Spatial Cross Spectrum: Reducing Incoherent Convective Background of Resolved Helioseismic Instruments

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Abstract. Measurements of low-order p modes and gravity modes are perturbed by the solar convective background. Such perturbation increases below 2mHz for intensity measurements and 1mHz for velocity measurements. While the low-degree modes have large spatial scales, the convective motions have much smaller spatial distribution. In this work, we take advantage of these different scale sizes to explore the use of spatial cross spectrum between different regions of the Sun. The aim is to reduce the incoherent background noise and, therefore, increase the signal-to-noise ratio of the signals that are coherent across the full disk. To do so we use the VIRGO/LOI instrument aboard SoHO and the GONG ground-based network to study the intensity and velocity spatial cross spectra.

1. Introduction

The detection of low-degree p modes and gravity modes are necessary to better constrain the structure and dynamics of the solar interior (García, Mathur & Ballot, 2008; García et al. 2008b; Mathur et al. 2007, 2008). The dominant solar background at frequencies below 2 mHz is the consequence of the surface manifestation of convection becoming an obstacle to the detection of low-degree low-order p and g modes (e.g. García et al. 2001, 2004, 2007 & 2008a). Looking at its spatial distribution we can distinguish two of these movements (e.g. Lefebvre et al. 2008): granulation motions, with horizontal scales of around 1,500 km; and supergranulation motions, with horizontal scales of around 30,000 km. We are interested in low-degree p and g modes having a few nodal lines in the solar surface. Thus, the idea is to build two time series using different combinations of pixels that cover different regions of the Sun. The evolution of the convection will be different in each time series (incoherent) while the modes will be mostly
the same (high coherence between the pixels). Then, we perform the spatial
cross spectrum between these two time series. To reduce the variance of each
point of the cross spectrum we take small subseries and we average all of them.
We call this method the Average Spatial Cross Spectrum (AvSCS).

2. Methods and Data Sets

To reduce the adverse effects of noise, two independent measurements, A and
B, can be made and we can extract the common signal by using cross-spectrum
techniques. The cross spectrum (CS) is defined as the complex product of the
Fourier transform of one data set, A, and the complex conjugate of the Fourier
transform of the other one, B, i.e.:

\[ S(\nu) = \langle A(\nu) \cdot B^*(\nu) \rangle \]

The CS enhances any coherent signals of short lifetimes improving their
signal-to-noise ratio (Appourchaux et al. 2007). The degree of coherence be-
tween the signals is measured using the coherency function, C, defined as:

\[ C(\nu) = \frac{\langle A(\nu) \cdot B^*(\nu) \rangle}{\langle (A(\nu) \cdot A^*(\nu)) \cdot (B(\nu) \cdot B^*(\nu)) \rangle^{1/2}} \]

This coherency function is equal to zero for completely incoherent signals
and unity for completely coherent signals. This method has already been used
in helioseismology, but only by combining two contemporary datasets (Elsworth
et al. 1994, García et al. 1998) or by interleaving one single time series (García
et al. 1999).

This study is based on the analyses of helioseismic imaged solar data. We
have tested the methodology on two different types of measurements: one from
LOI/VIRGO\(^1\) observing the Sun using photometry (4098 days of 1 minute sam-
ping rate from April 11, 1996 to June 30, 2007) and the other one from GONG\(^2\)
network measuring the Doppler velocity (730 days of merged images with 1
minute cadence from January 1, 2003 to December 31, 2004).

3. LOI Results

Two time series were built: A, pixels=1,6,4,7 and B, pixels=2,8,3,5 (see Fig,
7 of Fröhlich et al. 1995 for a full description of the pixels). In such way, we
mainly preserve the same visibility to the \(m\) components of the modes as in
disk-integrated observations.

We compute the AvSCS of subseries of 30 days and the result is plotted in
Fig. 1. The convective background has been reduced by an order of magnitude
at 1 mHz. The S/N of the \(p\) modes has been increased as well as the detection
lower limit has been pushed towards lower frequencies.

\(^1\)Fröhlich et al. 1995
\(^2\)Harvey et al. 1996
4. GONG Results

We decomposed the disk image of GONG into an LOI-proxy image. We performed a Backwards Difference Filter (BDF) to reduce low-frequency residuals from the rotation correction as well as other merging-related effects. We corrected the power spectrum from the effect of the BDF (García & Ballot 2008). Two time series were built using the pixels of the LOI-proxy, A=9,12 and B=10,11 and the AvSCS was calculated using subseries of 15 days (shifted every 5 days). The result is plotted in Fig. 2. The photon noise is reduced at high frequency as well as the convective noise at low frequency (30% coherence at 1mHz).

5. Conclusions

These preliminary results show that the Averaged Spatial Cross Spectrum could be a powerful tool to reduce the incoherent noise on helioseismic measurements. However, a trade off is required between the length of the subseries, the pixels used in the independent series and the reduction of the noise obtained. In the case of LOI/VIRGO series, we have shown that the reduction of noise is quite significant (1 order of magnitude using subseries of 30 days and a total time span of ~4100 days), while for the GONG time series an important noise reduction is also seen taking into account the reduced time series used (730 days). Longer series will be needed in the velocity measurements to better evaluate the method to detect new low-degree low order p and g modes.

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Figure 2. AvSCS (black) of 142 subseries of 15 days shifted every 5 days. The blue and green courbes are the averaged PSD of channels A and B.

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