The Simulation of Realistic BiSON-like Helioseismic Data

Stephen Fletcher and Roger New

Sheffield Hallam University, Sheffield, UK

Anne-Marie Broomhall, William Chaplin and Yvonne Elsworth

University of Birmingham, Birmingham, UK

Abstract. When simulating full-disc helioseismic data, instrumental noise has traditionally been treated as time-independent. However, in reality, instrumental noise will often vary to some degree over time due to line of sight velocity variations and possibly degrading hardware.

Here we present a new technique for simulating Birmingham Solar Oscillations Network (BiSON) helioseismic data with a more realistic analogue for instrumental noise. This is achieved by simulating the potassium solar Fraunhofer line as observed by the BiSON instruments. Intensity measurements in the red and blue wing of the line can then be simulated and appropriate time-dependent instrumental noise can be added. The simulated time-series can then be formed in the same way as with real data. Here we present the simulation method and the first generation of a BiSON-like instrumental noise time series.

1. Introduction

Simulating a realistic solar oscillations signal is an important task within Helioseismology. The use of artificial data, whose statistical characteristics and input parameters are known, allows for thorough testing, and may reveal biases in different analysis techniques. Most simulations to date have concentrated on accurately replicating the solar oscillation and background signals, with less thought put into simulating the instrumental noise sources associated with the collection of the data. Traditionally, instrumental noise has simply been treated as a constant time-independent source. However, in reality instrumental noise varies over time due to line of sight velocity variations – at least for resonant scattering spectrometers (RSS) commonly used to make full-disc measurements – and hardware changes. The current work seeks to introduce realistic simulations of instrumental noise into standard solar oscillation simulations.

2. Method

In order to accurately simulate instrumental noise, we must first understand how the oscillations are observed. At each of the six BiSON stations an RSS is used to measure the Doppler shift of the 770-nm solar absorption line. Each RSS contains a cell of Potassium atoms held at about 100°C. Detectors are placed at right-angles to the cell so that only resonantly scattered photons should be
counted. The absorption linewidth of the vapour cell is much smaller than the width of the Fraunhofer line because the temperature is much lower and there is no rotational broadening. Therefore, only light from a narrow band of the solar absorption line is detected by the RSS. By applying a magnetic field and making use of the Zeeman effect, the absorption line of the potassium atoms in the lab is split. Hence, by switching the state of circular polarisation of the input solar light, it is possible to measure the light intensity in one wing at a time.

As the solar absorption line undergoes a Doppler shift due to the orbital motion and spin of the Earth and due to solar oscillations, so the intensity measurements in the wings change. From these measurements a ratio, $R$, is formed to give a near-linear proxy for the velocity shift of the line:

$$R = \frac{I_b - I_r}{I_b + I_r} = \frac{I_{res}^b + I_{non}^b + I_{elec}^b + i_b - I_{res}^r - I_{non}^r - I_{elec}^r - i_r}{I_{res}^b + I_{non}^b + I_{elec}^b + i_b + I_{res}^r + I_{non}^r + I_{elec}^r + i_r}$$  \hspace{1cm} (1)

where $I_b$ and $I_r$ are the intensities in the blue and red wings of the line respectively. Background offset and instrumental noise will affect the intensity measurements used to form $R$ so the $I$’s can be expanded out into $I_{res}$ which is the desired contribution from resonantly scattered light and $I_{non}$, $I_{elec}$ and $i$ which are background sources due to non-resonantly scattered light, electronic offsets and noise respectively. In general these are all functions of time.

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

The first step in the simulation process was to estimate $I_{res}$ by fitting a Gaussian profile to an observed line obtained using Doppler velocity observations of the centre of the solar disc. The observations were taken by the Themis solar telescope located at Izaña, Tenerife [private communication with Rosaria Simonello]. The effects of solar rotation, limb darkening and Doppler imaging were all taken into account in order to generate a simulated line similar to that seen by the RSS’s at each of the BiSON stations (see Broomhall et al. 2007). The use of this more realistic line shape is an enhancement on earlier simulation work reported by Chaplin et al. (2005).

The “operating point” on the simulated line is evaluated from the Doppler shift due to the changing line of sight velocity of the Sun to each station (gravitational red shifts and convective blue shift are included). Artificial velocity oscillations can then be added to the velocity Doppler shift (Chaplin et al. 2008). Intensity “measurements” are made for $I_{res}^b$ and $I_{res}^r$ in the same way as with real data. At this point estimates of the various noise sources can easily be included. Finally, the ratio can be formed and analysed in the same way as with real data. A comparison of the daily ratio curve generated via the simulator compared with that from real data is shown in Fig. 1.

3. Preliminary Results

Different noise sources can be categorised by whether the noise they generate is correlated or uncorrelated in the two wings of the Fraunhofer line. Noise that
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Figure 1. Daily ratio curves for Las Campanas on two different dates. Real data are given by the grey line and simulated data by the black line.

Figure 2. Left panel: Yearly variation in the power spectral density for correlated noise (bottom), uncorrelated noise (middle) and shot noise (top). The solid line gives the moving mean over 50 days. Right panel: The moving mean over 50 days of the yearly noise variation in the instruments at Sutherland (bottom), Carnarvon (middle) and Izaña (top).

varies faster than the switching between the intensity measurements in the blue and red wings will likely be uncorrelated, while more slowly fluctuating noise will be correlated. Using the simulator the effects of these different types of noise can be tracked. The left panel of Fig. 2 shows the power spectral density of three different types of noise over the course of a year. The three cases represent uncorrelated noise with a constant amplitude, correlated noise with the same constant amplitude and shot noise (which is equivalent to uncorrelated noise with an amplitude proportional to $I$). The resulting noise power clearly varies throughout the year, with the correlated noise showing the largest variation and the shot noise the smallest. Although its variation is largest, the correlated noise case generates somewhat smaller absolute noise levels than the uncorrelated case.

The simulated noise can be compared with noise in real BiSON data. The right hand plots in Fig. 2 show the mean power spectral density of BiSON observations for frequencies from 8.0 to 12.5 mHz (well above the region of the solar oscillations), over a course of a year. The Carnarvon plot shows relatively high noise and a large variation similar to the correlated case. Izaña also has a fairly high noise level, but the variation over the year is fairly small indicating that most prevalent noise source may be shot noise. Sutherland has a much lower noise level but, unlike the simulations, its variation over the year shows 2 maxima. A possible explanation for this is that the instrumental noise is actually following a similar trend to the other plots, but the high frequency “tail” of the solar background maybe increasing the observed noise level in the 2nd half of the year.
In Figure 3, simulated velocity residuals on July 1st and 2nd 2007 for four different BiSON stations are shown. Neither solar oscillations nor background were included allowing for an unobstructed plot of the instrumental noise. The time series is generated assuming the residuals with lower noise are chosen when data overlaps.

Instrumental noise also varies on a daily basis, again due to the change in operating point on the solar line. This is very difficult to observe with real data due to the presence of the solar oscillations and background. Hence, the simulator is very useful for investigating the effect of this variation. Fig. 3 shows the simulated residuals of four different BiSON stations over July 1st and part of July 2nd (the solar oscillations and background have not been added). This trace represents the first attempt to generate such a realistic data set and makes an interesting comparison with previous simulations which assume constant noise. The type and level of the noise sources have been matched as well as possible to real data.

4. Discussion

A new BiSON simulator has been designed to more accurately mimic the instrumental noise generated in the data. We will now use the simulator to help us better understand the effect of instrumental noise on the precise mode parameters extracted from power spectra and on the detection of low power modes. In addition, our analysis here shows that a time series produced from multiple BiSON stations will have a varying noise profile suggesting that better statistics may be achieved by applying a weight to each of the time series points. This may be accomplished using a sine-wave fitting technique - see New et al from the proceedings of this meeting.

Acknowledgments. STF acknowledges the support of the Faculty of Arts, Computing, Engineering and Science (ACES) at the University of Sheffield and the support of the Science and Technology Facilities Council (STFC). We also thank all those associated with BiSON which is funded by the STFC.

References

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