model has on splitting measurements.

2. TIME SERIES AND FITTING TECHNIQUE

We have gathered a time series of 679 days using the MDI low-l data (Scherrer et al., 1995). The 180 bins of this dataset are weighted and added together using an optimal-mask technique (Kosovichev,1988; Toutain and Kosovichev, 1997). The advantage of this technique is to minimize the crosstalks between adjacent modes and thus to minimize their effect on splitting determination. Nevertheless as shown by Appourchaux et al.(1998) it is also possible to diagonalize the so-called leakage matrix and get similar results. We have worked on degrees l=1 and 2 only because they are the modes which provide most of the information on splittings in integrated velocity spectra. The fitting technique is a maximum likelihood fitting method performed in the Fourier domain for m-ν diagram (Schou, 1992; Appourchaux et al., 1997) and in the power domain for the integrated signal using a Lorentzian profile (Anderson, 1990). It is important to note that we assumed the amplitudes of the split components to be different.

3. SPLITTINGS

Using the full time series we have built 2 time series of 1 year with an overlap of 2 months and we have measured the splittings for l=1,2 for each of the three time series : first year, second year and 679-day time series. Figure 1 shows the l=1 sidereal splittings as a function of mode frequency for both integrated (thick line with diamonds) and resolved signals (thin line with stars). Top panel is for the first year of data, middle panel is for the second year and bottom panel is for the 679-day time series. Obviously resolved signals lead to more stable splittings especially for l=1. Above 3 mHz the estimation of l=1 splittings from integrated signal is rather difficult whereas with resolved signal it is still possible to measure splittings up to 3.5-3.8 mHz. For l=2 the increase of the number of mode multiplets helps in both case to get stable splittings. It is interesting to note that even with 2 years of data low-degree splittings are largely scattered, especially l=1 splittings. Tables 1 and 2 give the weighted mean of splittings for l=1 and 2. The weights are taken as the inverse of the square of the formal error of the splittings as it comes out from the fitting.

For l=1 the mean splitting for integrated velocity seems to be systematically higher than for resolved signal by about 20 nHz. This effect was already described by Appourchaux et al.(1998b) and Chang et al.(1998). They show with Monte-Carlo simulations that both mode blending, mode correlation or not constraining the amplitudes of m=±1 to be the same can lead to overestimate l=1 splittings. The bias in splitting determination is a function of linewidth, signal-to-noise ratio and observation duration.

For l=2 we find a good agreement between splitting for integrated and resolved signal. Nevertheless from Monte-Carlo simulation we come also to the conclusion that not constraining the relative amplitude of m=0,±2 can lead to overestimate l=2 splittings though to a smaller extend than for l=1. As expected m-ν diagram fitting gives smaller error bars because of the larger number of modes to fit. It is also noticeable that within the error bars the splittings are not changing with time, though the resolved data seem to indicate a small but systematic increase of the splitting between the first and second year. Nevertheless residual of crosstalks between modes can produce such an effect (Appourchaux et al., 1998a) and a more careful analysis is needed to confirm or not this time-dependence of the splittings.

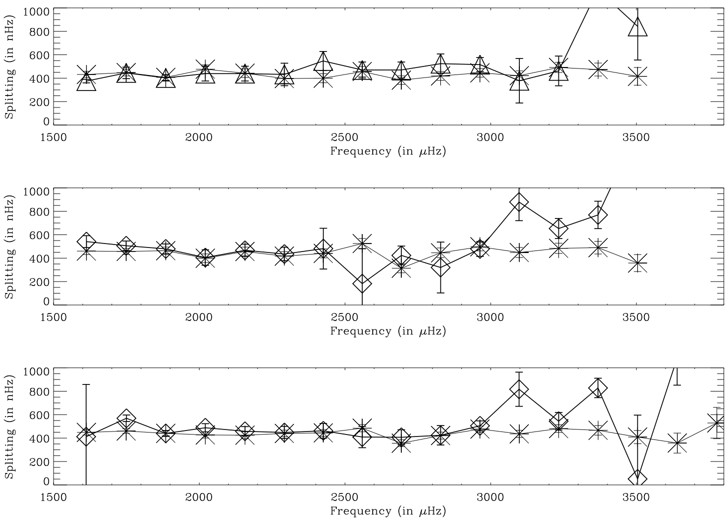

Figure 1. Sidereal splittings for l=1 as a function of mode frequency for integrated spectra(thick line with diamond symbols) and m-ν diagram (thin line with star symbols). Top panel is for the first year of data, middle panel is for the second year and bottom panel is for the full time series.

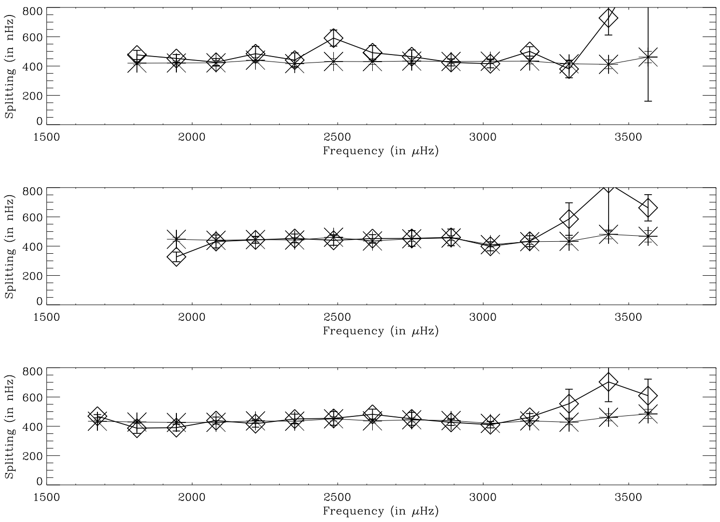

Figure 2. Sidereal splittings for l=2 as a function of mode frequency for integrated spectra(thick line with diamond symbols) and m-ν diagram (thin line with star symbols). Top panel is for first year of data, middle panel is for the second year and bottom panel is for the full time series.

Table 1. Mean sidereal splitting (in nHz) for l=1 and order n=12-21.

Signal	First year	Second year	679 days
integrated	441± 18	462 ± 23	461 ± 14
resolved	423± 11	441 ± 12	436 ± 9

4. EFFECT OF LINE ASYMMETRY ON SPLITTINGS

P-mode lines seems to exhibit a small line asymmetry which lead to mode frequency differences between velocity and intensity data (Toutain et al., 1997). In order to test the effect of asymmetry on splitting determination we have fitted the same data using a line profile as given by Nigam and Kosovichev (1998) instead of a Lorentzian profile. Moreover we have assumed that all components in a same rotational multiplet have a same asymmetry. Figure 3 shows the splitting measured with the asymmetrical profile both for l=1 (top panel) and l=2 (bottom panel) for the 679-day time series and table 3 gives the corresponding weighted mean splittings. A straight com-

Table 2. Mean sidereal splitting (in nHz) for l=2 and order n=12-21.

Signal	First year	Second year	679 days
integrated	451± 11	428 ± 11	431 ± 8
resolved	429± 5	442 ± 5	434 ± 4

parison between tables shows that as expected the splitting is a quantity which is not really sensitive to the line asymmetry. Therefore Lorentzian fitting does not bias the determination of splitting as it does with frequency if the line is asymmetric.

Table 3. Mean sidereal splitting (in nHz) for l=1,2 and order n=12-21 taking into account line asymmetry.

Signal	l=1	l=2
integrated	458± 15	429 ± 8
resolved	436± 9	434 ± 4

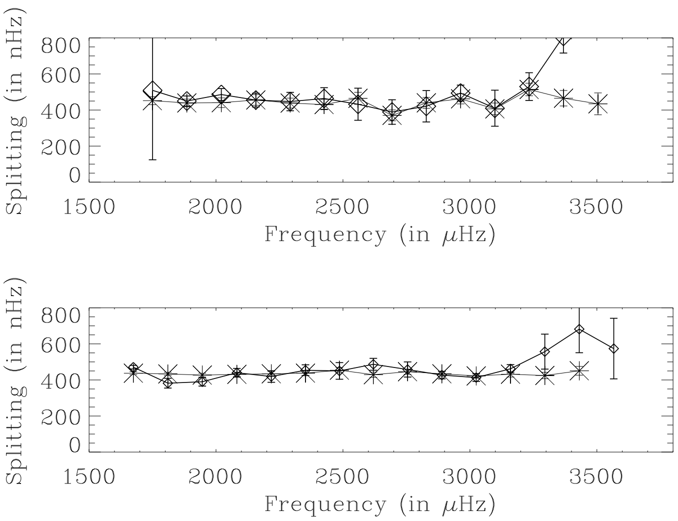

Figure 3. Sidereal splittings for l=1,2 as a function of mode frequency for integrated spectra(thick line with diamond symbols) and m-ν diagram (thin line with star symbols). Top panel is for l=1, bottom panel is for l=2. Full time series is used and line asymmetry is taken into account.

5. INVERSION

We have combined the low-degree p-mode splittings with splittings of 360 days of medium-l data from MDI. The rotation profile shown in Fig. 4 is obtained inverting these splittings with a optimal averaging technique. The results are plotted against the target positions of the averaging kernels, and thus represent a smooth extrapolation towards the center consistent with the data. The bump around 0.5 R comes from the medium-l data. Resolving the solar core needs obviously more splittings with a more accurate determination. Nevertheless a constant rotation rate below 0.4 R agrees well with the measured splittings.

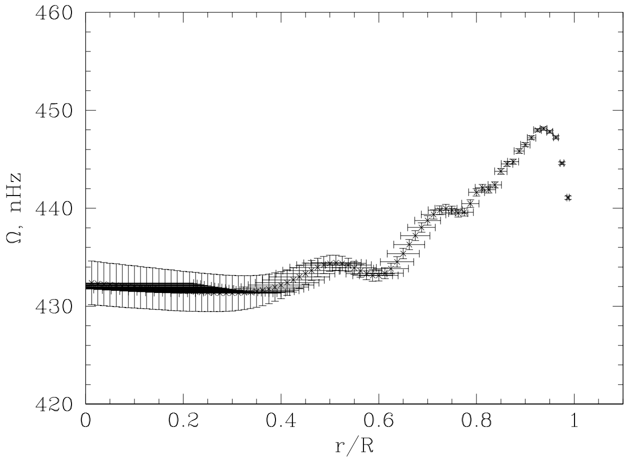

Figure 4. Rotation profile using low-degree mode splittings combined with MDI 360-day medium-l splittings.

6. CONCLUSIONS

Using two years of MDI data we have shown that the splittings of low-degree p modes are still difficult to be accurately measured. Depending of the method we use : fitting integrated velocity spectrum or m-ν diagrams, we get a slightly different mean splitting for l=1. The first method gives a mean splitting (461 ± 14 nHz) which is higher than the mean splitting obtained with the second method (436 ± 9 nHz) though in agreement within the error bars. The discrepancy is likely to be due to an effect of the mode blending in the integrated velocity spectrum or to the fact that the mode amplitude of m=±1 are assumed to be different when fitting l=1 modes in the integrated velocity spectrum. For l=2 both methods give almost the same mean splitting : 431 ± 8 nHz and 434 ± 4 nHz, respectively. Within the error bars the splittings for l=1,2 are almost time-independent though resolved data seem to indicate a small increase with time of the mean splitting. We have tested the effect of line asymmetry on the determination of splitting and found that splittings are not sensitive to the line profiles we used for fitting.

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