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Definitive Sun-as-a-star p-mode frequencies: 23 years of BiSON observations

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ABSTRACT

We present a list of 'best possible' estimates of low-degree p-mode frequencies from 8640 days of observations made by the Birmingham Solar-Oscillations Network (BiSON). This is the longest stretch of helioseismic data ever used for this purpose, giving exquisite precision in the estimated frequencies. Every effort has been made in the analysis to ensure that the frequency estimates are also accurate. In addition to presenting the raw best-fitting frequencies from our 'peak-bagging' analysis, we also provide tables of corrected frequencies pertinent to the quiet-Sun and an intermediate level of solar activity.

Key words: methods: data analysis – Sun: oscillations.

1 INTRODUCTION

It has been known for over 40 years that the surface of the Sun oscillates with a period of around 5 min (see Evans & Michard 1962; Leighton, Noyes & Simon 1962). Originally thought to be local in nature, observations of the 5-min oscillations using unimaged sunlight (i.e. Sun-as-a-star observations) proved that the oscillations were actually a global phenomenon (see e.g. Claverie et al. 1979). The oscillations are the detectable manifestation of acoustic waves that are generated by turbulent motion in the solar convection zone. Waves of certain frequencies interfere constructively leading to a large number of resonant p modes, so called due to the gradient of pressure being the dominant restoring force (see Ulrich 1970; Leibacher & Stein 1971).

In helioseismology, estimates of the frequencies of solar p modes are used as inputs to the inverse problem of trying to better constrain the parameters of solar models (see e.g. Christensen-Dalsgaard 2002). Hence, it is important to determine the frequency estimates to high precision and high accuracy.

The different resonant modes are characterized by three integers: the radial order, n, angular degree, ℓ, and azimuthal order, m. Low-ℓ modes travel deep into the solar interior, while higher degree modes are constrained within the outer regions. Hence, by determining frequencies of a full range of modes it is possible to use inversions to determine the structure of the solar interior as a function of depth. However, there are fewer modes to constrain these inferences for deeper regions of the interior. Hence, when dealing with low-ℓ modes, which are observed most effectively by global (i.e. Sun-as-a-star) observations, obtaining precise frequency estimates is particularly desirable.

The precision with which any p-mode frequency can be determined is directly related to the length of observations one makes. The Birmingham Solar-Oscillations Network (BiSON) (see Chaplin et al. 1996) has collected more than 30 years of observations of global helioseismology data and is therefore in a position to provide estimates of low-ℓ p modes to unprecedented levels of precision. In Section 2, we give details of the BiSON network and explain how the BiSON time series are generated. We also give the parameters of the particular data set used in obtaining the p-mode frequencies given in this Letter.

The most common method of determining the frequencies, which is used here, is to perform a Fourier transform of the time series in order to generate the frequency power spectrum. The modes are then parametrized by fitting an asymmetric Lorentzian model to the peaks, the parameters being frequency, height, width, rotational splitting and fractional asymmetry. This fitting is colloquially referred to as 'peak-bagging' analysis.

In order to give accurate estimates of these parameters, one needs a model that matches the underlying limit spectrum of the mode peaks as closely as possible. Here, we have employed the 'pseudo-global' fitting model of Fletcher et al. (2008, 2009a,b), which we describe briefly in Section 3.

The one drawback of using very long time series in order to determine highly precise frequency estimates is the presence of the solar cycle. During one activity cycle of the Sun, the p-mode frequencies change by up to 1 μHz, which is many times the precision with which we can estimate the frequencies. However, it is possible to track the change in frequency over time, and therefore the solar cycle effect can be accounted and corrected for. We present raw fitted frequencies and frequencies corrected for the solar cycle in Section 4 (for the cases of the quiet-Sun and intermediate levels of solar activity).

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2 THE BISON DATA

The BiSON network comprises six semi-automated and fully automated solar observing stations that are dedicated to collection of low-degree (Sun-as-a-star) helioseismic data. The stations are situated at various sites around the world in order to provide as continuous observations as possible. The six sites are at Mount Wilson in California, Las Campanas in Chile, Izaña in Tenerife, Sutherland in South Africa, Carnarvon in Western Australia and Narrabri in New South Wales.

At each of the six stations, a resonance scattering spectrometer (RSS) (see Brookes, Isaak & van der Raay 1978) is used to measure the Doppler velocity shift of the 770-nm D1 potassium absorption line. This is done by passing the incident solar light through a cell containing a vapour of potassium atoms at a temperature of about 100°C. Photons of the appropriate energy are resonantly scattered by atoms in the cell. As the light from this process is emitted isotropically it is possible, by placing detectors at right angles to the incident beam, to record only those photons which have undergone resonance scattering. The absorption cross-section of atoms in the vapour cell is much narrower than that of the solar Fraunhofer line because the temperature is lower and there is no rotational broadening. Therefore, the intensity of the recorded light will be proportional to the intensity of light emitted from a narrow band of the solar absorption line.

The intrinsic sensitivity of the RSS is improved by moving the passbands out on to the wings of the Fraunhofer line where the slope is greatest, and hence any given line shift will give a greater change in measured intensity. The vapour cell is placed in a longitudinal magnetic field, which causes the Zeeman splitting to occur. The single line is thus split into a multiplet with a separation dependent on the field strength. The magnetic field alters the atomic state in such a way that atoms will interact with circularly polarized light. The blueshifted component of the multiplet is sensitive to one hand of circular polarization, whilst the redshifted component is sensitive to the other.

By using a suitable combination of a linear polarizer and a quarter-wave plate, the incident light can be circularly polarized and hence, by switching quickly between the states of circular polarization, it is possible to measure the light intensity in the blue wing, I_b, and red wing, I_r, almost simultaneously. From these measurements, a ratio, R, is formed which gives a near-linear proxy for the velocity shift of the solar line:

$$R = \frac{I_b - I_r}{I_b + I_r}. \tag{1}$$

Finally, to obtain velocity measurements of the solar oscillations, a third-order polynomial function of the station-Sun line-of-sight velocity is fitted to R. The oscillation signal is then recovered by subtracting R from the polynomial function and calibrated using the fitted gradient of R versus station velocity.

These measurements of the solar oscillations are collected at each station and combined to form a continuous time series with a duty cycle of around 86 per cent (for 2007 and 2008). Izaña has been collecting data since 1976, hence there are over 30 years of BiSON data to call upon. However, with only one station collecting data and at only certain times of the year the fill for these early observations is only of the order of 10 per cent. During the mid 1980s and early 1990s, the remaining BiSON stations were gradually brought online and the window function improved to around 80 per cent and above.

In this Letter, we have chosen to work with an 8640-day set of 40-s cadence BiSON data running from 1985 April 4 until 2008 December 16. The start date corresponds to a time just after the third BiSON station came into use in Carnarvon, Western Australia. This means that the data set starts with a fill of around 20–30 per cent over the first few years which steadily improves to around 80 per cent by 1994 once all six stations were fully operational.

3 THE 'PSEUDO-GLOBAL' TECHNIQUE

The best way of determining estimates of the p-mode frequencies is to take the Fourier transform of the time series in order to get the frequency power spectrum. For Sun-as-a-star observations, the power spectrum has a very distinct pattern. A series of sharp peaks is seen that coincide with the various p-mode frequencies, with the largest peaks signifying the strongest modes at around 3000 μHz (i.e. a period of around 5 min).

On closer inspection, the peaks are seen to be grouped in pairs. These pairs consist alternately of $\ell = 0$ and 2 modes and $\ell = 1$ and 3 modes. In power spectra of long BiSON time series, it is also possible to make out the strongest $\ell = 4$ modes, which tend to have frequencies a little lower than the $\ell = 2$ modes (thus the $\ell = 0/2$ pair could be considered an $\ell = 0/2/4$ triplet). Even closer inspection reveals that all but the $\ell = 0$ modes are rotationally split. However, even with a very high-resolution spectrum this splitting cannot be seen at high frequencies since modes in this regime have short lifetimes, and consequently their peaks have large widths in the power spectrum.

To determine the frequency estimates, an asymmetric Lorentzian model is fitted to the various peaks in the frequency power spectrum. The traditional way of doing this has been to divide the frequency power spectrum into a series of fitting regions and fit the modes in pairs (i.e. $\ell = 0$ and 2 modes together and $\ell = 1$ and 3 modes together) (see e.g. Chaplin et al. 1999). This enables one to determine how the mode parameters depend on both frequency (overtone number) and angular degree without the need to fit the entire spectrum simultaneously.

However, recent work has shown that this method can result in systematic bias in the returned frequencies (Jiménez-Reyes et al. 2008; Fletcher et al. 2009a). The reason for this is that the model only accounts for modes whose central frequencies are within the fitting region. Therefore, power from modes whose central frequencies lie outside this region will not be accounted for. This imperfect match between the fitting model and the underlying profile can lead to bias in the mode parameters.

A global fitting approach where one fits the entire spectrum simultaneously would overcome this problem. However, it would mean using a fitting model with many hundreds of parameters which, when fitting a frequency power spectrum made up of more than 18 million points, leads to prohibitively long computing times. Also, such a complicated model may lead to an increased possibility of premature convergence.

Therefore, in order to eliminate the bias the 'pseudo-global' method of Fletcher et al. (2009a) was employed. This approach works by first setting up a model for the full spectrum (FSM) using the parameter estimates returned from the traditional 'pair-by-pair' method. Then, as with the pair-by-pair approach, the frequency power spectrum is divided into a series of fitting regions. Each region is then fitted using the FSM, but only the parameters of the modes within each particular fitting region are allowed to vary. In this way, we limit the number of parameters being varied at any one time, while still including information in the model from all the modes. A much more detailed account of this fitting method can be found in Fletcher et al. (2009a).

Two further improvements were made in the pseudo-global model used here as compared with the techniques used when determining previously published BiSON frequencies. The first is the inclusion of $\ell = 4$ modes in the model. Secondly, we take account of the gaps in the BiSON data by convolving the fitting model with the spectral window, as opposed to simply fitting for the prominent diurnal sidebands (see Fletcher et al. 2009b).

When employing the pseudo-global method, the fitting regions were 130 μHz wide and centred at the mid-point of the $\ell = 0/2$ and $1/3$ pairs. The $\ell = 4$ modes were also included in the model when these modes were visible. Within each fitting region, the following equation is used to fit the power spectral density, P, as a function of frequency, ν:

$$P(\nu) = \left[P'(\nu) + n(\nu) + \sum_{\ell m} \frac{f_{\ell m} A_l (1 + 2b x_{\ell m})}{1 + x_{\ell m}^2} \right] * W, \qquad (2)$$

where

$$x_{\ell m} = \frac{2[\nu - (\nu 0_\ell + m\delta\nu_\ell)]}{\Gamma_\ell}. \qquad (3)$$

W is the spectral window function and the asterisk denotes a convolution. P' is the power from the remainder of the power spectrum outside of the fitting region. A_l denotes the mode heights and $f_{\ell m}$ the relative m component fractional height ratios (assumed to take fixed values), b is the fractional asymmetry of the modes (fixed across the fitting region), $\nu 0_\ell$ are the mode frequencies, $\delta\nu_l$ are the rotational splittings and Γ_ℓ are the mode widths (fixed across m components). Finally, n is the background term given by the Harvey (1985) model to account for the solar granulation with a constant term, β to account for instrumental noise.

$$n(\nu) = \frac{2\sigma^2\tau}{1 + (2\pi\nu\tau)^2} + \beta, \qquad (4)$$

where τ and σ represent the time constant and standard deviation, respectively, of the granulation signal. Within the fitting region only the β term is allowed to vary. The values of σ and τ were fixed beforehand, by fitting the Harvey model to the low- and high-frequency regions of the frequency power spectrum (i.e. outside the region of the modes).

Once all the fitting regions have been covered, an improved set of parameter values (compared to those returned from the traditional fitting method) will have been determined for the entire spectrum. These new values can then be used to set up another model for the entire spectrum and the whole pseudo-global process can be run again. In general, the process only needs to be repeated one or two times before no further significant improvements are seen in the mode parameters between successive iterations.

Differences between the frequency estimates from the pseudo-global technique and the traditional approach are small. However, because of the high precision of the BiSON frequencies the differences are significant and also systematic. The frequencies from the pseudo-global technique are between 0.02 and 0.04 μHz (1σ–2σ) lower than those determined from a traditional approach over the region 2200–3500 μHz.

4 A DEFINITIVE LIST OF BISON FREQUENCIES

The raw, best-fitting frequencies from our pseudo-global peak-bagging analysis are listed in Table 1. We have augmented this list at very low frequencies with previously published BiSON frequencies that come from work where we deliberately targeted the low-frequency regime (Chaplin et al. 2002, 2007). We have included one additional frequency to those previously published, the $n = 7$, $\ell = 1$ at 1185.592 μHz, however only the $m = -1$ component was detected. To estimate the frequency centroid, we therefore added to the frequency of the observed component the mean rotational frequency splitting of nearby non-radial modes.

Tables of frequencies have to be used with care, because p-mode frequencies vary with the level of solar activity. We therefore provide sufficient information to enable our frequencies to be corrected

Table 1. Raw, best-fitting frequencies (in μHz) from our pseudo-global peak-bagging analysis.

n	$\ell = 0$	$\ell = 1$	$\ell = 2$	$\ell = 3$	$\ell = 4$
6	972.613 ± 0.002				
7		1185.592 ± 0.004			
8	1263.162 ± 0.012	1329.629 ± 0.004	1394.680 ± 0.011		
9	1407.481 ± 0.006	1472.836 ± 0.005	1535.861 ± 0.008	1591.575 ± 0.014	
10	1548.336 ± 0.007	1612.723 ± 0.007	1674.540 ± 0.008	1729.092 ± 0.016	
11	1686.601 ± 0.011	1749.285 ± 0.007	1810.314 ± 0.009	1865.307 ± 0.019	
12	1822.203 ± 0.011	1885.091 ± 0.009	1945.816 ± 0.013	2001.265 ± 0.017	
13	1957.431 ± 0.012	2020.810 ± 0.010	2082.131 ± 0.015	2137.821 ± 0.019	
14	2093.535 ± 0.013	2156.812 ± 0.014	2217.698 ± 0.018	2273.563 ± 0.026	2324.163 ± 0.051
15	2228.774 ± 0.014	2292.032 ± 0.015	2352.280 ± 0.017	2407.707 ± 0.025	2458.716 ± 0.076
16	2362.823 ± 0.015	2425.650 ± 0.014	2485.948 ± 0.019	2541.754 ± 0.023	2593.197 ± 0.053
17	2496.226 ± 0.016	2559.235 ± 0.015	2619.761 ± 0.018	2676.252 ± 0.022	2728.502 ± 0.038
18	2629.724 ± 0.014	2693.437 ± 0.013	2754.551 ± 0.016	2811.440 ± 0.020	2864.349 ± 0.033
19	2764.211 ± 0.014	2828.258 ± 0.013	2889.708 ± 0.016	2947.075 ± 0.018	3000.227 ± 0.034
20	2899.101 ± 0.012	2963.447 ± 0.012	3024.839 ± 0.016	3082.439 ± 0.022	3136.105 ± 0.032
21	3033.845 ± 0.012	3098.287 ± 0.013	3159.997 ± 0.017	3217.881 ± 0.024	3271.864 ± 0.048
22	3168.726 ± 0.014	3233.321 ± 0.016	3295.275 ± 0.021	3353.580 ± 0.037	3408.325 ± 0.069
23	3303.652 ± 0.019	3368.689 ± 0.021	3431.006 ± 0.030	3489.699 ± 0.049	
24	3439.152 ± 0.027	3504.397 ± 0.028	3567.248 ± 0.041	3626.408 ± 0.073	
25	3575.083 ± 0.046	3640.791 ± 0.036	3703.388 ± 0.065	3762.917 ± 0.102	
26	3710.938 ± 0.086	3777.436 ± 0.050	3840.118 ± 0.143	3900.029 ± 0.155	
27	3847.250 ± 0.177	3913.995 ± 0.066	3977.388 ± 0.297		
28	3984.507 ± 0.323				

Table 2. Corrected frequencies (in μHz), pertinent to an intermediate level of solar activity (see the text).

n	$\ell = 0$	$\ell = 1$	$\ell = 2$	$\ell = 3$
6	972.613 ± 0.002			
7		1185.592 ± 0.004		
8	1263.162 ± 0.012	1329.629 ± 0.004	1394.680 ± 0.011	
9	1407.481 ± 0.006	1472.836 ± 0.007	1535.862 ± 0.007	1591.575 ± 0.014
10	1548.335 ± 0.007	1612.723 ± 0.007	1674.540 ± 0.008	1729.092 ± 0.016
11	1686.601 ± 0.011	1749.285 ± 0.007	1810.314 ± 0.009	1865.306 ± 0.019
12	1822.203 ± 0.011	1885.092 ± 0.009	1945.815 ± 0.013	2001.264 ± 0.017
13	1957.433 ± 0.012	2020.811 ± 0.010	2082.130 ± 0.015	2137.820 ± 0.019
14	2093.538 ± 0.013	2156.813 ± 0.014	2217.697 ± 0.018	2273.563 ± 0.026
15	2228.779 ± 0.014	2292.035 ± 0.015	2352.280 ± 0.017	2407.709 ± 0.025
16	2362.831 ± 0.015	2425.655 ± 0.014	2485.950 ± 0.019	2541.758 ± 0.023
17	2496.237 ± 0.016	2559.242 ± 0.015	2619.766 ± 0.018	2676.259 ± 0.022
18	2629.741 ± 0.014	2693.450 ± 0.013	2754.561 ± 0.016	2811.455 ± 0.020
19	2764.233 ± 0.014	2828.279 ± 0.013	2889.726 ± 0.016	2947.101 ± 0.018
20	2899.133 ± 0.012	2963.478 ± 0.012	3024.867 ± 0.016	3082.471 ± 0.022
21	3033.886 ± 0.012	3098.327 ± 0.013	3160.028 ± 0.017	3217.916 ± 0.024
22	3168.773 ± 0.014	3233.358 ± 0.016	3295.301 ± 0.021	3353.602 ± 0.037
23	3303.698 ± 0.019	3368.721 ± 0.021	3431.019 ± 0.031	3489.712 ± 0.049
24	3439.195 ± 0.027	3504.417 ± 0.028	3567.255 ± 0.041	3626.420 ± 0.073
25	3575.121 ± 0.046	3640.799 ± 0.036	3703.386 ± 0.065	3762.911 ± 0.102
26	3710.972 ± 0.086	3777.430 ± 0.050	3840.096 ± 0.143	3900.013 ± 0.155
27	3847.277 ± 0.177	3913.974 ± 0.066	3977.350 ± 0.297	
28	3984.527 ± 0.323			

to an activity level of choice. This will help comparisons and combinations with observations made by other instruments, which do not span the 8640-day period covered here. We present two tables of frequencies, which were produced by applying suitable correction procedures to the raw frequencies listed in Table 1. We use the 10.7-cm radio flux (Tapping & DeTracey 1990) as our adopted proxy of the global level of solar activity. We have not corrected the $\ell = 4$ frequencies, for the reasons described near the end of this section. Corrections have not been applied to the very low-frequency modes (<1450 μHz), as these show very little cycle variation and the corrections would be insignificant at the level of precision of the data.

The list of frequencies in Table 2 is pertinent to an intermediate level of solar activity, which corresponds to a mean level of the 10.7-cm radio flux of $118 \times 10^{-22}\,\mathrm{W\,m^{-2}\,Hz^{-1}}$. The list in Table 3 is pertinent to the canonical 'quiet-Sun' level of the radio flux, which, from historical observations of the index, is set at $64 \times 10^{-22}\,\mathrm{W\,m^{-2}\,Hz^{-1}}$ (again see Tapping & DeTracey 1990). To

Table 3. Corrected frequencies (in μHz), pertinent to the canonical 'quiet-Sun' (see the text).

n	$\ell = 0$	$\ell = 1$	$\ell = 2$	$\ell = 3$
6	972.613 ± 0.002			
7		1185.592 ± 0.004		
8	1263.162 ± 0.012	1329.629 ± 0.004	1394.680 ± 0.011	
9	1407.481 ± 0.012	1472.835 ± 0.007	1535.859 ± 0.011	
10	1548.333 ± 0.007	1612.720 ± 0.007	1674.534 ± 0.008	1729.085 ± 0.016
11	1686.597 ± 0.011	1749.279 ± 0.007	1810.304 ± 0.009	1865.293 ± 0.019
12	1822.196 ± 0.011	1885.081 ± 0.009	1945.797 ± 0.013	2001.243 ± 0.017
13	1957.421 ± 0.012	2020.793 ± 0.010	2082.102 ± 0.015	2137.788 ± 0.019
14	2093.518 ± 0.013	2156.784 ± 0.014	2217.656 ± 0.018	2273.516 ± 0.026
15	2228.749 ± 0.014	2291.993 ± 0.015	2352.222 ± 0.017	2407.643 ± 0.025
16	2362.788 ± 0.016	2425.595 ± 0.015	2485.873 ± 0.019	2541.671 ± 0.023
17	2496.180 ± 0.017	2559.162 ± 0.015	2619.668 ± 0.018	2676.149 ± 0.023
18	2629.668 ± 0.015	2693.347 ± 0.014	2754.439 ± 0.017	2811.318 ± 0.021
19	2764.142 ± 0.015	2828.150 ± 0.014	2889.578 ± 0.018	2946.935 ± 0.021
20	2899.022 ± 0.013	2963.322 ± 0.014	3024.689 ± 0.018	3082.273 ± 0.025
21	3033.754 ± 0.014	3098.140 ± 0.015	3159.821 ± 0.020	3217.683 ± 0.028
22	3168.618 ± 0.017	3233.139 ± 0.018	3295.063 ± 0.025	3353.335 ± 0.041
23	3303.520 ± 0.021	3368.469 ± 0.023	3430.748 ± 0.034	3489.409 ± 0.053
24	3438.992 ± 0.030	3504.129 ± 0.030	3566.949 ± 0.044	3626.078 ± 0.075
25	3574.893 ± 0.048	3640.475 ± 0.038	3703.044 ± 0.067	3762.530 ± 0.105
26	3710.717 ± 0.088	3777.067 ± 0.052	3839.717 ± 0.144	
27	3846.993 ± 0.177	3913.570 ± 0.068	3976.930 ± 0.298	
28	3984.214 ± 0.323			

obtain low-degree frequencies pertinent to a level of activity higher than quiet-Sun, a linear interpolation can be performed between the values in Tables 2 and 3 (or a linear extrapolation may be carried out if the chosen activity level is higher than 118×10^{-22} W m^{-2} Hz^{-1}). Both frequency tables have been produced so that the frequencies correspond to the *frequency centroids* of the low-degree modes. The frequency centroids carry information on the spherically symmetric component of the internal structure.

The Sun-as-a-star data do not always provide estimates of the centroids by default. That is because only $\ell + 1$ of the $2\ell + 1$ components in each non-radial mode are seen clearly in the observations (those with even $\ell + m$). At times of low solar activity, components in the non-radial modes are arranged symmetrically in frequency: then peak bagging of the Sun-as-a-star data *does* give the required centroids. However, at times when there is significant surface activity – as in our 8640-day time series – the components are not arranged symmetrically in frequency, and so because some components are missing from the Sun-as-a-star observations we measure a slightly different frequency to the centroid. It is possible to make a correction for this effect, as discussed in detail by Appourchaux & Chaplin (2007). We have applied such a correction to give the 118×10^{-22} W m^{-2} Hz^{-1} frequencies in Table 2.

The frequencies in Table 3 are corrected to the quiet-Sun level, using a procedure that by definition corrects to the expected quiet-Sun *centroid* frequencies. The procedure assumes that the frequency correction can be parametrized as a linear function of the chosen activity proxy. The BiSON correction is self-consistent. First, we divide the long BiSON time series into shorter pieces in order to quantify the sensitivity of the frequencies to the changing 10.7-cm flux (by linear regression). We then use this information to calibrate our correction. Since we could not obtain robust estimates of the $\ell = 4$ frequency shifts using our data, we did not attempt to correct the frequencies of these modes. There are gaps in the BiSON time series (e.g. due to inclement weather, and very occasionally instrument problems). The window function of the BiSON observations was therefore also applied to the time series of the 10.7-cm radio flux.

Full details of the correction procedures will be published elsewhere (Broomhall et al. 2009).

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