BiSON Primer

Yvonne Elsworth, William J. Chaplin
University of Birmingham, Edgbaston, Birmingham B15 2TT

and

Roger New
Sheffield Hallam University, Sheffield S1 1WB

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Contents

1 BiSON Data Collection, Calibration and Analysis Primer

1.1 The BiSON Spectrometers: Collection of the Data

All vintages of the BiSON spectrometers (see Appendix C in the BiSON grant application) use resonant scattering of light from the Fraunhofer line of potassium at 769.9 nm to measure the shift between the solar line and the same potassium resonance in atoms in the laboratory. Although different collection optics, modulation devices, and detectors are used in different instruments, the schematic diagram in Fig. 1 applies in principle to all BiSON spectrometers.

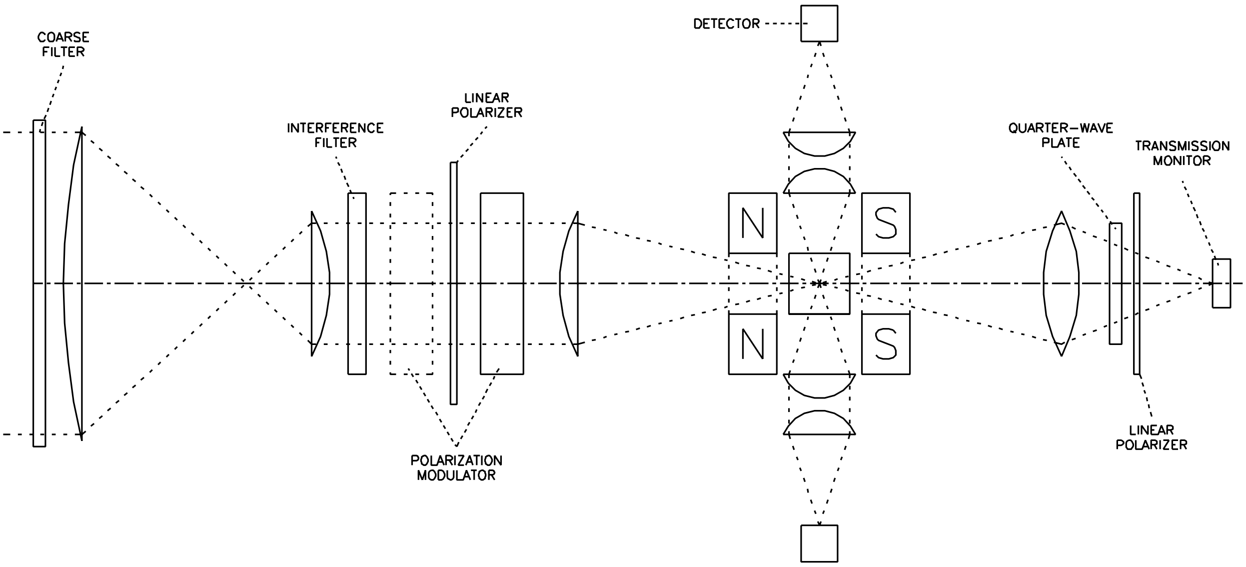

Figure 1: Schematic diagram of a BiSON resonant-scattering spectrometer.

Towards the rear (right-hand end of the diagram) of the instrument, a heated glass cell containing potassium is placed between the pole pieces of a permanent magnet ($B \approx 2\,\mathrm{kG}$). Holes in the pole pieces allow a beam of sunlight to traverse the cell; light scattered at right angles to the solar beam is collected and imaged onto detectors.

At the fields employed in our spectrometers, we are concerned with the anomalous Zeeman effect. Because we work with a magnetic field whose orientation is along the optical axis, and because several of the individual components are very close together, the potassium vapour essentially provides one scattering component in each wing of the solar Fraunhofer line as shown in Fig. 2; the laboratory lines are much narrower ($\sim 0.8\,\mathrm{km\,s^{-1}}$) than that of the Sun because the vapour temperature is only about 400 K and the solar line is broadened ($\sim 8\,\mathrm{km\,s^{-1}}$) by temperature, turbulence effects and rotation.

The Zeeman components are sensitive to the state of circular polarization of the incident beam. Circularly polarized sunlight is able to excite only one of the two Zeeman responses. In the instrument, the sunlight is indeed circularly polarized, but the state is switched from left-hand to right-hand — thus switching the detected scattering from between the blue (I_{B}) and red (I_{R}) wings of the solar line. Because the solar line profile is nearly symmetrical and linear over the region of interest, having allowed for background counts, the ratio

$$\mathcal{R} = \frac{I_{\mathrm{B}} - I_{\mathrm{R}}}{I_{\mathrm{B}} + I_{\mathrm{R}}}$$

is approximately a linear measure of the relative line-of-sight velocity of the solar surface, which can be expressed as

$$V_{\mathrm{obs}} = k\mathcal{R},$$

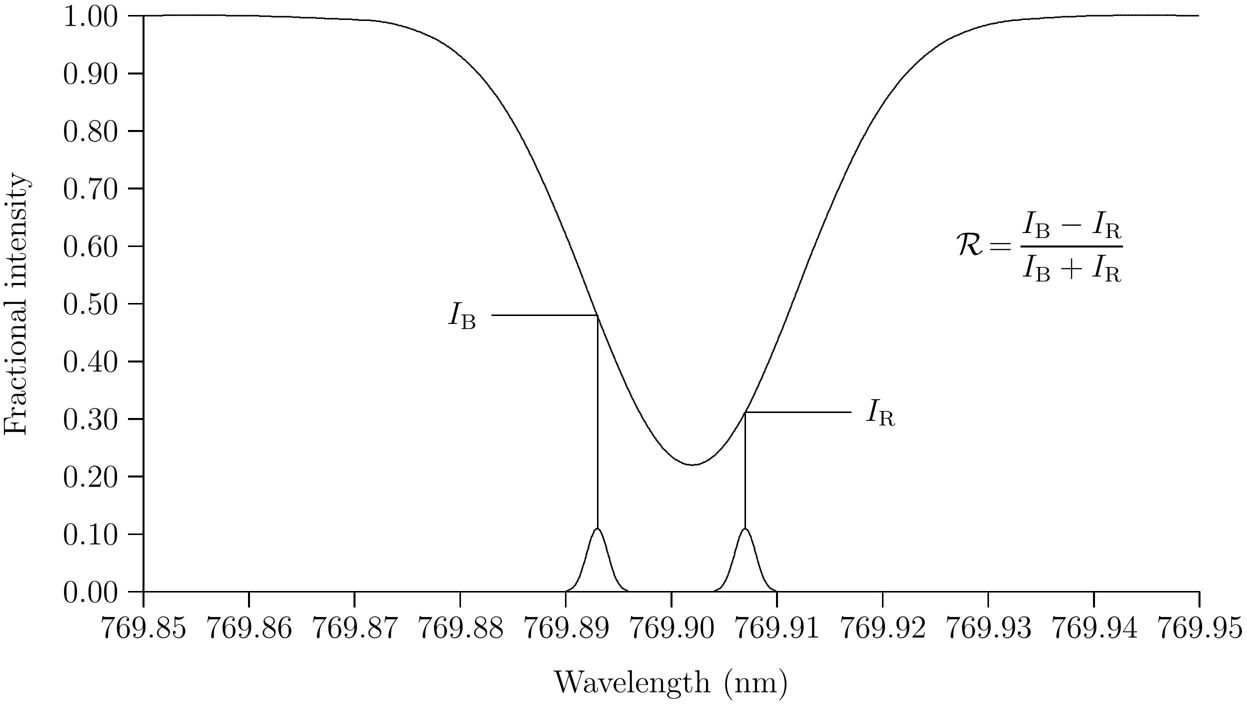

Figure 2: The Fraunhofer line.

where the constant of proportionality, k, is typically $3000\,\mathrm{m\,s^{-1}}$ [1]. The ratio is calibrated to the line-of-sight velocity on a daily basis by using the diurnal variations due to the Earth's rotation (see Section 1.2 below).

To study the five-minute oscillations, the solar velocity must be determined with a cadence of about one minute or less. BiSON initially used a forty-two-second cadence but now employs one at forty seconds. To reduce sensitivity to atmospheric variations, the polarization is switched rapidly and the data acquired over a forty-second interval are averaged to provide our primary measure of solar-versus-laboratory line-shift.

The resonant-scattering system employed in the BiSON instruments has several strengths — there is an atomic standard of frequency within the apparatus and the measurement is of small differential effects (K atoms on the Sun are compared with K atoms in the laboratory). This ensures that BiSON instruments are inherently extremely stable. Careful temperature stabilization of key components, such as interference filters and detectors, adds to the stability.

Fig. 1 indicates the provision of a 'transmission' detector. The signals from this device can be useful for diagnostic work and, with suitable polarizing optics, can provide an aid to setting up and monitoring the performance of the modulation device. The diagram also shows that a second polarization modulator can be added to the linear polarizer. This makes the instrument sensitive to the state of circular polarization of the solar line — it allows the Zeeman splitting of the solar line, and hence a globally averaged value for the photospheric magnetic field — the so-called Solar Mean Magnetic Field (SMMF) — to be determined [2, 3, 4]. In the instruments which have to date been equipped to measure magnetic field (Sutherland and Las Campanas), the two polarization modulators operate at frequencies of the order of 100 Hz.

1.2 Calibration of the Data

Routine calibration of daily data collected at each of the network sites is performed by our Data Analysis Assistant, Mr John Allison (see Section 7.6 on page 16 in the BiSON grant application). He oversees receipt of daily data from the stations via Internet and modem transfer. Because of differences in instrument vintages and capabilities, some preprocessing may then be required to ensure all data are in a standard format ready for calibration.

A typical day of data consists of about 1000 determinations of the ratio, each being an average over 40 seconds (see Fig. 3). Variation in the raw observable (the ratio) is made up of contributions from: the spin of the Earth; the orbital motion of the Earth about the Sun; a substantial DC-offset due to the solar gravitational redshift; instrumental offsets, and the complex velocity distribution patterns that cover the solar surface, *e.g.,* those arising from the trapped p modes. The data are readily calibrated, given the terrestrial location of the observatory, and the epoch of the observations. An ephemeris is used to compute the spin and orbital elements of the motion at the times of observation, so that changes in the raw observable can be matched to absolute changes in velocity. Calibration of the raw data to velocity is achieved by making a daily third-order polynomial fit of the raw (ratio) observable on the ephemeris velocity [5], the latter having had offsets, such as the gravitational red-shift, removed. Residual velocities from the fit are then due to solar oscillations and noise. Sections of data contaminated by bad weather or instrumental breakdown must be flagged, logged and removed before the fit is made.

The calibration procedures are applied using the BiSON RED and ORANGE suites of C++ software codes. The standard pipeline has recently been upgraded to also generate calibrated SMMF residuals from those sites that measure the magnetic field.

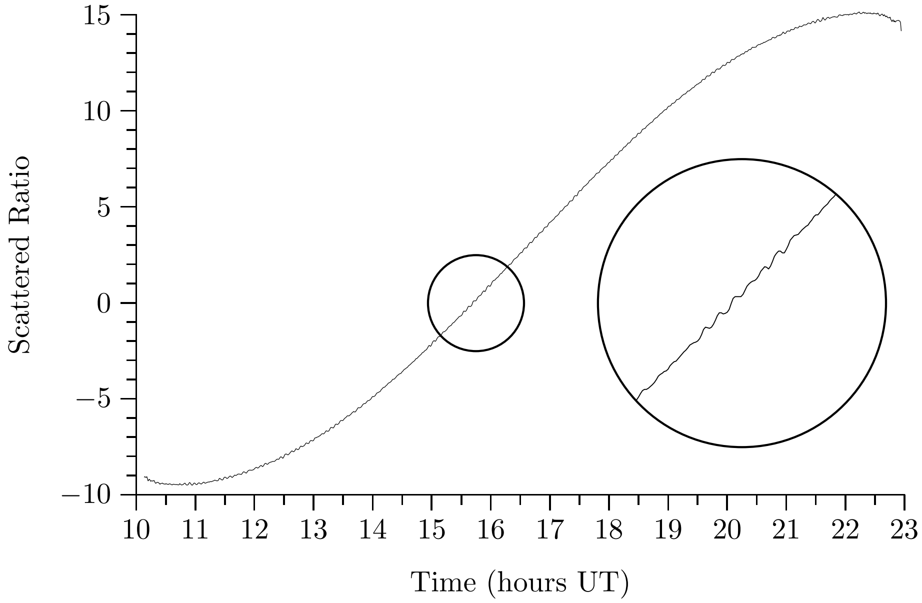

Figure 3: A day of data collected at our Las Campanas site. The diurnal change in velocity due to the rotation of the earth is very well defined and, on top of it, the five-minute solar oscillations with an rms amplitude of 1–2 m s^{-1} can be seen. The inset shows a magnified region of the trace.

Fig. 4 shows some 3 hr of calibrated BiSON velocity residuals. These data were collected at a time of the day when our sites at Las Campanas in Chile (dark line) and Sutherland in South Africa (faint line) were viewing the Sun simultaneously. The level of agreement between the two signals serves as a testament to the excellent quality of the instrumentation and the high precision of the collected data. The residuals are strongly periodic, having a typical RMS velocity of the order of 1 m s^{-1}, and exhibit strong beats: they are dominated by the response to roughly 100 low-degree p mode multiplets, densely spaced in frequency.

1.3 Concatenation of Data: Generation of Multi-Site Timeseries

While some analysis projects can make use of individual days of calibrated data, the majority demand that daily data from all of the stations be concatenated to give a well-filled timeseries

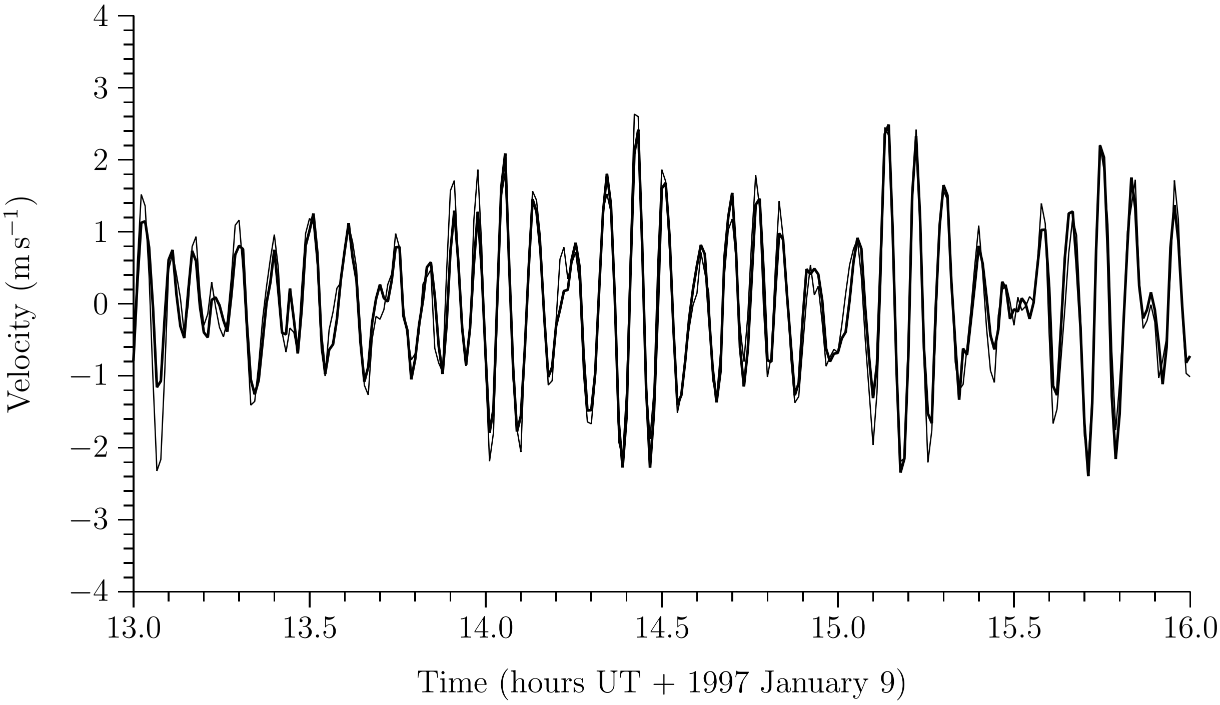

Figure 4: A three-hour segment of overlap data, collected at Las Campanas in Chile (dark line) and Sutherland in South Africa (faint line) on 1997 January 9.

covering periods of in some cases many years. The required length of timeseries depends upon the objective. In order to study the low-frequency modes timeseries must be as long as possible. This is because these modes are very weak, and, since they are long lived, they give rise to peaks in the frequency domain that are very narrow. The signal-to-noise ratio and resolution in frequency must therefore be maximized.

Solar cycle studies demand the high temporal resolution necessary to follow the changes on different parts of the cycle. Analysis of the observations in subset lengths of a few months provides a good compromise — the length is short enough to track changes, while at the same time long enough to give good S/N and resolution in frequency.

Before daily calibrated BiSON residuals are combined, further stages of data processing and data selection may be applied:

Removal of Low-Frequency 'Footprints' Daily data from those stations that house equatorially mounted spectrometers often exhibit unwanted low-frequency behaviour — or a 'footprint' — that is quasi-oscillatory in nature. A suite of codes has been developed that fits a model to this low-frequency artifact, allowing it to be removed from daily residuals [6, 7]. In the model, the artifact is described in terms of subtle guiding errors.

Optimized Data Selection Differences in instrumental capability and performance mean data from some BiSON stations map better to particular science problems than do others. For example, instruments with superior low-frequency performance give excellent data for observing the low-frequency p modes. A further set of software codes make intelligent selections of daily data to put into a concatenated time series, dependent upon the usage to which the timeseries will be put. Selection criteria are set by multi-parameter minimization of information on the noise performance of each day of data. The method has been applied with notable success to give timeseries optimized for low-frequency studies [7].

Timing Errors Regions of data overlap between stations allow use of cross-correlation techniques to search for timing errors. Codes developed by our Network and Data Preparation PDRA, Mr Steve Hale (see Section 7.4 in the BiSON grant application) are used to find, and log timing errors. Recent work, conducted as part of the BiPSAL programme (Section 5, beginning on page 10, in the grant application) has shown that even small timing errors, of a few 40-s samples, can lead to unwanted low-frequency artifacts in the calibrated velocity residuals. When timing errors are found, the daily data must therefore be re-calibrated.

Once filtering, and quality selection, has been applied, daily residuals are combined in a coherent manner to form a time series ready for subsequent analysis. This is accomplished by an IDL suite of codes written by Mr Hale [8]. These codes are a consolidation of, and a major development on, codes written over a decade ago. Choices can be made as to how to make the combination. For example, in regions of overlap data from all available sites may be combined in a weighted manner to give the final residuals, thereby taking advantage of the extra statistical precision afforded by having data available simultaneously from more than one station [9].

Fig. 5 is an example of a 6-day segment from a concatenated time series of calibrated velocity residuals. This segment has data contributions from all six BiSON stations.

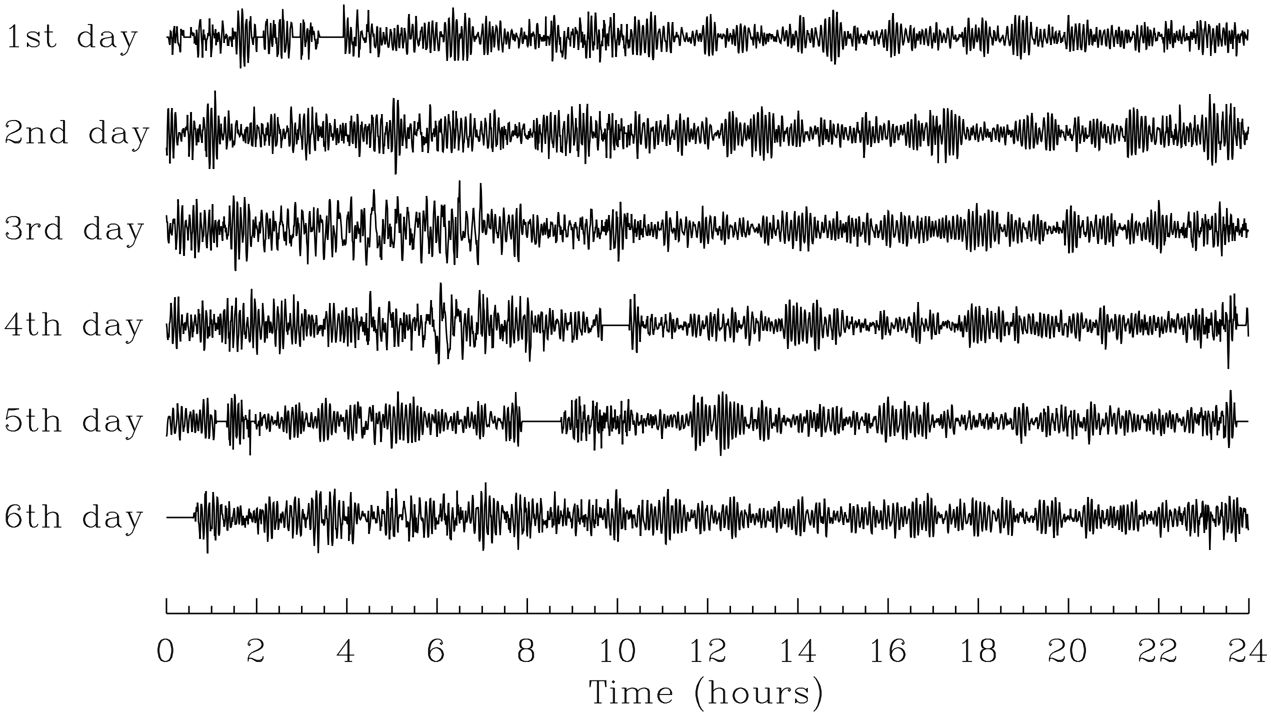

Figure 5: Concatenated timeseries made from the coherent combination of data from all six BiSON stations. This is an example of a 6-day segment.

1.4 'Peak Bagging' — Fitting the Modes

Fig. 6 is a power spectrum made from a 64-month-long timeseries of concatenated BiSON residuals. The rich structure shows the low-degree, core-penetrating modes. The input data for probing the solar interior are the parameters that describe these mode peaks. The mode frequencies are used as input for inferring the hydrostatic structure (sound speed, density). The frequencies are also affected by the near-surface magnetic activity, giving information on the solar cycle and the solar dynamo. The mode frequency splittings carry information on the internal rotation, and (more subtly) the effects of the magnetic fields, while the powers, widths and asymmetries of the peaks carry information on the excitation and damping mechanisms, and by implication the solar convection.

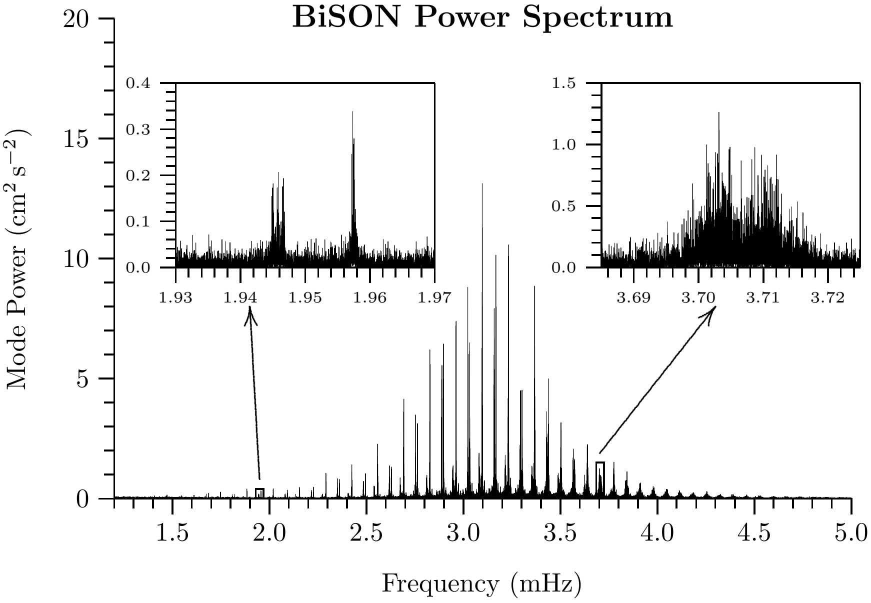

Figure 6: A power spectrum made from a 64-month-long timeseries of concatenated BiSON residuals, showing the low-degree p modes. The insets show mode pairs from low and high-frequency parts of the spectrum.

Accurate, and precise, mode parameter data are a vital prerequisite for robust, accurate inference on the internal structure. The parameters in question are usually extracted by fitting a suitable model to the peaks in the spectrum.

Modes appear paired off in the low-degree spectrum — the $l = 0$ modes lie close in frequency to the $l = 2$; while the $l = 3$ lie close to the $l = 1$. Owing to their close proximity in frequency, the modes must therefore be fitted in pairs. Each fit can involve the simultaneous variation and optimization of up to twenty free parameters (remember that each non-radial mode is comprised of several components). The optimization is achieved by varying the parameters iteratively to maximize the ‘likelihood’ of the model; or, put another way, to give that estimate of the underlying model that makes the observed mode spectrum most likely. Fig. 7 shows the results of fitting $l = 2/0$ (quadrupole/monopole) mode pairs at low, intermediate and high frequencies.

This figure illustrates nicely the changing nature of the p-mode spectrum, the most conspicuous change being an increase in peak width (decrease in mode lifetime) at high frequency. This increase of width results first in the individual components of a mode multiplet (middle panel), and ultimately adjacent modes of different l, blending together (lower panel). This places different demands upon the numbers and types of parameters that can be fitted, and the type of fitting technique that is best applied (*e.g.,* standard ‘hill climbing’ or genetic routines) in different parts of the spectrum.

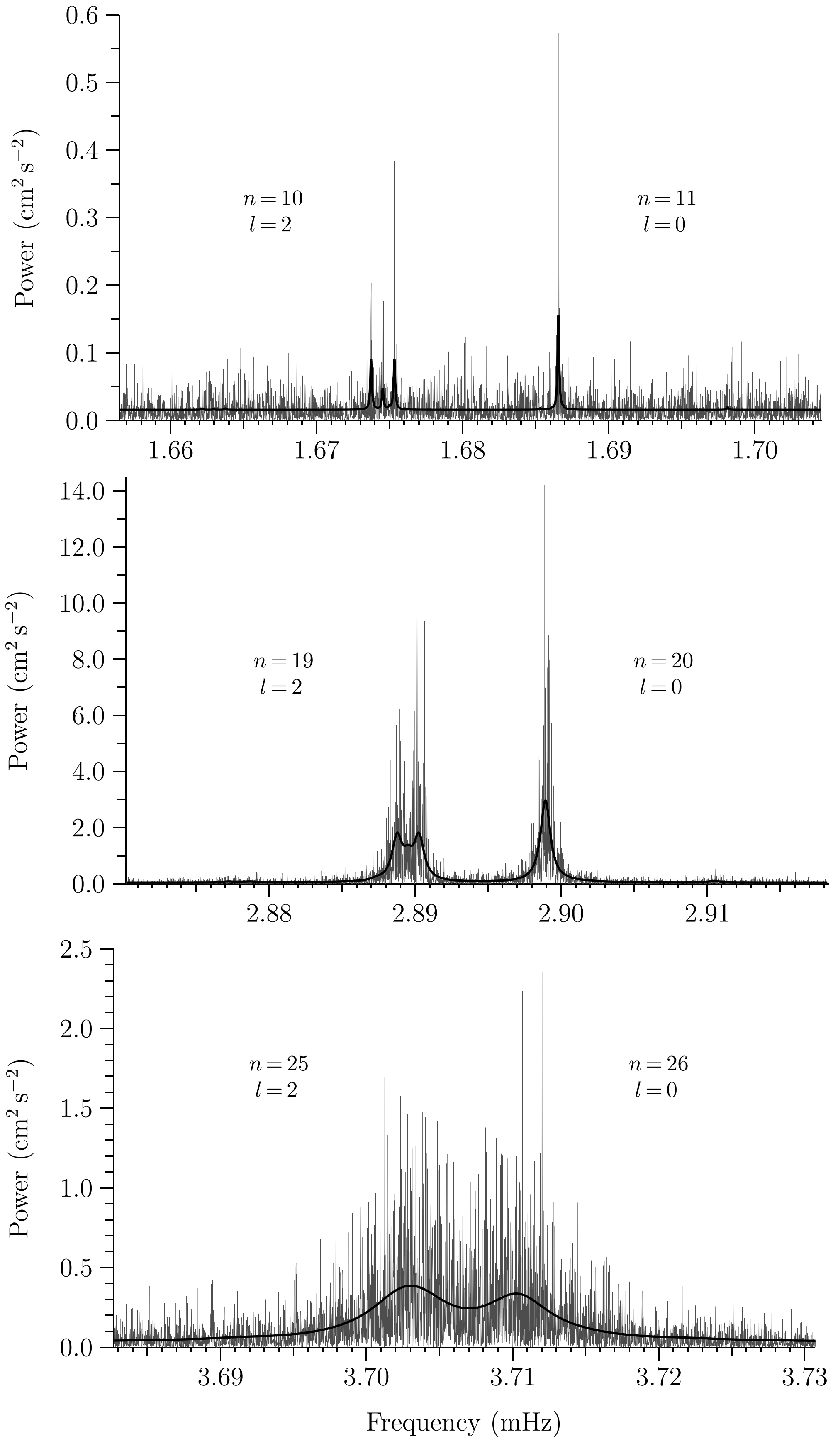

Figure 7: Analogous $l = 2/0$ mode pairs, in a spectrum made from 32 months of BiSON data, at low (top), intermediate (middle) and high (bottom panel) frequencies. The bold line in each panel is a fit to the underlying multi-parameter mode structure.

2 The Need for a Network

Here we explain why, in order to maximize our science return, long datasets are required with a high fractional fill of useful data (*i.e.,* excellent continuity). This can be achieved by a reliable network. Furthermore, in the context of achieving our science goals, it is important that the BiSON continues to collect data of the highest quality. This much was recognized by the PPARC Solar System Science Strategy 2002–2012 document, which noted "... Data from the solar satellite missions have not superseded but only reinforced the requirement for BiSON to continue...".

2.1 The Need for Long Data Sets

- The acquisition of data over many years allows long-term phenomena to be studied, for example the 11-year solar activity cycle (strictly 22 yr if one takes the change of magnetic polarity into account). As discussed in the BiSON grant application, the mode parameters (*e.g.*, frequency, damping and power) are affected by the changing activity, and study of these variations can be used to better understand the origins and nature of the cycle itself. Accurate measurement of the impact of the cycle on the modes is of vital importance for attempts to remove the effects of surface activity from the frequencies, so that an 'uncorrupted' picture can be formed of the deep interior of the Sun (*e.g.*, see Section 5.1 in the grant application).

  The extensive BiSON database now extends over a large part of three 11-yr cycles. However, only since 1992 has the BiSON operated in its current 'high fill', 6-station configuration, and analysis of earlier data is made more difficult because of the low duty cycles.

- Very long time series are needed in order to uncover the very low-frequency modes. As discussed in the grant application, since these modes are extremely long-lived their resonant peaks are expected to be extremely narrow (in frequency). The lifetimes of modes below $\sim 1000\,\mu$Hz are so long as to make their peaks unresolvable in decade-long datasets [10]. This attribute does carry the advantage that the signal-to-background ratio will increase *linearly* with time. However, the need for continued observation is clearly indicated, to allow proper study of all parameters of these modes in the required, very long datasets.

  To summarize, the only route to detect weak modes is to have long data sets *and* low background noise. At the lowest frequencies where there are currently secure mode identifications, noise levels in the BiSON and GOLF Doppler velocity data are similar, and superior to those in the MDI and GONG Doppler data. This is one reason why BiSON has such an important rôle to play in the Phoebus collaboration, whose aims are to uncover the low-frequency p and g modes (see Section 4.2 in the BiSON grant application).

- Modes that reside in the well-studied part of the p-mode spectrum are usually well resolved, so that their characteristic lifetimes are shorter than the length of the sets that are used to observe them. While the signal-to-background ratio remains essentially constant over time for such modes, it is nevertheless vital to continue to collect as much data as possible because the precision with which their parameters can be determined improves with the square root of time. We have demonstrated that this is indeed the case when real data are analyzed.

- The availability of long time series is also advantageous for determining accurately subtle mode characteristics, such as asymmetry in the shapes of the mode peaks (Section 4.5 in the BiSON grant application) and asymmetry in the frequency spacing of components within multiplets (from the effects of near-surface magnetism; see [11, 12]). Effects like these must be correctly modeled and measured in order to obtain accurate and well-understood estimates of mode frequencies and splittings for inversions.

- Troublesome artifacts that arise during analysis of low-l data show a tendency to reduce in severity as dataset length increases. An excellent example comes from the problem of extracting estimates of the rotational splitting at high frequencies.

  We have addressed this issue at length in several papers, most recently in the first solarFLAG study [13]. In summary, the splitting introduced by the rotation is less than $1\,\mu$ Hz in magnitude. At high frequencies, the widths of the modes increase to sizes comparable to, or greater in size than, the splitting. It therefore becomes difficult to infer reliably the splitting, because the peaks 'blend' together; indeed, it has been shown that the fitted values overestimate the true values. This effect is illustrated in Fig. 8.

  These high-frequency splittings probe rotational behaviour in the deepest parts of the solar core, where the rotation is poorly constrained. It would clearly be advantageous to find some means of reducing this 'bias'. It transpires that one solution is to observe for longer. Even with the well-filled $\approx$ 13-yr BiSON dataset now available, some bias is still present, particularly at the very highest frequencies — continuation of BiSON is therefore extremely important in this context.

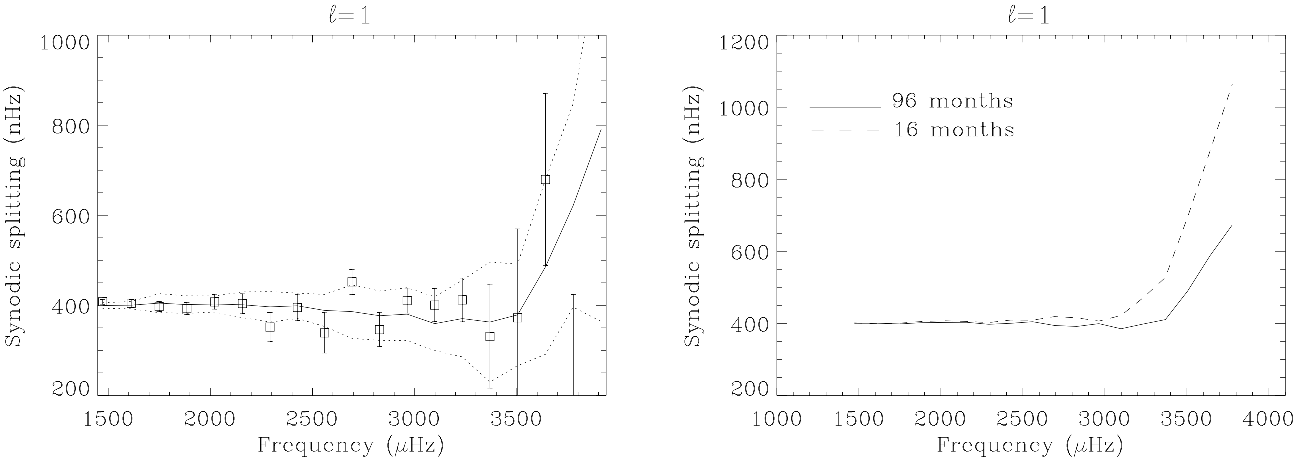

Figure 8: Left-hand panel: The mean rotational splittings of monopole ($l = 1$) modes extracted from the analysis of 96 months of BiSON data (symbols with errors), together with predictions from simulations (solid line with dotted envelope representative of 1σ error per fit). The simulations assumed an underlying splitting of $0.4\,\mu$Hz for all modes. Right-hand panel: the impact on the magnitude of the extracted splittings of changing the dataset length (simulated data, again assuming an actual splitting of $0.4\,\mu$Hz).

2.2 The Need for Continuity

In addition to being long, the ideal helioseismic dataset should also be as nearly continuous as possible.

- Periodic breaks introduce spurious frequencies and sidebands. Of particular nuisance are the diurnal sidebands — their spacing of $11.57\,\mu$Hz coincides with important spacings between some of the adjacent $l = 2$ and 0 modes. The more numerous the breaks in the timeseries, the more severe are the resulting sidebands. The sidebands can, for example, cause difficulties for extraction of frequency asymmetry in the $l = 2$ multiplets. For this reason, observations from a single site, or from a reduced network, are of limited value in this context.

  If there are breaks in a dataset from a ground-based network the likelihood is that some will be due to a common feature of one of the stations — perhaps one station is temporarily down and the data quality at the ends of the days of the neighbouring stations is poor. While occasions like this will be transient, they will nevertheless introduce modulation of the solar signal at the diurnal frequency. Even a truly unbroken data set acquired by a ground-based network is likely to show at some level diurnal effects due to atmospheric and other instrumental variations through each observing day. Spacecraft do not offer complete immunity: twenty-four-hour artifacts are visible even in the SOHO data from GOLF, MDI and VIRGO.

- What is more damaging are the effects of the quasi-random nature of the distribution in time of many of the gaps. This has the effect of redistributing power between the modes to give a complicated broad-band background. We have studied in detail the impact of this through the application of BiSON window functions to both artificial data and near-uninterrupted observations made by the GOLF instrument on board the *ESA/NASA* SOHO satellite [14].
- From both this and other work we find that the introduction of the complicated background between the modes (see Fig. 9) makes it more difficult to extract reliable estimates of the mode excitation and damping parameters (*i.e.,* widths, powers and peak asymmetries). These effects can be compensated for via analysis (again, see [14]) provided the duty cycle is at the typical $\approx 80\%$ BiSON (or higher) level. However, the contamination is much more difficult to allow for if the fill is allowed to drop much below this. A fill of 70% has been found empirically to be necessary to enable worthwhile studies of individual mode excitations and decays [15].

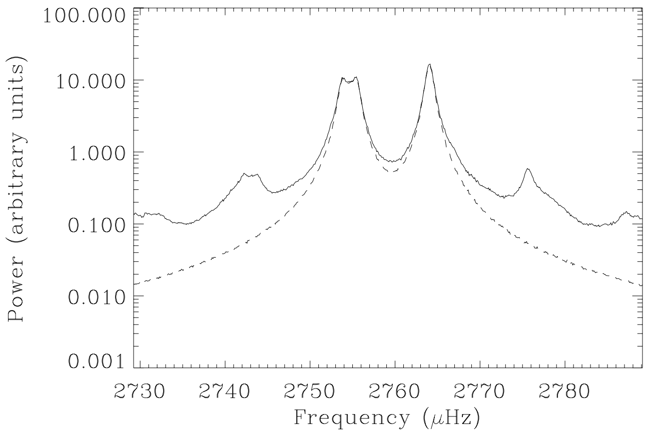

Figure 9: The effects of a ~ 75-per-cent-fill window function in the frequency domain. Here, 1000 independent realizations of the same, artificial $l = 2$, $n = 18$, $l = 0$ $n = 19$ mode pair – with each component possessing an underlying Lorentzian peak profile – were generated in the time domain. The solid line shows the mean power spectrum obtained by adding the independent frequency spectra, with each dataset having first been modulated (in the time domain) by an 8-month BiSON window function; the dashed line illustrates the mean spectrum obtained without multiplying through by the window, and is the combined 'limit' profile expected for no window-function contamination. Both spectra have been normalized to the same maximum power to emphasize visually the introduction of additional background.

- As a result of the extra background, the prominence of modes is reduced. This effect is strongest near the centre of the spectrum. While more modest in size, the impact at low frequencies is still very important — under low signal-to-noise conditions, where mode peaks can come and go as they beat strongly with background noise, we need every advantage we can get. In short, a high data fill increases the likelihood of detecting the scientifically valuable low-frequency modes.

2.3 The Usefulness of Overlaps in Coverage

To check the solar origin of transient phenomena (such as unusually large mode excitations), it is essential to have data from more than one source to allow comparisons and correlations to be made. From a practical point of view, building redundancy into an observational strategy also covers for the inevitable, occasional failure of components or systems, takes account of some weather problems, and allows basic checks of instrumental performance to be performed.

Correlations between time series obtained at different stations of the BiSON have contributed to our estimation of the solar noise background, which comes from the granulation. Measurement of this noise is required in searches for low-frequency modes that make use of coincidences present in different datasets. As discussed in Section 4.2 in the BiSON grant application, we are leading development of such techniques — for application on BiSON, GOLF, MDI, GONG and VIRGO data — as part of the Phoebus collaboration.

Overlap between different datasets has also been integral to our identifying a solar-cycle component in the observed time variation of the peak asymmetry (Section 4.5 in the BiSON grant application), a result that has potentially opened up a new area of study for the field.

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