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# Analysis of asymmetric $p$-mode profiles in GOLF data

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**Abstract.** We show here evidence for the necessity of an asymmetric form in modelling the profile of an acoustic mode in the power spectral density. The analysis was performed on a 805-day series of GOLF data ($\ell$=0 to 3). The assumptions used for the fits are discussed and their consequences quantified, in particular for the optimum choice of the fitting spectral window. Values are given for the bias on the mode parameters (frequency, width, splitting) when using a Lorentzian fit. The bias depends on the degree $\ell$ and on the frequency, and when taken into account leads to variations in the mode parameters with degree more consistent with theoretical expectations.

**Key words:** methods: data analysis – Sun: oscillations – Sun: interior

## 1. Introduction

For many years now, the analysis of increasingly precise $p$-mode data has been used to understand the internal structure of the Sun. Only the low-$\ell$ modes (those with $\ell < 4$) are effective in providing information about the Sun's central regions and these can be observed using the integrated light from the entire solar image. Since these modes contain integral information from the entire Sun, inversion to give the core structure requires also a good precision for the higher-$\ell$ modes localised in the outer layers. It is the precise frequencies of the mode resonances which are important for determining the speed of sound in the interior of the Sun. On the other hand, the multiplet splittings can offer knowledge of the internal rotation, and the resonance widths carry information on the excitation and damping of the modes.

All of these parameters are determined through a fit of theoretically expected profiles to the Fourier spectrum of the observed oscillations. However, this procedure is complicated by a number of difficulties. These include the stochastic nature of the excitation process, the existence of a background solar noise or "continuum", the close multiplet structure of many modes due to rotational splitting and the effects of overlapping wings from the many neighbouring resonances. To these must be added "noise" introduced by the instrumentation and by any lack of continuity in the observing sequence.

A commonly accepted representation of the resonance profiles has been as pure Lorentzians in Fourier space as would result from the transform of a damped sine-wave (Anderson et al. 1990). However, in the last few years, attention has been drawn to the possible asymmetry of these resonances (Duvall et al. 1993, Gabriel 1993, Abrams & Kumar 1996, Toutain et al. 1997). As we discuss later, the fitting of asymmetric profiles results in a small systematic shift in the measured frequencies. The application of a uniform shift appears to have very little influence on the inverted solar core parameters, which are related more to *differences* between frequencies. To improve the interpretation of the core, we are therefore looking for the slope, or higher order effects, in the resultant corrections.

It is clear from the above that we are interested in the highest possible precision in measuring these frequencies. It is with the much improved observing conditions from space using the SOHO instruments that we can hope to advance these studies. A recent study by Toutain et al. (1998) has interpreted some first results of the low-$\ell$ asymmetries from VIRGO and MDI. Here we analyse the results from GOLF. The GOLF instrument has produced, up to the temporary loss of SOHO in June 1998, an 805 day time series of data with exceptional stability and continuity (greater than 99 %). In this paper we measure the corrections to frequencies, splittings and line-widths obtained from asymmetric fitting.

## 2. Mode asymmetry

The use of an arbitrary asymmetric form for the fitting profile may serve to improve the quality of the fit, but it cannot provide us with a valid resonance frequency. By assuming a physical ba-

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sis for the asymmetry and adopting a derived parametric form for the fitting profile, the resonance frequency is obtained as one of the parameters in the fitting process. This frequency corresponds neither with the maximum, nor the centroid of the profile, but is systematically to one side. It is for this reason that fitting an asymmetric resonance with a Lorentzian profile leads to systematic errors in frequency.

In many areas of physics, the mixing of a resonant frequency with the nearby spectral continuum leads to an asymmetric profile, when the continuum is correlated with the resonance. This arises because the reversal of phase at the resonant frequency leads to a switch from addition to subtraction with the continuum. This effect, well-known in atomic spectroscopy, produces the familiar Fano profiles in autoionising lines, seen in absorption (Fano 1961).

In helioseismology, asymmetry has been interpreted by a number of authors (Duvall et al. 1993, Abrams & Kumar 1996) as due to the interaction between the resonant cavity mode and the local emission from discrete sources. However, this effect alone failed to explain the observation that the sign of the asymmetry is reversed when viewed in intensity and velocity. Recently, Nigam & Kosovichev (1998) modified the principle by adding also a correlation between the resonance and the background continuum, or solar noise. Since the solar noise, or granulation, is regarded as the source of excitation of the modes, it is reasonable to suppose that a part of this noise would be correlated with the modes. After some simplifying approximations, they offer the expression:

$$P(x) = A\frac{(1+Bx)^2+B^2}{1+x^2}+n \qquad (1)$$

suitable for fitting to the observed spectrum where $x = 2(\nu - \nu_0)/\Gamma$ and $A, \Gamma, \nu_0, n$ are the mode amplitude, linewidth, central frequency and uncorrelated linear background noise respectively. The parameter $B$, which controls the asymmetry, contains the effects of correlated noise and of the source, the two factors that are claimed to be responsible for asymmetry. It is with the use of this expression that Toutain et al. (1998) have successfully explained the difference in sign between VIRGO and MDI asymmetries, confirming Nigam's predictions. Until the availability of this formula, we had been studying the asymmetry in GOLF using the Fano profiles (Thiery 1997), which include only the effect of interaction with the continuum. The present work has been carried out using Nigam's formula. Fig. 1 shows a typical example of a Lorentzian and an asymmetric fitting to a GOLF resonance.

## 3. Fitting the GOLF data

The GOLF series used covers the 805 days between April 11, 1996 and June 25, 1998, with more than 99% continuity. The GOLF raw data have been converted to velocities using the calibration techniques described by García (private communication) prior to carrying out an FFT transform on the entire series, with a sampling time of 80 seconds. Only the GOLF detector PM2 has been used in this analysis.

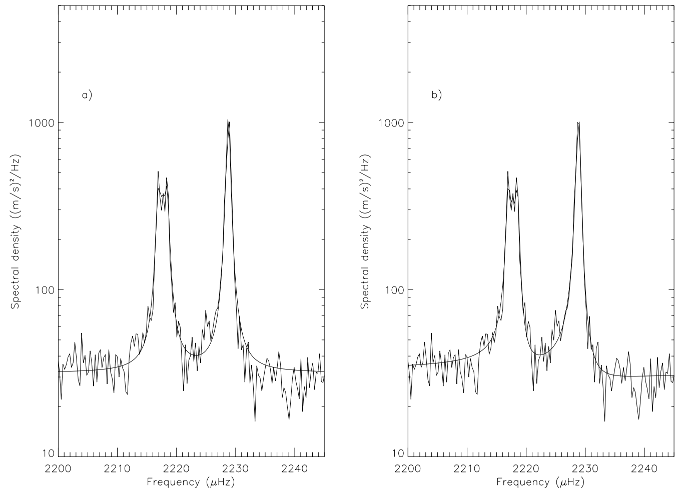


**Fig. 1a and b.** Example of fitting (modes $\ell$=0, $n$ =15 and $\ell$=2, $n$ =14) using Lorentzian profiles **a** and Nigam profiles **b**. Note the improved agreement (visible in the wings) between the fit and data when the asymmetry is taken into account. The resolution for the plot is reduced to 0.29 $\mu Hz$.

The classical fitting technique in this domain consists of fitting a simple Fourier power spectrum, often using codes derived from those offered by Appourchaux et al. (1998). For such a spectrum, $\chi^2$ statistics are applicable and the fitting is then by the *maximum likelihood method*.

The entire analysis was limited to the spectral range 2000 $\mu Hz$ to 3600 $\mu Hz$. Our objective requires very high precision, which we cannot obtain reliably outside of this range. Above 3600 $\mu Hz$ the modes overlap seriously. Below 2000 $\mu Hz$, the signal to solar background ratio is smaller and, more importantly, the number of bins which contribute to the line is small due to the smaller linewidth. These limitations are particularly critical for the asymmetry parameter.

A critical point is the choice of the spectral window used for fitting the p-modes profiles, i.e. how much of the spectrum we fit at a time. Some workers choose to fit the entire $p$-mode spectrum, arguing that this is the only way to correctly take account of the effect of the far wings from distant modes (Roca Cortés et al. 1998). This can be done only if the model profile assumed for the modes is valid everywhere in the window or if the residual errors are negligible compared with errors due to the stochastic noise. It also assumes that the overlapping far wings are additive on a scale of spectral power, which is not evident. As the Nigam formula used in this paper is obtained by a Taylor expansion around the eigenfrequency of the mode (Nigam & Kosovichev 1998), we adopted the approach of fitting only those close multiplets that have an evident overlap, i.e. fitting was carried out over limited spectral ranges with the neighbouring $\ell$=0 and $\ell$=2 grouped together, as were the $\ell$=1 and $\ell$=3. The choice of a precise window is discussed in Sect. 5 and corresponds to a trade off between the effects of the stochastic noise and of the validity of the formula. This alternative to a fit of the whole spectrum has the cost of considering the contribution of other resonances as a flat "background". In all cases, there ex-

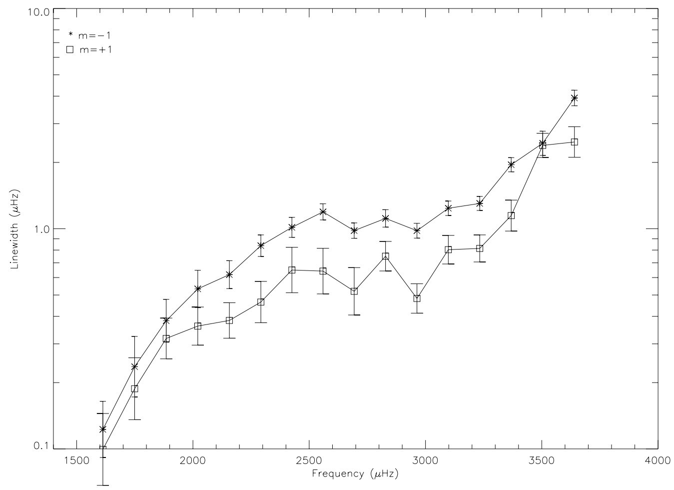


**Fig. 2.** Linewidth of the components of the $\ell$=1 modes using a Lorentzian fit, when both widths are independent free parameters.

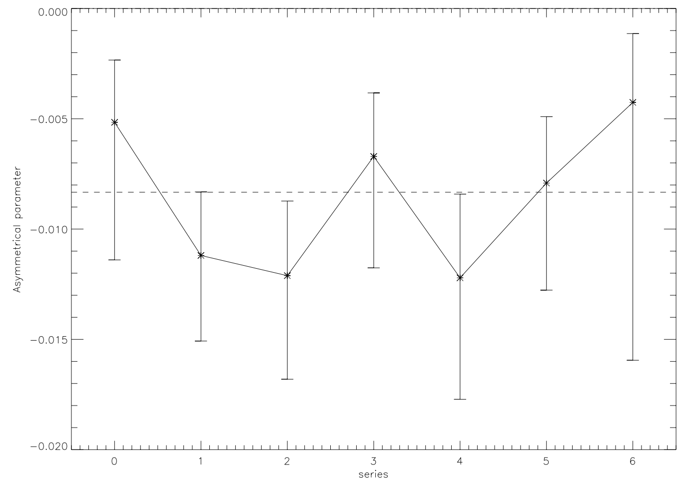


**Fig. 3.** The asymmetric parameter for independent successive 115 days sub-series (example of the mode $\ell$=0, $n$=20). The dashed line corresponds to the value obtained from the entire time series.

ists an unknown continuous component due to solar noise (plus perhaps instrumental noise) for which arbitrary parameters are used. In the present work, we performed tests and simulations to quantify the errors due to our assumptions. These include that the background is represented by a constant value, the slope being assumed to be zero over the limited range of window. All of the components in the fitted range were assumed to have the same asymmetry factor, but the linewidth was allowed to vary with the degree. The relative amplitude of the mode components was taken as a fixed empirical function of |m|, which was derived by taking a mean over observations from different orders. For $\ell$=2, we use $A^2(m{=}2)/A^2(m{=}0)$=1.7 and for $\ell$=3, $A^2(m{=}3)/A^2(m{=}1)$=1.7 (Lazrek, private comunication).

Here, the splitting is defined as the mean for each multiplet of the separation between the modes $\Delta m$=1.

The uncertainty quoted here for each parameter determined is the statistical error obtained from the fitting program, using appropriately the covariance matrix of the fit. We performed Monte Carlo simulations (based on a method developed by Fierry Fraillon et al. 1997) which confirm the reality of these uncertainties.

## 4. Evidence of asymmetry as a property of p-modes

In this section, we first show that a non-negligeable unexpected effect obtained when fitting the modes with Lorentzian profiles can be explained by the presence of asymmetry. We then checked that this asymmetry is not an apparent one, but is due to an intrinsic property of the p-modes.

### *4.1. Evidence of an effect*

If we leave free the width of the two components of an $\ell$=1 mode, a Lorentzian fit gives a systematic and significant difference between the two widths. As shown by Fig. 2, this difference can reach a factor of 2. We show by fitting Lorentzian profiles to simulated asymmetric ones that this effect can be totally explained by the asymmetry of the profiles. We also checked that the widths of the two components of an $\ell$=1 mode converge to the same value when fitting with the asymmetric formula. As shown further, the $\ell$=0 modes exhibit an asymmetry of the same magnitude. This argues against the $\ell$=1 effect being due to a real difference between the width of the $m$ components.

### *4.2. Solar activity*

An apparent asymmetry of the profiles might arise as a result of a slow drift of the frequencies combined with a change in amplitude. Solar activity, by moving the outer boundary of the acoustic cavity, changes the propagation times and thereby the frequencies of the modes during the cycle. It has been estimated that, when the previous solar cycle approached maximum activity, the frequencies increased (Pallé et al. 1989, Elsworth et al. 1990), up to about 0.4 $\mu Hz$ and at the same time the energies of the modes decreased by nearly 30% (Anguera Gubau et al. 1992). Although Fierry Fraillon et al.(1998) did not find any effect of activity on GOLF frequencies over the first 690 days of our series, we preferred to check the temporal stability of the asymmetry parameter. To do this,we have analysed separately seven subseries of 115 days duration. Fig. 3 shows clearly that the asymmetry factor is of the same magnitude for the subseries as for the entire series, even at solar minimum, confirming that change in activity over the 805 days observed is insufficient to account for our measured asymmetries.

### *4.3. Influence of background*

In the fitted range there exists a background signal due to the solar convective motion (Harvey 1985, Pallé et al. 1995) as well as the far wings of all of the other modes. Our fitting assumes this background to be flat in the fitting window. To see whether the real slope could produce the apparent asymmetry, we performed an asymmetric fit on a synthetic $p$-mode Lorenzian profile superimposed with a curve simulating convective background slope. This slope was estimated in the 700-1100 $\mu Hz$ range, and then extrapolated to our domain of study. The apparent asymmetry, $B$, obtained is at most -0.0004 which is some 50 times lower than the values measured in real data (see Sect. 5).

On the other hand, to study the influence of the wings, we simulated synthetic spectra by adding all of the $p$-modes profiles determined by separate Lorentzian fits. Individual asymmetric fits were then made on this synthetic spectra. The asymmetry obtained is mostly positive with a maximum of 0.0008. This confirms that it is adequate to assume a flat background over the limited range used in our fitting technique.

### 4.4. *Influence of high $\ell$ modes*

Finally, we have carried out tests to see whether the existence of higher degree modes might compromise our fitting procedures. For the simulations, we have taken values of the amplitude and frequencies of these modes derived by one of our authors in a separate study (T. Roca Cortés, private communication). The $\ell$=4 mode, which would tend to increase the apparent $\ell$=2 asymmetry, is not inside our fitting window. Our simulation shows that its wings have a negligible effect on the results we obtain.

For the $\ell$=5 mode, which would tend to decrease the apparent $\ell$=0 asymmetry, the window we use normally includes less than half of the mode structure. In this case the uncertainty on the anticipated amplitude of this mode is too large to be useful. Instead, we have investigated our fit with the real data, a fit in which we do not take account of the existence of the $\ell$=5 mode. We displace progressively the high-frequency limit of the fitting window, until it includes all of the anticipated $\ell$=5 mode. It is found that the resulting parameters for the pair $\ell$=0 - $\ell$=2 vary negligibly with the window size, indicating that there is a negligible effect from neglect of the $\ell$=5 mode.

## 5. Results

### 5.1. *Choice of the fitting window*

To obtain approximate values of all of the parameters, including the asymmetry factor, $B$, we make a preliminary fit to each of the pairs $\ell$=0 - $\ell$=2 and $\ell$=1 - $\ell$=3. These values are then used as input parameters in simulations, aimed at quantifying the interaction between the components during the fitting procedure.

In the first simulation, we apply the Nigam fitting on only one of the two components of a pair, in order to measure the influence of the neighbouring mode. This shows that for the pair $\ell$=0 - $\ell$=2, the influence of one mode on the other is such that fitting separately leads to a significant error on the asymmetry parameter (up to a factor of 2 at 2700 $\mu Hz$). For the pair $\ell$=1 - $\ell$=3, fitting $\ell$=3 alone leads to large errors (the sign of $B$ may even be reversed). However, due to the relatively low amplitude of the $\ell$=3 mode, the situation is more favourable for $\ell$=1, which can reasonably be fitted alone up to n=22, with an error inferior to 10 % on $B$ and insensitive to the choice of the $\ell$=3 $B$ parameter.

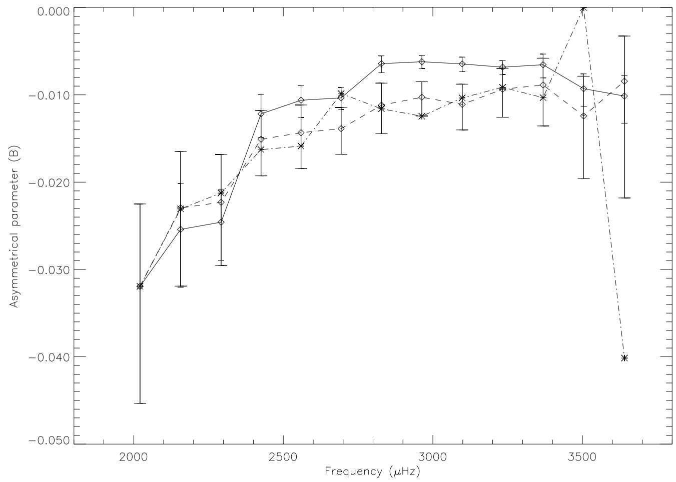


**Fig. 4.** Determination of the asymmetry parameter on the data for $\ell$=1: effect of the fitting window. Diamonds refer to the global fit of the pair $\ell$=1 - $\ell$=3 and stars for $\ell$=1 alone. The dashed line refers to the optimized window and the solid line to a larger window.

With confidence in the possibility of fitting the $\ell$=1 alone, we then examine the influence of the fitting window width on the determination of $B$. We might anticipate two effects, limiting the window width in opposing senses: the Taylor expansion used to derive the Nigam expression is valid close to the resonance and may therefore require a small window width, whilst the effects of stochastic excitation noise are minimised by increasing the amount of data through the use of a wider window. Fits using GOLF data show that for the $\ell$=1 fit alone, the variations of measured $B$ with the window width are consistent with the stochastic noise effect alone. This gives us a reasonable estimate of $B$ for $\ell$=1, which we can use to examine the validity of the $\ell$=1 - $\ell$=3 pair fit. We examine fits on this pair for different window widths. We find that a window width value exists for which $B$ is compatible with the value when fitting $\ell$=1 alone. As seen in Fig. 4, the residuals (shown as a function of frequency) are not systematic, but are consistent with the stochastic effect. Also shown in the figure is the effect of a larger window, for which random errors are reduced, as expected, but the determinations are systematically too small.

For $\ell$=3, we must also verify that the window is appropriate, i.e. that it does not extend too far to high frequencies. Using the reliable estimate of the $\ell$=1 asymmetry already obtained, we check the influence of the high-frequency side of the window for $\ell$=1 alone. No bias was found on $B$ when this limit was chosen identical to that of $\ell$=3 in a global $\ell$=1 - $\ell$=3 fit, giving confidence in the choice of window and the resulting $\ell$=3 asymmetry parameter. The window width chosen for the $\ell$=1 - $\ell$=3 pair, optimized for the $\ell$=1 alone, varies from 27 $\mu Hz$ for $n$=14 up to 38 $\mu Hz$ for $n$=25.

For the pair $\ell$=0 - $\ell$=2, individual fitting being impossible, we extrapolate the results of $\ell$=1, to derive an initial window width. To gain in statistics, we increased slightly the width of the extrapolated window, checking at each step that $B$ was not biased and that the $\ell$=4 wing does not enter the window.

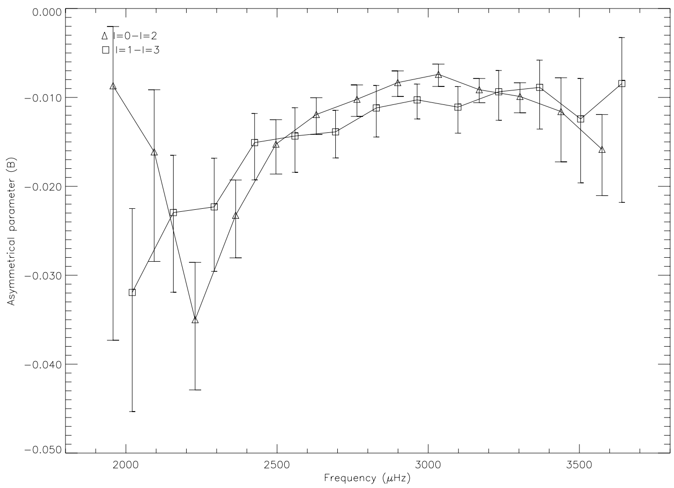


**Fig. 5.** The asymmetric parameter as a function of frequency assuming that it is the same for the two components of each pair.

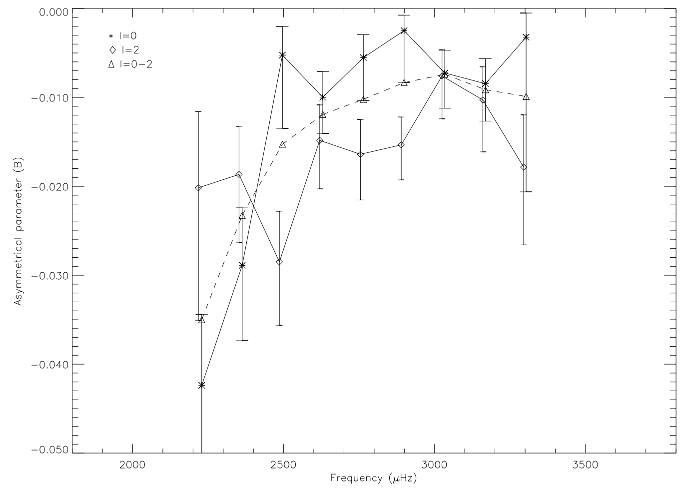


**Fig. 6.** The asymmetric parameter as a function of frequency, allowing a variation between $\ell$=0 and $\ell$=2. The dashed line corresponds to the curve of Fig. 5.

### *5.2. Asymmetry parameter*

Fig. 5 shows the variation of the $B$ parameter with frequency for the pairs $\ell$=0 - $\ell$=2 and $\ell$=1 - $\ell$=3, with the optimized windows. These are found to be consistent with the results of Toutain et al. and do not show a clear difference between the two pairs. To study an eventual $B$ dependence on degree, we performed also the same fitting but leaving free the two values of $B$ inside a pair. As already indicated, the value of $B$ for $\ell$=1 is not modified. The value of $B$ for $\ell$=3 is not useful, displaying very large error bars, even when it is fitted alone with the fixed wing of $\ell$=1 included in the formula.

For modes $\ell$=0 and $\ell$=2, Fig. 6 suggests that the asymmetry of the mode $\ell$=0 is on average lower than for $\ell$=2. Moreover, Fig. 6 exhibits a mirror effect between the $\ell$=0 and $\ell$=2 curves which is explained as following: first, starting with different values of $B$ for $\ell$=0 and $\ell$=2, Monte-Carlo simulations show that the fitting procedure is capable of reproducing the two values on average without bias, and when forcing them to be equal in the fitting, the value obtained is on average the mean value of the two. Second, the length of the time series is such that the variation of $B$ with radial order is very smooth when only one value is taken for the pair $\ell$=0 - $\ell$=2. These two properties of convergence and smoothness explain why the effects of stochastic excitation on the curves obtained when separate asymmetry parameters are allowed, lead to anticorrelated variations. As far as a difference of $B$ in the pair $\ell$=0 - $\ell$=2 is concerned, we checked if the overlap of the two modes could bias in opposite ways the estimation of their $B$ parameter producing an apparent difference. Monte Carlo simulations show that there is an equal probability to get either the $\ell$=0 $B$ greater or the $\ell$=2 $B$ greater, when the two parameters are equal in the simulated profile. This permits to estimate the probability that the lower asymmetry for the $\ell$=0 mode is real. It is found to be 93%, which is marginally significant due to the low number of radial orders in the statistics.

## 6. Bias introduced when fitting a Lorentzian profile to an asymmetric resonance

### *6.1. Determination of a bias uncertainty*

The uncertainty on a bias (frequency, line width or splitting) cannot be calculated from those corresponding to the quantities delivered by the two kinds of fits, because these uncertainties are not dependent, the stochastic excitation being the same in the two cases. To compute a bias uncertainty, we perform Monte Carlo simulations: for each radial order and mode pair, we simulate 200 stochastic realisations of a Nigam's profile. For each realisation, we do a Nigam and a Lorentzian fit. Then, for each mode parameter, the histogram of the difference between the two results gives the uncertainty we require. Note that the uncertainty on a bias can be significantly smaller than the uncertainty on the absolute value of the mode parameters (see Figs. 7 to 12).

### *6.2. Bias on the frequency*

The frequency difference between symmetric and asymmetric fits is plotted versus the frequency in Fig. 7 for the different modes. There is a systematic shift for all the modes: the frequency infered from fitting a Lorentzian profile is lower than those using an asymmetric profile. The mean value of the bias is about 42 nHz for $\ell$=0, 85 nHz for $\ell$=1, 54 nHz for $\ell$=2 and 24 nHz for $\ell$=3. Not only the bias but also its variation with frequency is an important input for the inversion because the difference between frequencies has more impact on the deduced solar structure than frequencies themselves. The difference between the behaviour of $\ell$=1 and the other degree modes can be understood and reproduced in simulations (Lorentzian fitting on pure Nigam profiles). $\ell$=1 behaves as an isolated mode (see Sect. 5.1) and is influenced not only by $B$ but predominantly by $\Gamma$. For $\ell \neq 1$, the influence of the neighbouring mode dominates.

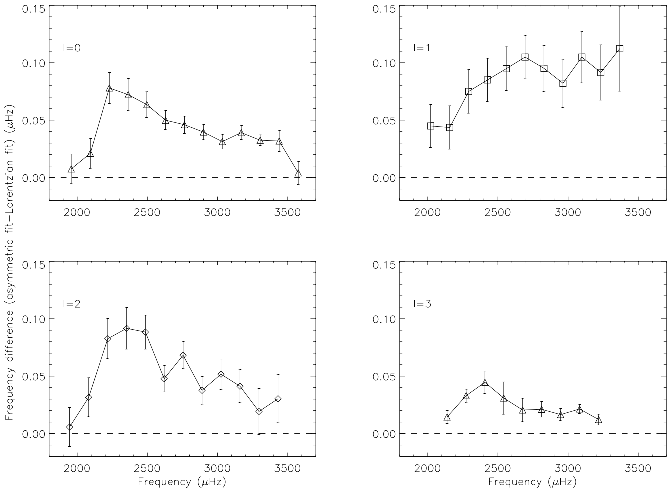


**Fig. 7.** The frequency difference between asymmetric and Lorentzian fittings as a function of frequency and mode degree. The errors bars are computed by Monte Carlo simulations as described in the text.

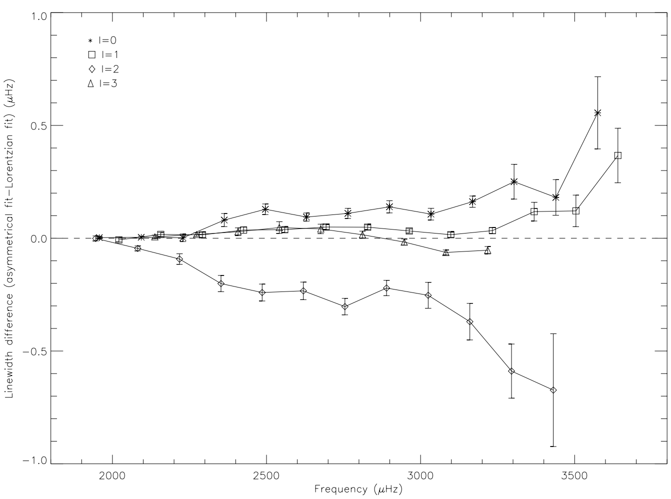


**Fig. 8.** The linewidth difference between asymmetric and Lorentzian fittings as a function of frequency and mode degree.

The frequencies inferred from asymmetric fitting are given in Table 1.

### 6.3. Bias on the linewidth

The width difference between symmetric and asymmetric fitting depends on the mode degree and on the frequency (see Fig. 8): the widths inferred from a Lorentzian profile are lower than those from an asymmetric profile for degree $\ell$=1 and $\ell$=0 and inversely for $\ell$=2. For $\ell$=3 the sign is frequency dependent. The same simulations than those mentioned in the previous subsection show that the influence of the components on each other in a multiplet is dominant for the sign of the bias. The evolution with the radial order is, as for the frequencies, influenced by both the line width and the neighbouring mode.

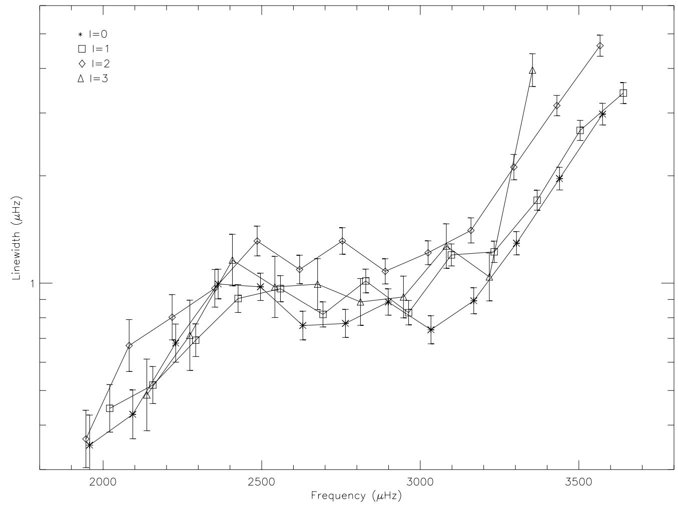


**Fig. 9.** Determination of the linewidth using Lorentzian profiles.

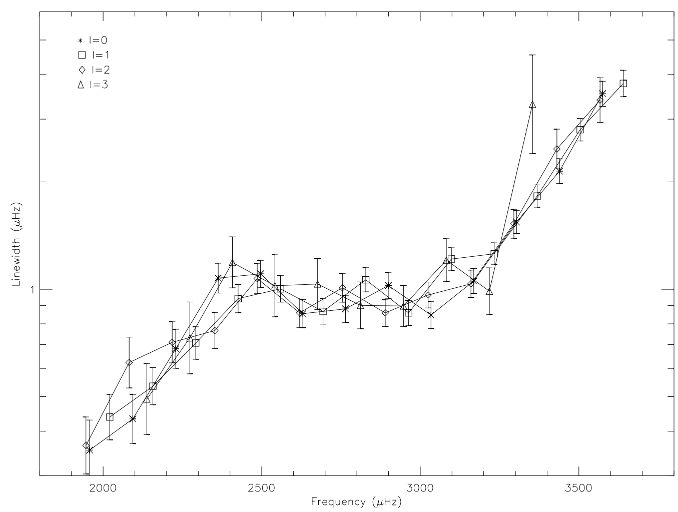


**Fig. 10.** Determination of the linewidth using the Nigam formula.

The importance of this is such that when the asymmetry is taken into account, the dispersion of the width with the degree is considerably reduced as shown by Figs. 9 and 10.

### 6.4. Bias on the splitting

The difference between determinations of the rotational splitting based on Lorentzian or asymmetric profiles depends on the degree (see Fig. 11) and the difference increases with increasing frequency for modes $\ell$=1 and $\ell$=2. As for the width, the sign of the bias depends on the degree, which we also confirmed by the simulations. The Fig. 12 shows the results obtained and Table 2 gives mean values over frequency for the two kinds of fits. Note from Table 2 that, as we would expect, the uncertainty induced by the stochastic excitation is not reduced when using an asymmetric fit, but the dispersion with the degree is somewhat reduced by a more valid fit. In particular, the relatively low value for the splitting of the $\ell$=2, observed here in the Lorentzian case and reported in some publications

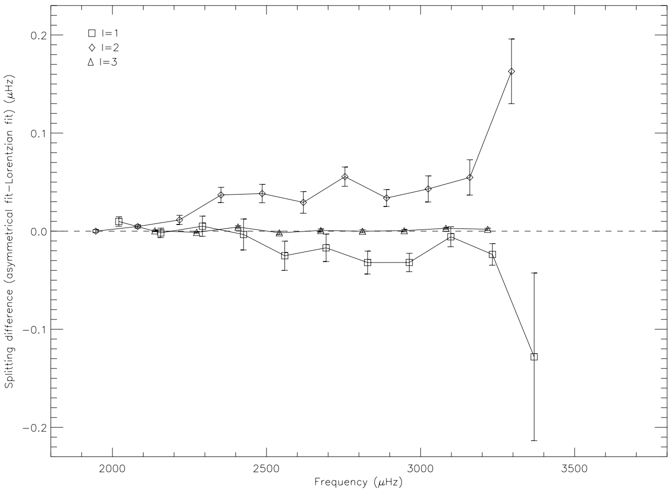


**Fig. 11.** The splitting difference between asymmetric fitting and Lorentzian fitting, as a function of frequency and mode degree.

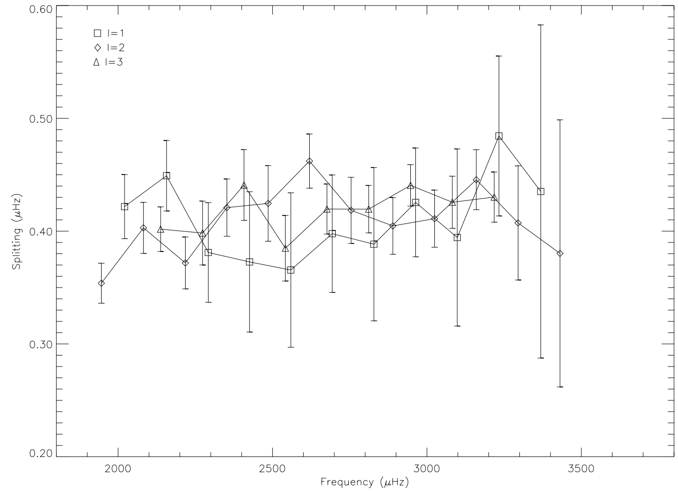


**Fig. 12.** Determination of the splitting (synodic) using the Nigam formula. Results for higher frequencies have larger errors bars and are not shown here.

**Table 1.** Frequency and errors in $\mu Hz$ derived from asymmetric fitting for modes $\ell$=0, $\ell$=1, $\ell$=2 and $\ell$=3 with radial orders from $n$=12 to $n$=25. The observation duration is $T$=805 days.

| $n$ | $\ell$=0 | $\ell$=1 | $\ell$=2 | $\ell$=3 |
|---|---|---|---|---|
| 12 | . | . | 1945.75± 0.03 | . |
| 13 | 1957.43± 0.03 | 2020.84± 0.03 | 2082.10± 0.05 | 2137.71± 0.06 |
| 14 | 2093.51± 0.03 | 2156.81± 0.03 | 2217.75± 0.05 | 2273.42± 0.10 |
| 15 | 2228.84± 0.04 | 2292.05± 0.04 | 2352.32± 0.04 | 2407.64± 0.10 |
| 16 | 2362.83± 0.05 | 2425.57± 0.05 | 2485.86± 0.05 | 2541.56± 0.07 |
| 17 | 2496.20± 0.04 | 2559.25± 0.05 | 2619.63± 0.04 | 2676.23± 0.06 |
| 18 | 2629.74± 0.04 | 2693.40± 0.04 | 2754.48± 0.05 | 2811.45± 0.05 |
| 19 | 2764.16± 0.04 | 2828.17± 0.05 | 2889.58± 0.04 | 2946.98± 0.05 |
| 20 | 2899.07± 0.04 | 2963.31± 0.04 | 3024.71± 0.04 | 3082.23± 0.06 |
| 21 | 3033.77± 0.03 | 3098.18± 0.05 | 3159.86± 0.04 | 3217.82± 0.06 |
| 22 | 3168.66± 0.04 | 3233.14± 0.05 | 3295.14± 0.06 | 3353.85± 0.17 |
| 23 | 3303.39± 0.05 | 3368.56± 0.07 | 3430.80± 0.09 | 3489.79± 0.21 |
| 24 | 3439.05± 0.07 | 3504.10± 0.08 | 3566.87± 0.14 | 3626.20± 0.28 |
| 25 | 3574.80± 0.11 | 3640.37± 0.12 | . | . |

(Lazrek et al. 1997, Gizon et al. 1996), is no longer obtained in the asymmetric case. Moreover, the use of the Nigam formula permits a good determination of the splitting farther in the high frequency range than with a Lorentzian formula.

## 7. Conclusions

Precise p-mode resonance frequencies are required if we aim to improve the precision of the inversions for the interior sound speed. With this in mind, we have investigated the importance of asymmetry in the p-mode resonance profiles. It is known that these effects will in general be small for low-$\ell$ global resonances and also reversed for velocity measurements compare for intensities one. A detailed study, using GOLF data, simulated GOLF data and Monte Carlo simulations has shown that meaningful measurements of asymmetric effects can be performed. When the GOLF data is fitted using asymmetric fitting based upon the Nigam formulation, a number of anomalies, previously encountered with Lorentzian fitting, tend to go away. Such anomalies include the variation of resonance widths amongst members of a multiplet. The dispersion of many of the fitting parameters is also reduced when using asymmetric fitting.

**Table 2.** Average and standard error in $nHz$ of the synodic splitting over $n$ when using asymmetric or Lorentzian fitting.

| | $\ell$=1 | $\ell$=2 | $\ell$=3 |
|---|---|---|---|
| order | 14-22 | 13-21 | 13-21 |
| asymmetric | 406.± 20. | 418.± 10. | 418.± 8. |
| Lorentzian | 422.± 20. | 384.± 10. | 417.± 8. |

We have also investigated the optimum choice of spectral window, when using these fittings. This is a compromise between large windows, for which the fitting procedure may become formally less valid, and small windows, which increase the statistical uncertainty due to stochastic excitation effects. The breakdown in validity of the fitting procedure for large windows is manifest in our studies. This may be due to a limitation in the approximation used in the profile expression adopted, but may also be due to a formal error in assuming that the profiles are additive on a scale of spectral energy. For this reason we exclude the idea of fitting together the entire p-mode spectrum, when using asymmetric profiles.

The asymmetry parameters derived are claimed in the literature to be due to two distinct physical processes: the existence of direct signals from excitation sources and the interaction of the resonances with correlated solar noise. These two processes make contributions to the asymmetry parameter with the same functional form, within the approximation used here. It is therefore difficult to see how we can hope to separate these effects, in order to determine the height of the excitation region, unless we make the arbitrary assumption that one or other of the effects is negligible.

Work is now in hand to use these improved GOLF frequencies for inversions. This is being reported in a second paper (Basu et al. 1999). As always, it is important to have good frequencies also for medium-$\ell$, in order to carry out this inversion. At the time of writing, MDI medium-$\ell$ frequencies are only available based on Lorentzian fitting. Although we are using these, there is an obvious inconsistency with our improved asymmetric frequencies. Improved inversions must therefore await the availability of asymmetric data at both low and medium-$\ell$.

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