The acoustic cutoff frequency of the Sun and the solar cycle

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Abstract. The acoustic cutoff frequency –highest frequency for acoustic solar eigenmodes– is an important parameter of the solar atmosphere because it determines the upper boundary of the p mode cavities. At frequencies beyond this value, acoustic disturbances are no longer trapped waves but traveling waves. Interferences amongst them, originate higher frequency peaks -the pseudomodes- in the solar acoustic spectrum. Using data from GOLF and VIRGO instruments aboard SoHO spacecraft, we determine the acoustic cutoff frequency using the coherence function between both sets of data, velocity and intensity. By using data gathered by these instruments during the whole lifetime of the mission (1996 till present), it is found a variation of this parameter with the solar magnetic activity cycle.

1. Introduction

The acoustic cutoff frequency $\nu_{ac}$ is an important parameter of the solar atmosphere, given (in isothermal conditions) by $\nu_{ac} = c/2H_p$, $H_p$ being the pressure scale height and $c$ the sound speed. Theoretically, its value is of $\sim 5000 \mu$Hz while from observations, a higher value has been obtained [1]. The resonant acoustic waves (p modes) are trapped in resonant cavities with lower boundary ranging from the center of the Sun up to the surface (depending of their angular degree and frequency) and their upper boundary at the surface where $\nu = \nu_{ac}$. Only acoustic oscillations with frequencies $\nu < \nu_{ac}$ are trapped in the resonant cavities beneath the photosphere. For $\nu > \nu_{ac}$, acoustic disturbances are no longer trapped and propagate as traveling waves through the chromosphere to the base of the corona. These high-frequency peaks, hereafter, pseudomodes, show a clear structure beyond $\nu_{ac}$ [2, 3, 4, 5, 6, 7, 8]. In the acoustic spectrum of the Sun, the frequency separation between consecutive modes of the same degree $\Delta \nu_{n,l} = \nu_{n,l} - \nu_{n-1,l}$ increases slightly between $\sim 5000-5500 \mu$Hz. This variation is due to the transition that takes place from trapped to traveling behaviour. If this frequency separation ($\Delta \nu_{n,l}$) increases around $\nu_{ac}$, all the peaks with $\nu > \nu_{ac}$ will be shifted respect to the peaks with $\nu < \nu_{ac}$. We try to find at which frequency this shift takes place being this value a good measurement of the acoustic cutoff frequency. Using the SoHO data for the whole mission we study a possible relation of this value with the phase of solar activity cycle. It is also important to remember that an enhancement has been observed in the pseudomodes region during some magnetic events such as flares [9,10].

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2. Data sets
We use VIRGO/SPM(three colors) [11], intensity data and GOLF velocity data [12,13]. Time series of 800 consecutive days (shifted 50 days respect to the previous one) are constructed, giving a total of 85 time series from April 1996 to May 2010. Each of these 800 days time series are then sub-divided in 4-day time series. Their corresponding power spectra and coherence function are computed and the results averaged. A sample of the resulting power spectra are shown in Figure 1, where the pseudomodes signal is clearly visible.

In the present analysis, the coherence function between intensity and velocity is used instead of the use of the power spectra in order to avoid electronic contamination in the intensity data at around 5550 µHz and because the coherence function contains the coherence signals of both datasets.

3. Analysis
The Intensity-Velocity (I-V) coherence function (black curve, figure 2a) is fitted to an exponentially modulated sine wave (blue curve) between 3000 µHz and 5500 µHz to take into account the decreasing amplitude of p modes and the background. In addition, between 5000 µHz and 6500 µHz, only a single sine wave function is fitted (pseudomodes amplitudes do not vary significantly with frequency).

Both fitted curves, p modes (blue one) and pseudomodes (red one) are extended to the whole frequency range from 3500 to 6500 µHz, their maxima computed and its position plotted in Figure 2a: Black filled circles, maxima of the coherence function; Blue filled circles, Maxima of the exponentially modulated sine wave fitted to the p mode range between 3500 and 5500 µHz; Red filled circles, maxima of the sine wave fitted to the pseudomodes range between 5000 and 6500 µHz.

The frequency difference between all consecutive maxima of the coherence and of the fitted curves are computed and plotted in Figure 2b: blue circles for p modes and red squares for pseudomodes. The blue circles are close to zero in the p mode range because the fitted exponentially modulated sine wave, blue curve in figure 2a, models very well the p modes behaviour. But when the pseudomodes region begins to be considered, the difference between the maxima increases because the frequency separation of pseudomodes is different to the one of p modes. The red squares are close to zero in the pseudomode region because the fitted
Figure 2. Coherence function and $\nu_{ac}$ determination. a) Black line: coherence function. Blue line: Exponentially decay sine wave fitted to the coherence function between 3500 and 5500 $\mu$Hz (end of the p mode range) and plotted extended up to 6500 $\mu$Hz. Blue and black filled circles are the maxima of the fitted sine wave and coherence function respectively. Note how the coherence shifts to higher frequencies from $\sim$5000 $\mu$Hz onwards. Red line: Cosine fitted to the frequency range between 5000 and 6500 $\mu$Hz (pseudomodes range) and plotted extended to 3500 $\mu$Hz. Red and black filled circles are the maxima of the fitted cosine and the coherence function. b) Blue circles: frequency differences between the maxima of the coherence function and the fitted (3500-5500 $\mu$Hz) exponentially modulated sine wave. Red squares: frequency differences between the maxima of the coherence function and the fitted cosine (5000-6500 $\mu$Hz). Two parabolas segments are fitted around the region where both curves cross, to obtain the best estimation of $\nu_{ac}$. Sine wave, red curve in figure 2a, reproduce nicely the pseudomodes behavior. But in the p mode range the differences increase because the frequency separation between p modes and pseudomodes is different.

Looking around 5000 $\mu$Hz, blue points are always below the red ones for lower frequencies and always above for higher frequencies. The frequency interval between the transition of blue points from below to above the red points (pointed out with a hexagon) is the frequency interval of the acoustic cutoff value. These two limits are the lower and upper limits of $\nu_{ac}$. A more accurate determination of $\nu_{ac}$ is performed by fitting two parabolas (one for red points and one for blue points) in the interval 4500 $\mu$-5500 $\mu$Hz and computing the crossing frequency point of them. This is considered as the best feasible determination of $\nu_{ac}$.

4. Results
The results obtained from the analysis of the coherence function for each one of the VIRGO/SPM channels, are the same within error, so the values of $\nu_{ac}$ have been averaged and shown in Figure 3 (left) with their associated errors. The corresponding Solar Radio Flux values for the same period are shown on the right plot. A clear positive correlation between both parameters is clearly noticeable and deserves further investigation and evaluation.
Figure 3. Acoustic cutoff frequency as a function of time as calculated from the data set (left panel) and the measured Solar Radio Flux (right panel), showing a high correlation with the acoustic cutoff frequency determinations.

5. Conclusions
The analysis of the coherence function between SoHO-Intensity (VIRGO)/SPM) and -Velocity (GOLF) data has allowed a precise determination of the acoustic cutoff frequency of the solar atmosphere. Its variation along the continuos 14-year of the mission, shows a significant variation with the Solar activity cycle and positively correlated. This result is in agreement with previous determination of the solar acoustics radius of the Sun [14] found to be negatively correlated with activity. This work is still in progress.

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