FIRST RESULTS ON P-MODES FROM GOLF EXPERIMENT

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Abstract. The GOLF experiment on the SOHO mission aims to study the internal structure of the sun by measuring the spectrum of global oscillations in the frequency range 10^{-7} to 10^{-2} Hz. Here we present the results of the analysis of the first 8 months of data. Special emphasis is put into the frequency determination of the p-modes, as well as, the splitting in the multiplets due to rotation. For both, we show that the improvement in S/N level with respect to the ground-based networks and other experiments is essential in achieving a very low degree frequency table with small errors ($\sim$ 2 parts in 10^5). On the other hand, the splitting found points to a solar core which does not rotate slower than its surface. The line-widths do agree with theoretical expectations and other observations.

Key words: sun–helioseismology, sun–oscillations, sun–rotation, sun-interior

1. Introduction

Helioseismology uses the temporal and spatial properties of solar oscillations to study the solar interior. The quality of analysis as measured by the precision of the deductions and the ability to probe all parts of the sun's interior is dependent on the acquisition of observations of the widest possible range of solar oscillation modes and with the greatest precision possible. The SOHO satellite includes three helioseismology instruments which aim to cover in a complementary manner a wide range of oscillation measurements. GOLF is one of these helioseismology instruments and emphasizes the lower frequencies utilising global oscillations of the line-of-sight velocity vector of the solar photosphere as measured by the full-disk integrated light.

At present only higher radial orders of the pressure or p-modes have been well identified in the solar oscillation spectrum, whether the observation is spatially integrated (Claverie et al. 1979, Grec et al. 1980) or spatially resolved (Duvall and Harvey 1983). The mode amplitudes favour the observations of periods around 5 minutes, these resulting in some of the best data reported to date (Anguera Gubau et al. 1992, Elsworth et al. 1994, Gelly et al. 1997, Chaplin et al. 1996c). Spatially integrated data favours the low degree modes, which are limited to l = 0, 1, 2 and 3. The possibility of detecting ℓ=4 in GOLF data was predicted before launch (Régulo, 1995) and nowadays the tallest modes are barely detectable in ground-based networks (Chaplin et al. 1996b) and better in our preliminar analysis (Lazrek et al. 1997).

Frequencies below 2 mHz are very difficult to observe from the ground due to a combination of decreasing amplitude and increasing terrestrial and solar noise. The lowest frequency p-mode with $\ell = 0$ and $n = 1$ has a period of the order of 60 minutes, and has never been identified. An important objective of GOLF is to measure the p-modes below 1.5 mHz and to study their entire predicted range up to the cut-off frequency.

A number of factors determine the shape and width of the observed p-modes. These include the limited coherence time of the oscillations and variations in amplitude and phase with time, due to the physical process of excitation of the modes. A different and time-invariant reason for fine structure in certain resonances lies in the splittings due to solar rotation. Such splittings have been well-observed for intermediate and high-ℓ p-modes and found to correspond approximately to the solar rotation period (Duvall and Harvey 1983). Although for low-ℓ modes the splitting have been measured by several groups (Claverie et al. 1979; Toutain and Fröhlich 1992; Jiménez et al. 1994; Lazrek et al. 1996; Chaplin et al. 1996a) the precision is not good enough yet, showing a high scatter which do not help much in constraining the solar core rotation (Fossat, 1995).

Moreover, all of the above parameters are susceptible to systematic variation with the 11 year solar activity cycle. Frequencies of very low l-value p-modes (between 2 and 5 mHz) have been found to vary with time, on scales of the solar activity cycle (Woodard and Noyes 1985, Gelly et al. 1988). This correlates very well with several solar activity indices, such as sunspot number, magnetic field measurements and other indices, UV and 10.7 cm radio flux (Pallé et al. 1989, 1990a,b; Elsworth et al. 1990b; Régulo et al. 1994). The experimental data converge to an average value, over radial orders n, for the frequency shift of $0.45 \pm 0.04\mu$Hz (peak to peak), with a maximum at solar activity maximum. This limits the length of the data series to be jointly analysed as it would throw more noise in the line shapes of the modes. Notice that the data used in this work has been taken at the minimum of solar activity, therefore forming a coherent data set.

2. Data, Time series and Power Spectra

The technical principle employed by GOLF is to measure the Doppler wavelength shift of the solar Na D Fraunhöfer lines by comparison with an absolute standard given by a sodium vapour cell within the GOLF instrument. It uses the optical resonance technique to isolate a narrow region of the solar sodium resonance line. The solar absorption traverses a sodium vapour cell which has an intrinsic (thermal) absorption line width of $\sim$ 25 mÅ. Thus a 25 mÅ slice of the solar line is absorbed and re-emitted in all directions. Part of the signal re-emitted at 90 degrees is recorded by suitably positioned detectors. By placing the cell in a longitudinal magnetic field of 5000 gauss, the absorption line is Zeeman split into two components displaced from the original by $\pm \sim$ 108 mÅ(D1 case). If the incoming solar flux is now analysed circularly using a linear polariser followed by a quarter-wave plate, it is possible to select first one, then the other absorption component, respectively left and right circularly polarised, and thus measure the amplitude of a point on each of the two wings of the solar profile at: I_b and I_r. If the cell magnetic field is now increased/decreased sequentially, by a small amount, we can measure two more points, further separated in wavelength: I_b^-, I_b^+ and similarly in the red wing of the line. This technique is similar, in principle, to that carried out in ground-based measurements of solar oscillations, as for example in the IRIS or BiSON networks (Grec et al. 1991; Brookes et al. 1978); however, some innovations have been introduced which are fully described in Gabriel et al. (1995) as well as the whole GOLF instrument.

However, due to occasional malfunction of the rotating mechanisms which allow the polarising elements to rotate, it was decided to stop them on the 10th of April at positions which only select the blue wings of the lines (Na doublet). In this way we ensure the continuity in the acquisition of measurements having a duty cycle of nearly 100% but sacrifice observations on the red side of the lines (Gabriel et al. 1997). In this blue-wing only operating mode, the working cycle of the instrument is now basically I_b^-, I_b^+ measured sequentially at 5 s intervals by two different PM tubes. With these measurements several signals can be defined, of which we underline two:

$$Y^B = (I_b^+ + I_b^-) - < I_b^+ + I_b^- > \tag{1}$$

$$X^B = (I_b^+ + I_b^-) / < I_b^+ - I_b^- > \tag{2}$$

where $< Z >$ stands for a high pass-band filter over a time much longer than the signals to be measured (i.e. longer than $\sim$10 hours) that has been applied to the Z time series in its Fourier space (see García, 1996; Régulo et al. 1997). Notice that both signals can be calibrated in velocity units in a procedure that is being improved and it will be described shortly elsewhere; in fact, in this paper the calibrations are judged to be accurate to within

20%. Data analysed here starts in mid April and lasts until mid December for a total of around 8 months, with a duty cycle greater than 99%. The data has been analysed independently by at least four groups using any of the signals above described. Yet preliminary results based on four months of data have been shown in Grec et al. (1997).

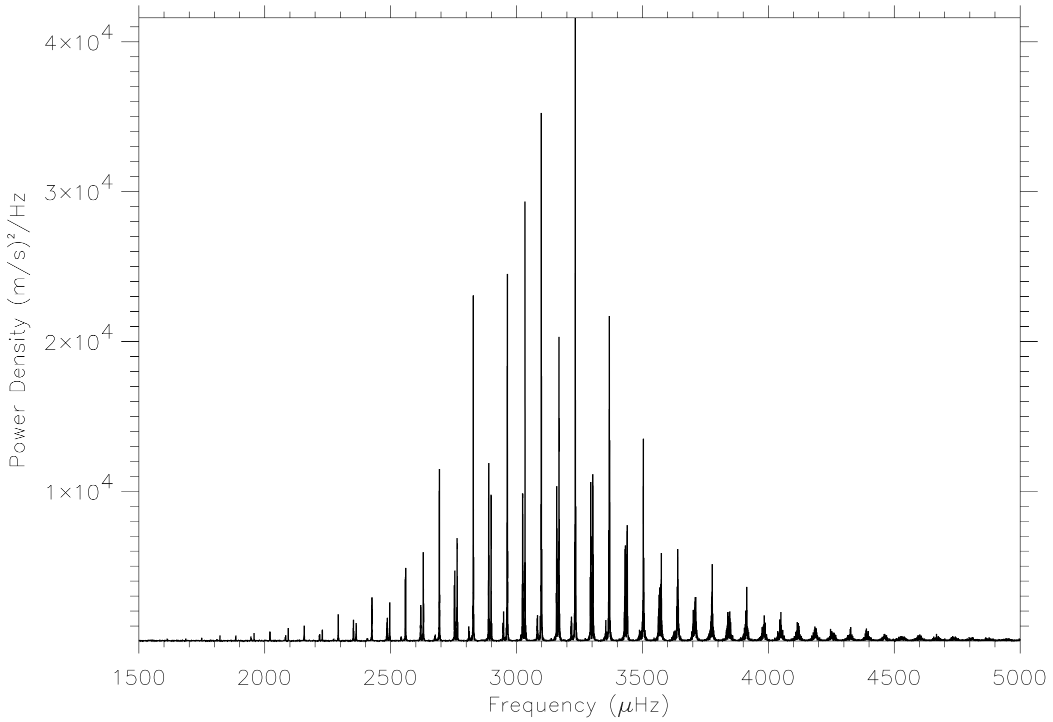

Fig. 1. The acoustic p-mode spectrum of the Sun, as measured using the first eight months of GOLF data.

To calculate the power density spectrum, each group has used the methods available and with which he has more experience. The standard method, which consists in taking an FFT of the time series, calculating the power spectrum and fitting this power spectrum using a maximum likelihood technique to fit lorentzians to the peaks present (Lazrek et al. 1996; Gelly et al. 1997; Anderson et al. 1990). Also the cross-spectrum between the signals obtained by each PM tube separately has been calculated and used to show the low noise level achieved and to help in the search for modes at lower S/N levels.

The power spectra look very similar independently of the method used. One example can be seen in Fig. 1, where the overall spectrum of the p-modes can be seen. The regularity in the spacing of the peaks is clearly

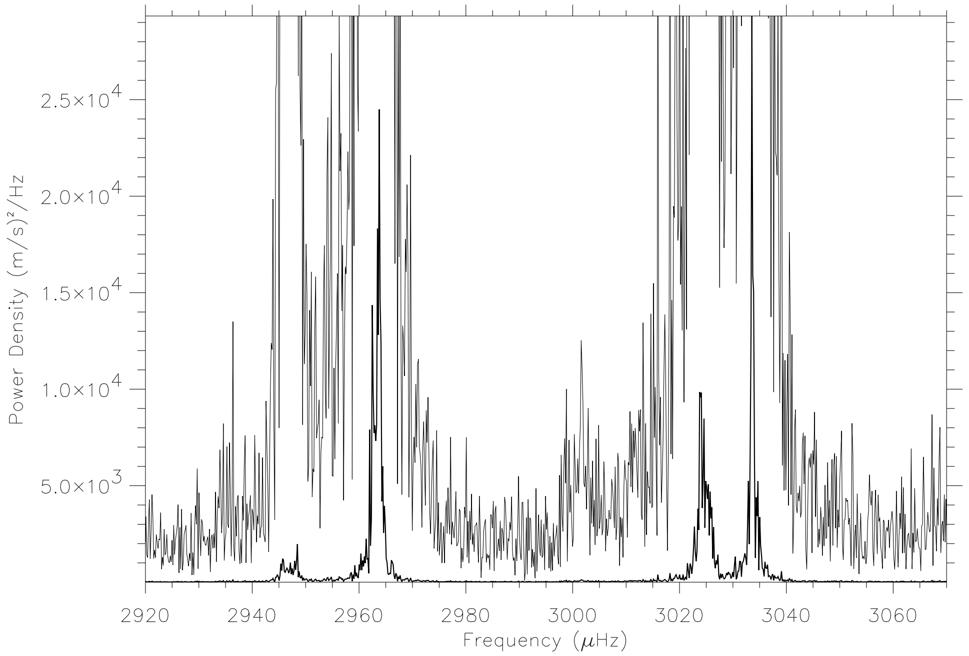

Fig. 2. A slice of the acoustic p-mode spectrum of the Sun. Bold line corresponds to the spectrum in the units shown on the vertical axis, while the thin one represents the same spectrum multiplied by 100. Notice the clear presence of modes of different degree: ℓ=3, 1, 2 and 0 (from left to right) in the bold line and the ℓ=4 and 5 in the thin one. Also hints of the ℓ=6 and 7 are visible (see text).

shown as predicted by the asymptotic theory of global oscillations, as well as the increasing line-width of the peaks as frequency increases denoting the fact of lower damping times as n increases. A slice of this spectrum at the region of highest power is shown in Fig. 2, where discrete modes can be seen; these modes are readily identified as having different ℓ values which from left to right are 3, 1, 2 and 0. Notice also that no sidebands are visible due to the high continuity in the data. Also plotted is the same spectra multiplied by a 100; this is done for two reasons: the first one to show the very low noise level in between these modes and the second one, to better look at the "noise" between peaks and actually discover the broad peaks ℓ=4, at $\sim$3000 μHz, clearly present and also traces of the ℓ=5, at $\sim$3050 μHz; less clear however, but already some hints of ℓ=6 and ℓ=7 situated at $\sim$2961 μHz and $\sim$3005 μHz on the wings of much higher peaks.

Acoustic modes with frequencies less than 2 mHz are very difficult to observe from ground due to a combination of decreasing amplitude of the modes and increasing terrestrial noise and also "solar noise" produced mainly in the convection zone. From space, free from terrestrial noise, the so-

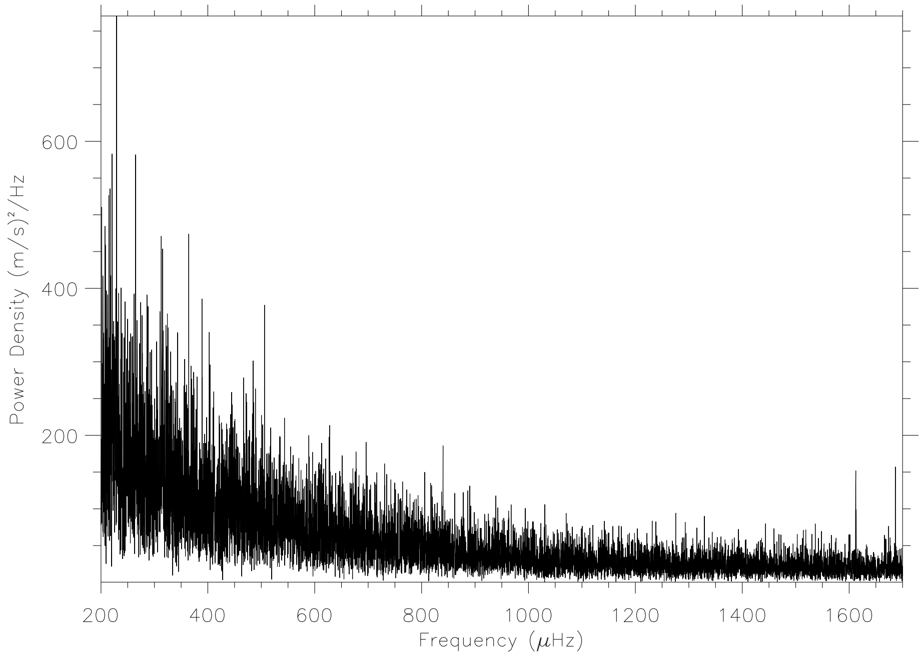

Fig. 3. The p-mode spectrum at lower frequencies where the decrease in amplitude of the modes merge with the increase in the so-called "solar noise", non-coherent solar velocity signals, resulting in a S/N≤1.

called "solar noise" also prevents the identification of p-modes below 1.5 mHz up to the present (see Fig. 3). Notice however, that one is tempted to suggest that below 800 μHz there is enough signal so that some of the peaks might be identified as real modes. It is expected that with more data, the solar non-coherent signals that conform the "solar noise" will be washed out and the modes will stand up because of their increasingly high coherence time as frequence decreases (Elsworth et al. 1990a).

3. Frequencies

The shape of each line in the multiplets is a spiky lorentzian profile as a consequence of the successive random excitations of the mode which limits the coherence time of the oscillations. Therefore the fit to these lines have the shape of lorentzians plus a constant level of noise. The mean power density spectrum for each multiplet is of the form:

$$P_{nl}(\nu) = \sum_{m=-l}^{m=l} \frac{S_{nlm}(\Gamma_{nlm}/2)^2}{(\nu - \nu_{nlm})^2 + (\Gamma_{nlm}/2)^2} + N, \tag{3}$$

consequently, using any of the methods mentioned, one can find the frequency ν_{nlm}, line-width Γ_{nlm}, power S_{nlm} and background noise N.

To start with, only modes of degree up to ℓ=4 have been systematically searched for and independently fitted. The result of the different fits ended with frequency tables which have been merged into only one in the following way: the frequencies found for each (n, ℓ) multiplet have been averaged. The errors on each frequency determination are the statistical errors that come out from the fitting programs by using appropriately the covariance matrix of the fits; however, the final error has been set as the average value of all determinations.

The final frequency results are shown in Table I. Notice that towards lower frequencies the identification become increasingly difficult due a poor signal-to-noise level (see Fig. 3); here the dispersion found among each group's identifications is larger than the standard errors quoted by each of them showing clearly that different identifications were made. In these cases, we quoted the first findings inside brackets avoiding mentioning other equally possible identifications down to n=1. Probably, new data will help in undisputely identifying such modes. On the other hand, at frequencies $\geq$3.5 mHz, the line-widths become too broad; the fitting of only one multiplet at a time is no longer possible and they have been fitted in pairs: ℓ=0,2 and separately ℓ=1,3.

On the other hand, during the time when the data analysed here has been obtained, the solar activity on the Sun has remained at a very low level (the average of the monthly averaged sunspot number is $\sim$ 8) and therefore the contribution to the variation of frequencies is negligible.

4. Splittings

The identification of the degree of the modes fitted can be done by comparison with the theoretical predictions coming from the eigenvalues of the linearised partial differential equations which describe the oscillations of the Sun. However, there is still another observational way of determining the degree of the modes due to the splitting of the lines caused by the loss of spherical symmetry, already assumed by the theory above mentioned. This loss of symmetry can be produced by the rotation of the Sun and/or the presence of global intense magnetic fields in its radiative interior.

Taking the solar rotation as an axial perturbation, each acoustic mode is split in (2ℓ+1) modes, each with a different m (azimuthal degree) value which goes from ℓ to -ℓ, each separated by an amount proportional to the rotational velocity value of the sunlayers in the cavities where the modes propagate.

$$\delta\nu_{nlm} = \nu_{nlm} - <\nu_{nl}> \simeq m \frac{\bar{\Omega}}{2\pi} \tag{4}$$

TABLE I
Frequencies and errors, in μHz, as measured by GOLF instrument. Bracketted frequencies are possible identifications with S/N$\leq$1.

n	ℓ=0	ℓ=1	ℓ=2	ℓ=3	ℓ=4	ℓ=5
8		1329.49±0.64	1393.51±0.49			
9	(1407.77±0.32)	1472.71±0.13	(1535.95±0.13)	1591.57±0.80		
10	1548.40±0.04	1612.74±0.08	1674.31±0.21	1729.68±1.80		
11	1686.54±0.04	1749.29±0.04	1810.17±0.16	1865.26±1.37		
12	1822.20±0.05	1885.08±0.04	1945.73±0.09	2001.21±0.65	(2046.30±1.50)	
13	1957.45±0.06	2020.81±0.04	2082.06±0.07	2137.75±0.19	(2187.40±2.00)	
14	2093.51±0.04	2156.80±0.09	2217.80±0.12	2273.23±0.19	2321.94±1.00	
15	2228.69±0.07	2291.80±0.08	2352.32±0.08	2407.85±0.28	2460.10±1.00	
16	2362.69±0.08	2425.48±0.08	2485.89±0.10	2541.65±0.14	2593.70±1.00	
17	2496.04±0.06	2559.21±0.08	2619.64±0.12	2676.19±0.19	2730.00±1.00	(2778.10±0.50)
18	2629.82±0.08	2693.27±0.07	2754.43±0.08	2811.46±0.11	2864.52±0.47	2913.70±0.30
19	2764.05±0.07	2828.01±0.10	2889.64±0.08	2946.95±0.12	3000.94±0.53	3050.20±0.30
20	2898.83±0.07	2963.33±0.08	3024.65±0.09	3082.28±0.14	3137.24±0.49	(3185.77±0.30)
21	3033.68±0.06	3098.10±0.08	3159.91±0.09	3217.91±0.15	3274.01±0.77	
22	3168.53±0.06	3233.22±0.08	3295.22±0.13	3353.88±0.48	3410.00±1.50	
23	3303.22±0.09	3368.55±0.09	3430.97±0.15	3490.24±0.67	3547.60±2.00	
24	3438.72±0.12	3503.86±0.14	3566.62±0.24	3626.21±0.71	3686.70±2.00	
25	3574.50±0.16	3640.02±0.20	3703.23±0.43	3763.05±2.30		
26	3710.54±0.51	3776.46±0.25	3838.99±0.79	3901.29±2.00		
27	3846.77±0.27	3913.53±0.32	3977.19±0.86	4036.00±2.25		
28	3984.09±0.60	4049.20±0.40	4113.82±1.75	4173.55±3.05		
29	4119.95±0.91	4186.25±0.51	4250.88±2.16	4309.66±3.30		
30	4258.79±1.94	4325.00±0.66	4389.01±2.13	4450.00±3.50		
31	4395.22±2.07	4462.28±1.84	4527.00±3.00			
32	4535.00±2.62	4600.42±1.52				
33	4672.70±3.00	4736.60±2.00				
34	4808.00±3.00	4876.50±2.00				

where $< \nu_{nl} >$ is the frequency averaged over m and $\bar{\Omega}$ is an appropriate average of $\Omega(r,\theta)$ over the cavity sampled by the modes.

However, due to the angular symmetry of the spherical harmonics, which are the angular part of the eigenfunctions solutions of the oscillations problem, only the modes with $(\ell+m)$ even, will be observable. Therefore, modes with degree 1, 2, 3, and 4 will be observable as multiplets with 2, 3, 4 and 5 components respectively. The relative height of each component can be calculated and predicted (Christensen-Dalsgaard, 1989) and, although they will vary along the year due to the apparent precession of the solar rotation axis, such variation is very small; a bit higher could be the one due to the relative movement of the satellite and the Sun, which will yearly slightly modulate the height of each (n, ℓ, m). This is being studied quantitatively for the particular case of the GOLF blue-wing operating mode.

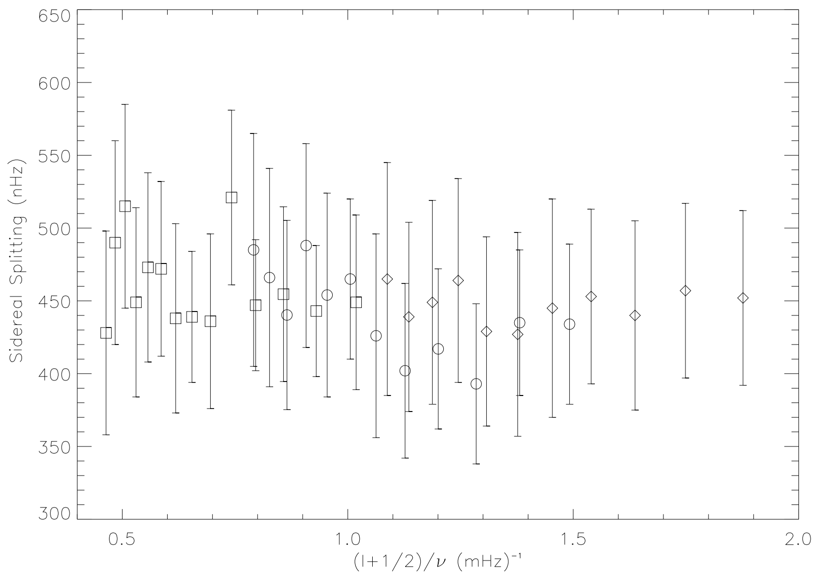

Fig. 4. The sidereal splitting found for each mode plotted against $(\ell + 1/2)/\nu$ which is directly related to the lower turning point of the modes. Open squares, open circles and diamonds are for ℓ=1, 2 and 3 respectively.

4.1. Individual determinations

Therefore is this multiplet structure (n, ℓ, m) what is fitted in the power spectra. There is a variety of methods to solve the problem of the non-linear fitting and the use of several of them will certainly increase the confidence in the results and reduce the amount of uncertainty that the numerical methods could throw onto the result. However, the statistical uncertainty which will only depend on the number of realisations of the excitation of the mode will still remain unchanged. Another problem resides in the fact that the fit is non-linear, and therefore the result might depend on the needed starting values for the parameters to be fitted. This has been checked carefully and arrived to the conclusion that the variations in the results are smaller than the errors quoted (obtained from the fit).

In these determinations we use the outputs of the analysis done to find the frequencies of the multiplet lines, in which we define the splitting as half the difference between two consecutive components of a given multiplet,

TABLE II
Sidereal splittings and errors, in nHz, as obtained using the methods described in the text.

	ℓ=1	ℓ=2	ℓ=3
order	9-22	10-21	11-21
Collective	452±14	438±20	456±20
Individual	458±28	437±29	447±15

being this difference set equal for all components. Notice that only for $\ell \geq 3$ we could have information on the splitting of different m components of the multiplet other than those with $\ell = m$; these will give information on the latitudinal dependence of the rotation rate. The results can be found in Fig 4 where they are plotted as a function of $(\ell+0.5)/\nu$ which is directly related to the inner turning point of the modes $2\pi(r/c)_t$. Also weighted averages over all splitting values of the modes with the same ℓ have been computed and they are presented in Table II. The error bars here are not the error of the average value but the square root of the variance of the distribution of the individual values.

4.2. Collective methods

On the other hand, to increase the statistical significance and decrease the uncertainties to the minimum, a single measurement for all multiplets of different n and equal ℓ can be calculated. We call these methods collective measurements; they are based on the assumption that the frequency variation of the rotational splitting of modes with the same degree (due to their slightly higher penetration into the solar core) is very small compared to the precision with which it can be measured; therefore these variations will be statistical fluctuations of the energy distribution within each multiplet. As a consequence, the end product here will be one splitting value for all multiplets with the same degree.

Several methods have been applied here, which are improved versions already extensively described in Lazrek et al. (1996) also applied to IRIS ground-based data. The methods are:

1. Iterative method. It consits in fitting all the multiplets with enough S/N and whose line-width is smaller or of the same order than the splitting to be measured. It is made in two steps: the first one consists in assuming a given value for the splitting of all multiplets; then they are individually fitted and the central frequency, line-width, power and noise are determined. In a second step, the values fitted are injected as

starting values for the fit and on a single fit for all multiplets, a single value for the splitting is finally determined. This value is then used to restart again the process with step one. The method converges quite rapidly within a few iterations to a unique value; the process is then repeated for each ℓ value multiplets.

2. Average spectrum method. In this case, the central frequency of each multiplet is determined from a standard fit to the spectra. Then each multiplet is normalised in order that all multiplets have the same energy, and they are all averaged around their own central frequencies; an averaged multiplet line profile is obtained. Then the splitting is obtained after a least squares fit of this averaged profile. Notice that this method relies heavily on the good determination of the central frequencies of each multiplet. See Fig 5 for a plot of the averaged spectrum for the quadrupole multiplets.

3. Average of auto-correlations. Here the normalised auto-correlation function of each multiplet is calculated along an interval of a few μHz. Then the average of these autocorrelation functions is made and the splitting is found by least squares fitting the appropriate number of gaussians or lorentzians to this average. Notice that here there is no need of having previously fitted any function to the multiplet, so no "a priori" knowledge is needed; however the fit is less precise because the function is much smoother than before.

4. Average of cross-correlations. Here the method is a mixture of the two mentioned above. The time series is divided in two slices and the spectrum is calculated for each one. Afterwards, the cross-correlation between two frequency intervals equally large and centred on the same central frequency of a given multiplet is made. The average of the cross-correlation functions is taken for all multiplets of a given degree and the splitting is calculated as the method described above (3).

The result of applying all these methods to the spectra is presented in Table II where the weighted average of the four outputs of the methods is given. The estimated error bar is calculated starting from the statistical error of one frequency measurement and taking into account the number of components, the S/N ratio and the number of modes. All the methods gave values within one standard deviation, which is quoted as the error bar.

Notice the excellent agreement between individual and collective methods. Moreover, it is convenient to note that two other groups that have also calculated the splittings of some modes, using methods similar to the individual method described above, gave values whose average coincide with those of Table II, within errors, but had a higher dispersion than the one shown in Figure 4.

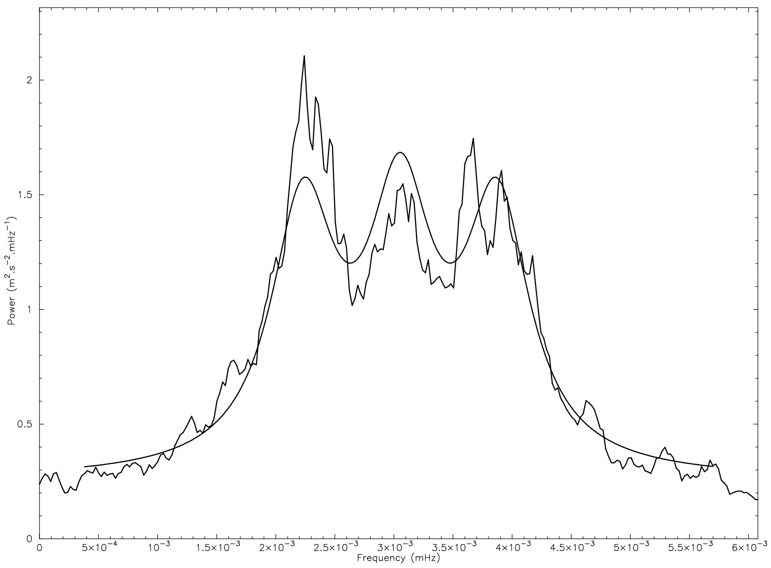

Fig. 5. A folded line shape for ℓ =2 multiplet showing the triplet structure from which the splitting can be easily calculated.

5. Line-widths

The estimation of the Γ_{nlm} (see equation (3)) of the modes can be obtained from the fit. However an "ad hoc" fit using also the maximum likelihood technique on the power spectrum has been used. Each multiplet (n,ℓ) was fitted with (ℓ+1) components as one should expect for full disk observations. In such fits, neither the central frequency nor the separation of the multiplet components were free parameters. The central frequency was imposed to a tabulated value given by a predetermined frequency table in full agreement with Table I. The separation between the multiplet component was derived from the $\ell = 1$ averaged splitting value in the 'collective' method and was identical for all modes.

This partial fitting allows to distinguish better the uncertainties arising from the frequencies and splitting measurements from the actual uncertainties on the widths. We only give a value for the width when we think that it conveys a physical meaning: above $n = 22$ the width becomes greater than the separation due to the splitting, but still a correct estimation can be performed. Above $n = 26$ the width becomes greater than the separation between $\ell = 0$ and $\ell = 2$, the multiplets loose their identity as such and this fit does not work, so we do not calculate the widths any further. At low frequencies the low S/N ratio for two of the even groups did not permit to give a reliable estimate. The error bars have been computed using a modelisation of the spectrum and a Monte-Carlo simulation of the statistical dispersion

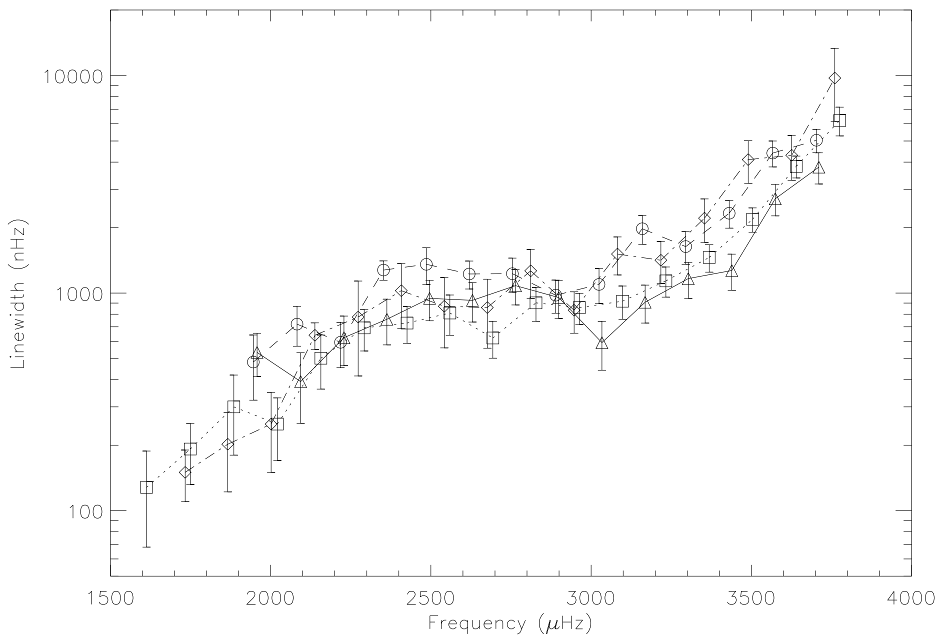

Fig. 6. Line-widths of the p-modes from GOLF experiment. Triangles, open squares, open circles and diamonds are for ℓ=0, 1, 2 and 3 respectively.

of the results. This dispersion is then fitted by a modified Poisson law giving the σ of the distribution (Fierry-Fraillon et al. 1997).

Our final values are shown on Figure 6. The values found here agree very well with the ones measured by Elsworth et al. (1990a) using a similar experiment. Also, within the 1σerror-bars, the absolute values are perfectly comparable with the measured IPHIR widths (Toutain and Fröhlich, 1992) and more recently with the VIRGO measurements (Fröhlich et al. 1997). The exponential behaviour of the widths is clearly visible for all degrees, and supports well the hypothesis of stochastically excited p-mode through the turbulent convection (Goldreich and Murray, 1994). In this context, the departure from this trend, or "plateau", between 2.4 to 3.2 mHz first described by Libbrecht (1988) is fairly visible. The dip in the plateau at about 3.1 mHz reported by Fröhlich et al. (1997) is mostly visible on the ℓ=0 mode and suggest a decrease in the damping of the modes in the region where they have their highest amplitude. Longer data sets will be necessary to measure widths below 1.5 mHz as we are getting near the resolution limit for the smaller widths. The longer apparent lifetime, or phase coherence, measured so far is about 28 days.

6. Discussion

The frequency table presented here is the most complete one done up-to-date having identified over 100 multiplets. We can compare this list with the one obtained with the BiSON ground-based network (Elsworth et al. 1994) completed with the low-n and ℓ=4 values recently reported (Chaplin et al. 1996b,c). We obviously take the list measured at the minimum of solar activity. Out of the 75 frequency determination in common with ours, 99% coincide within 3σ (combined errors), 87% within 2σ and 52% within 1σ. Taking into account that the two determinations do not come from a coeval set of data, we believe the agreement is quite good and reflects that in periods of low solar activity the Sun seems to have the same structure. The differences have to be adscribed to the presence of some sideband structure, even having duty cycles of $\sim$ 70% as those obtained by the integrated sun ground-based networks, which increases the background noise.

The comparison with the other ground based network IRIS is not directly possible as the frequency tables published (Gelly et al. 1995) correspond to year 1991,1992 and 1993 all years with high solar activity which would shift the frequencies towards higher values than the ones found here by an amount several tens of times the errors quoted. However, it can also be compared to a relatively older frequency list obtained by Anguera Gubau et al. (1992) coming from only one observing site. Out of 88 frequency determinations in common with ours, 84% coincide within 3σ, 64% within 2σ and only 36% within 1σ showing the great difficulty of measuring frequencies in a spectra full of side-bands coming from the lack of continuity in the data taken from one observatory.

Finally we could compare the frequency table found here with the ones predicted by a standard solar model, such as the model S calculated by Christensen-Dalsgaard et al. (1996) which include the best parameters to that date and also considers the diffusion of the He and heavy elements in the interior of the Sun. The relative frequency differences (in the sense observed minus predicted) are shown in Fig. 7 where it can be seen that up to frequencies of 2.2 mHz, the differences are within observational errors (around 20 nHz), however from here on the differences increase up to about $\sim$ 3.5 parts in 10^3 and it stabilises (see Turck-Chièze et al. 1997, for a more complete analysis).

The splittings found here (see Table II and Fig. 4) can be compared with those found by both ground-based networks using the same technique: IRIS (Lazrek et al. 1996) and BiSON (Chaplin et al. 1996a,d). With the first one, the agreement is excellent for all degrees which agree within errors, while with the second, the agreement is within 3σ (combined errors) but their average value, at the closest epoch to us (year 1995), is lower than ours by $\sim$50 nHz. However their value obtained near the latest solar activity

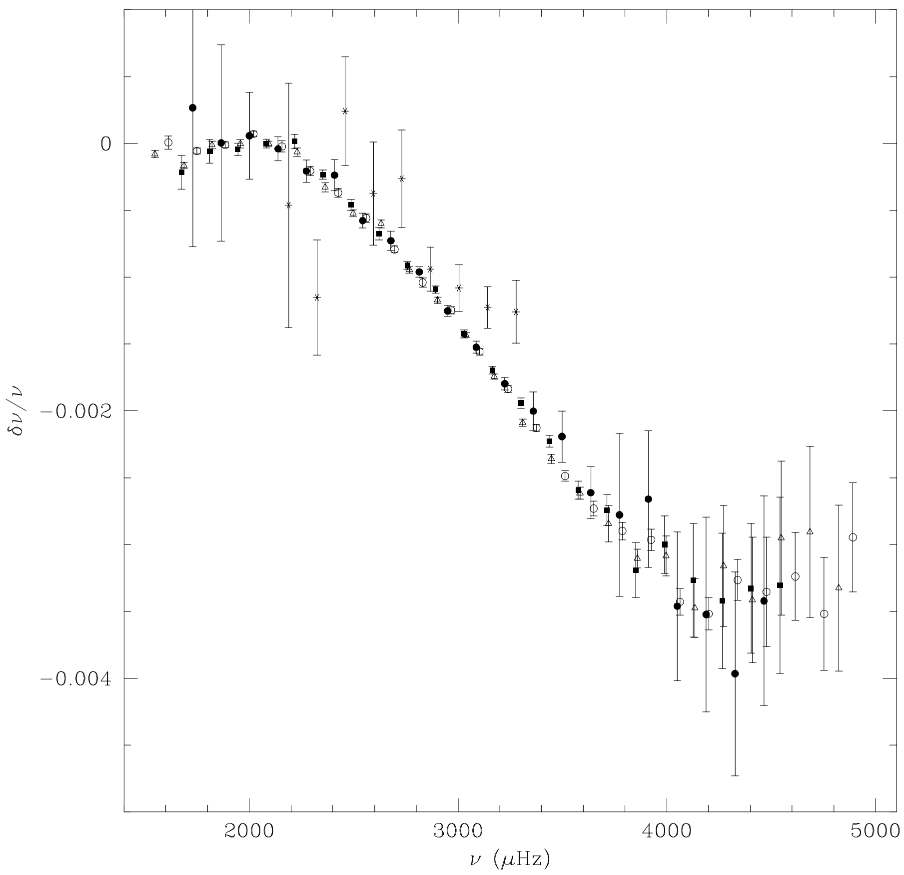

Fig. 7. Relative frequency differences between the observed frequencies and the predicted ones by a solar model including diffusion (Christensen-Dalsgaard et al. 1996). In order to actually see the error bars, specially in the lowest orders, $\pm 1\sigma$ bars have been plotted. Triangles, open squares, open circles, full circles and stars are for ℓ=0, 1, 2, 3 and 4 respectively.

minimum (1985-1987) seems to be much closer to the value obtained here. On the other hand, they can also be compared with the results found by Toutain and Kosovichev (1994) using data collected by the IPHIR sun-photometer on board PHOBOS satellite, back in 1988. In fact, their results agree well with ours, being only some 10 nHz higher, well lower than the combined error bars.

Our results can be interpreted in terms of a non-slowly rotating core; probably it rotates faster than the surface. This has implications in the quadrupole moment of the Sun and in the angular momentum transport in its interior. This splittings should be injected in a rotation inversion programme, with data from higher-ℓ modes, which could allow a complete set to infer the solar rotation profile with depth and latitude; this exercise will be done in the near future using the excellent data that the three Helioseismology experiments on-board SOHO are obtaining (Toutain et al. 1997).

Individual mode splitting determinations with errors much smaller than the ones presented here will be very difficult to obtain. In our opinion only g-mode frequencies have the potentiality to throw new light into this rather poor known solar core rotation rate. These are the expectations in the near future when more data will allow the measurement of such, otherwise, elusive modes.

7. Conclusions

The first analysis of $\sim$ 8 months of observations taken by GOLF on board SOHO reveals the quality of the data being stored. The S/N level of the signal at the 5 min oscillations band (where the p-modes lie) is the best ever achieved reaching several thousands which is readily checked by the clear presence amongst the noise of modes of $\ell \geq 5$ never seen before in integrated sunlight experiments. This supports the idea of having such an instrument to detect solar oscillation modes in stars other than the Sun.

The frequency list presented is the most complete to date, even being a result where the full information of the spectrum has not been extracted yet. At low frequencies, the identification is still not possible due to the "solar noise" throwing peaks into the spectrum which do not allow the unambiguous identification; however it is expected that with more data this will be possible and the full spectrum of p-modes will be reachable by GOLF. The rotational splittings have been extracted and the values found seem to rule out the possibility of a slow-rotating core; the precise rotation of the solar core remains to be calculated through inversion of data that requires information on much more modes than the ones found here (those of higher ℓ values), which are being observed by the other two helioseismology instruments on board SOHO.

Other parameters that require more attention are being studied, at the time of writting this report, such as the linewidths and the energy of the modes and the noise. New methods of analysing the data are being used which seem to yield more accurate fits to the power spectra.

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