Investigating the correlation between high-frequency global oscillations and solar flares

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Abstract. Global oscillations have been observed in the high-frequency spectrum in velocity and intensity measurements above the acoustic cutoff frequency of the solar atmosphere. In a recent work, strong correlation at high frequencies, determined between helioseismic spectra and soft x-ray flux has been cited as evidence that solar flares may be one of the mechanisms whereby these high-frequency oscillations are excited. We investigate the possible dependencies of the correlation coefficient, computed for helioseismic and soft x-ray data, on the pre-processing and data analysis, and the instruments used for data acquisition.

1. Introduction
Ever since Wolff (1972) suggested the theoretical possibility of solar flares stimulating free oscillations in the Sun, several attempts have been made to establish this using observational data (cf. Karoff 2008; Kumar et al. 2010). Recently, Karoff & Kjeldsen (2008) claimed to have provided evidence supporting Wolff’s idea by showing a high correlation between the high-frequency helioseismic power spectra and the solar x-ray flux (1–8 Å). More recently, Kumar et al. (2010) also presented evidence of increase in the energy of high-frequency global acoustic oscillations during the occurrence of major solar flares.

In this work we have reproduced the results of Karoff et al. (2008) by calculating frequency-time plots for acoustic data obtained from the blue, green and red channels of the Sun PhotoMeter (SPM), and then correlating the power spectra with soft (1–8 Å) x-ray flux obtained from the Solar X-ray Imager (SXI) on board the Geostationary Operational Environmental Satellites (GOES). SPM is part of the Variability of solar IRradiance and Gravity Oscillations (VIRGO) experiment on the Solar and Heliospheric Observatory (SOHO) spacecraft. However, we do not get the same results when correlating the (ℓ=0) spherical harmonic time series from the Global Oscillation Network Group (GONG) instruments with the GOES soft x-ray flux data.

2. Frequency-time and correlation plots
We generally follow the procedure described by Karoff et al. (2008) and use the least-squares spectra method (Lomb 1976) to calculate the power spectra of substrings of the helioseismic time series. For comparison purposes, we also calculate the power spectra using FFT and the results are shown in the correlation plots in figure 2. We calculate the power spectra of time strings of various lengths to bring out any dependencies in the correlation coefficient on the length of the time strings. The power spectra of these time series are normalized by the duty cycle of the
time strings, and then stacked vertically (1 Jan 1996–31 Dec 2005) to produce frequency-time (f-t) diagrams (figure 1).

We correlate both the unsmoothed and smoothed f-t diagrams with x-ray flux time series, in order to determine the effect of smoothing on the results. The unsmoothed f-t diagrams are correlated with the daily averaged x-ray flux data. Roughly following Karoff et al. (2008), smoothing is done with a 2-d Gaussian filter with widths 30 µHz in frequency and 20 days in time. The x-ray flux data is smoothed by a triangular running mean of 20 days to ensure compatibility in temporal resolution with the f-t diagram.

The Pearson correlation coefficient (Rice 2007) is computed for the power spectra “time series” at each frequency bin, and the GOES x-ray flux (1–8 Å); this yields the correlation coefficient as a function of frequency (figure 2). All time strings with zero variance, and with duty cycles less than 70% for GONG and less than 90% for SPM are not included in the calculation of the correlation coefficient. These rejected data are indicated as horizontal dark blue strips of various widths in the f-t diagrams.

**Figure 1:** (From left to right) Daily averaged x-ray flux (smoothed by a running triangular mean 20 days in width); frequency-time (f-t) diagram (smoothed by a Gaussian filter 20 days wide in time and 30 µHz wide in frequency) for 8-day time strings of SPM level-1.8 blue channel disk integrated intensity (ordinate: 1996–2005; abscissa: 3–8 mHz); slices of f-t diagram at 3.22 mHz, 5.24 mHz & 7.22 mHz. Dark blue horizontal strips in f-t diagram indicate rejected data.

### 3. Pre-processing and data analysis

#### 3.1. SPM level-1.8 disk integrated intensity time series

The SPM level-1.8 time series (blue, green and red channels) are available at ftp://ftp.pmodwrc.ch/pub/data/irradiance/virgo/SSI/. On analyzing these time series we were able to reproduce the results in Karoff et al. (2008). For the blue channel we get correlation coefficient values of ~0.4 at higher frequencies (figure 2b). FFT and the Lomb method...
yield results that are different, especially in the higher frequencies (figures 2a & b). From figures 2b & c we can see that smoothing before correlating does significantly raise the correlation coefficient as was suggested in Chakraborty et al. (2010). We also find that the correlation coefficient increases with the length of the time string.

3.2. GONG Doppler velocity spherical harmonic (ℓ=0) time series
The GONG Doppler velocity spherical harmonic (ℓ=0) time series was obtained from ftp://gong2.nso.edu/TSERIES/. In this case the correlation coefficient values reach ∼0.2 at higher frequencies (figure 2e). FFT and the Lomb method yield practically indistinguishable results (figures 2d & e). Here too, the correlation coefficient increases due to smoothing, and with the length of the time string (figures 2e & f). It also seems that the p-mode power spectra (around 3 mHz) are anti-correlated with the soft x-ray flux data (figures 2e & f). This p-mode frequency anti-correlation is also seen in the SPM level-1.8 correlation plots (figures 2b & c). This merits further study.

![Figure 2](image-url)

Figure 2: Pearson correlation coefficient as a function of frequency for: SPM level-1.8 blue channel (a) 8-day time string, FFT, smoothed; (b) 8-day time string, Lomb, smoothed (cf. figure 1); (c) 8-day time string, Lomb, unsmoothed; GONG (ℓ=0) (d) 8-day time string, FFT, smoothed; (e) 8-day time string, Lomb, smoothed; (f) 1-day time string, Lomb, unsmoothed.

4. Discussion and future work
We studied the correlation coefficient as a function of frequency by analyzing data from different instruments. FFT and the Lomb method yield results that are different for SPM (cf. figures 2a & b), but virtually indistinguishable for GONG (cf. figures 2d & e); the reason for this is not understood and needs investigation. SPM and GONG show very different values for the correlation coefficient at all frequencies (cf. figures 2b & e). Both SPM and GONG data show some anti-correlation between helioseismic and soft x-ray flux data in the p-mode region.
Removal of long-period oscillations from the time series using a running mean does not have any significant effect on the correlation coefficient at higher frequencies. Outlier removal does influence the correlation coefficient: the higher the standard deviation used in outlier removal, the higher the correlation in the higher frequencies. We have investigated the possibility of legitimate signals being accidentally removed in an effort to meet statistical requirements. Calculating f-t diagrams using longer time strings and/or smoothing the f-t diagram and the x-ray flux before correlating them increases the correlation. As the correlation coefficient varies with smoothing and the length of the time series, it is not possible to accurately interpret the values depicted in figure 2. At this point we have yet to reach any firm conclusions; further analysis is required.

Time series from more instruments, such as, the Michelson Doppler Imager (MDI), Luminosity Oscillations Imager (LOI/VIRGO) and the Global Oscillations at Low Frequencies (GOLF) instrument aboard the SOHO spacecraft, and eventually the Helioseismic and Magnetic Imager (HMI) on board the Solar Dynamics Observatory (SDO), need to be analyzed. The raw data from these instruments need to be carefully pre-processed (filtering, outlier removal, etc.) so as not to introduce systematic errors in subsequent analyses. B. Kumar (personal communication) suggested correlating the helioseismic data with hard x-ray flux data as it is associated with the possibly more relevant impulsive phase of a solar flare. The analysis needs to be carried out rigorously, and the correlation coefficient needs to be suitably normalized with respect to the appropriate parameters, e.g., dimensions of the smoothing window, to give us more confidence in the correlation found. Analytical methods such as the postflare/preflare power ratio distribution described in Chakraborty et al. (2010) to determine the statistical significance of acoustic power perturbation with respect to flare activity on the Sun may be used as an independent method of verifying the results presented in this paper.

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