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High frequency signals in the solar atmosphere as a result of the interference between acoustic sources

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Abstract. High frequency waves in the upper layers of the solar atmosphere are believed to show a negligible amplitude when the contribution function of the spectral lines used to infer the velocity field is much larger than their characteristic wavelengths. Moreover, line formation effects in a dynamic atmosphere can mimic high frequency power due to MTF (Modulation Transfer Function) variations.
We implemented a simple interference model in a numerical code which is able to simulate the pattern generated by a distribution of acoustic sources in a stratified atmosphere with various characteristic spatial scales between the sources, representative of different convection regimes. We show how interference between randomly distributed acoustic sources placed at the base of the photosphere can produce high frequency signals whose spatial distribution is constant along large vertical scales and, therefore, not suppressed by the integration along the MTF.

Key words. Waves - Sun: photosphere - Sun: Chromosphere

1. Introduction

Recent works on high frequency waves in the solar atmosphere have revealed that their behaviour is more complex than believed in the past (Fleck et al. 2010a,b; Straus et al. 2010).
In particular, some important question have been addressed suggesting that the observed high frequency signals can be the result of rapid height variation of the velocity response function, in the presence of strong velocity gradients (Keil & Marmolino 1986). In this work we investigate the behaviour of high frequency signals and report some results obtained through our simulation code based on the interference mechanism between acoustic sources placed at the base of the solar atmosphere.
By assuming that the acoustic sources mainly coincide with downflows in the intergranular lanes and that the pulses have a gaussian shape (Skartlien & Rast 2000), we are able to investigate the power spectrum and the LoS (Line of Sight) signals at various heights above the photosphere.
Our simulations show that the high frequency LoS signal may be the result of cooperation between the sources and is related to the

Send offprint requests to: M. Stangalini characteristic temporal and spatial distribution of the sources: this effect is the result of the time delay between different sources, which we expect to be not synchronized, and the wavefronts delay as they reach the LoS. Moreover, in a recurring occurrence of sources in specific positions, the interference pattern can produce a standing high frequency power enhancement halfway between the sources.

2. The simulation code

The simulation code was developed in IDL and Python. The high modularity of the code allows us to easily simulate different atmospheric conditions: stratified 2D or 3D atmosphere with constant sound speed, stratified 2D atmosphere with a sound speed dependent on the height, spatial and temporal distribution of the sources extracted from real high spatial resolution LoS velocity maps from IBIS data (Cavallini 2006), and spatial distribution of the sources forced to match a given characteristic granular scale.

Although the code includes some of the basic real features of the solar atmosphere it cannot be considered as a simulation code which allows us to entirely model the physical complexity of wave propagation in a stratified plasma.

Our aim is to show some simple effects due to the interference and the cooperation of many acoustic sources. For this purpose, a simple gaussian pulse has been used to model the acoustic source and a radiative damping of the generated wave amplitude with a time scale of 100 s has been introduced as described by Skartlien & Rast (2000).

The common parameters to the entire set of simulations are:

- pixel scale: 7 km
- time resolution: 2 s
- computational domain: 256 × 128 pixels
- radiative damping with a time scale of 100 s
- gaussian sources with positive and normalized density fluctuations

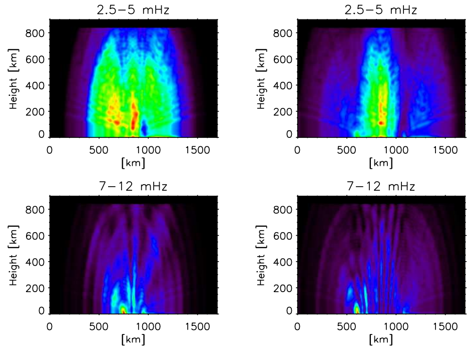

Fig. 1. Power distribution for the cases with a distance scale of 200 km (left) and 500 km (right). It is worth to note that at high frequency the features become sharper. The sources positions are 800 km and 1000 km (left panel) and 600 km and 1100 km (right panel).

The sound speed at photosphere has been assumed to be equal to $v_{x0} = 7$ km/s but in order to take into account the variations of the sound speed with altitude above the photosphere, we can include a behaviour as that described in Kurucz (1998).

3. Dependence of the power distribution on the characteristic spatial scale

We investigated the energy distribution dependence on the characteristic scale, that is the distance between the sources: for the sake of simplicity we report the results for sources fixed at a distance of 500 km and 200 km respectively. The sources are not synchronized and their blinking time is random (but it is the same for the both simulations).

The results are shown in Fig. 1. The sound speed is constant for both axes: $v_{x0} = 7$ km/s and $v_z = 14$ km/s.

The power distribution at high frequencies become sharper and is present even in between the location of the sources.

In Fig. 2 the power spectrum of the signal measured at 140 km of altitude is shown, for both cases in which sources are closer (dashed line) and where they are more distant (continuous

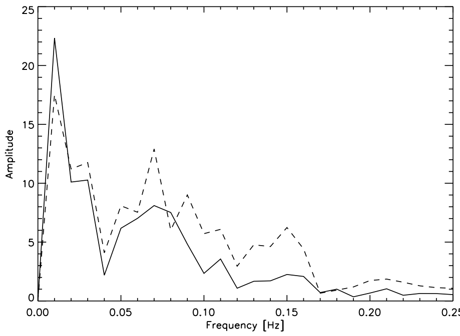

Fig. 2. Power spectrum at 140 km above the photosphere in the middle of the sources locations for the case in which the distance between the sources is equal to 200 km (dashed line) and 500 km (continuous line).

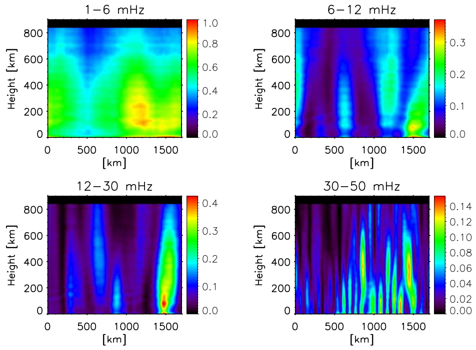

Fig. 3. Power maps in four different frequency bands, from 1 mHz to 50 mHz. The position of the sources has been extracted from real LoS velocity maps. The color map has been normalized to the peak in the band 1 − 6 mHz.

line). When the sources are closer the power at high frequencies is enhanced.

This effect can be explained as a combination of interference and wavefronts time lags. In both the above simulations, the waiting time between the pulses is random thus creating a time lag between the wavefront coming from the two locations in the photosphere. Even if the sources are synchronized there exists some location in which there is a difference in the arrival time of the wavefront from the two locations in the photosphere. The frequency of the measured signal depends on this time lag and not only on the pulse shape itself.

4. Vertical reconstruction of the power generated by a real slice of the photosphere.

As mentioned above, the simulation code is able to extract the positions of the acoustic sources from real LoS velocity maps.
In this case, we have extracted the position of the sources setting a threshold of 700 m/s (blueshifts) in a real LoS velocity time series acquired with IBIS (Viticchié et al. 2009), the interferometric monochromator installed at DST. The data were obtained in the Fe 6301 line and we restricted our attention to a small 1D region (30 arcsec). In Fig. 3 the simulated power maps are shown for six different frequency bands covering the Fourier spectrum from 1 mHz to more than 40 mHz. High frequencies power maps show sharper structures whose spatial distribution is mainly constant with height and not coaligned with the sources positions.

In the same simulation we studied the effect of the spectral line response function. We have integrated the signals coming from two layers with a thickness of 130 km, a typical response for a photospheric spectral line. The heights of formation are at 150 and 300 km respectively. In Fig. 4 it is shown the integrated signal at 150 km (continuous line) and at 300 km (dashed line). It is clear that, they are well correlated with a greater time lag at the beginning of the simulation, when the interference pattern is not set yet. As the interference pattern begins to operate, the time lag becomes smaller and the two signals overlap much better even if the are measured at different altitudes above the photosphere.

Fig. 5 also shows the power spectra for these two integrated signals. Both spectra show the same shape with many peaks at high frequency.

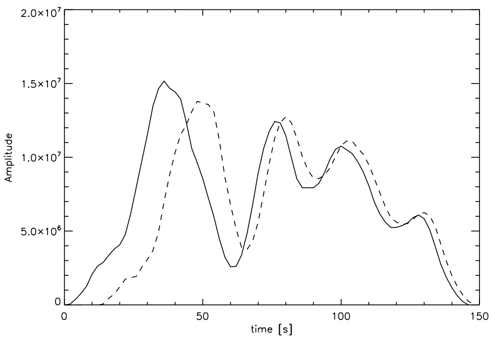

Fig. 4. Signals integrated in a slab of 130 km of thickness. The continuous line represents the signal coming from 150 km and the dashed line represents the signal measured at 300 km.

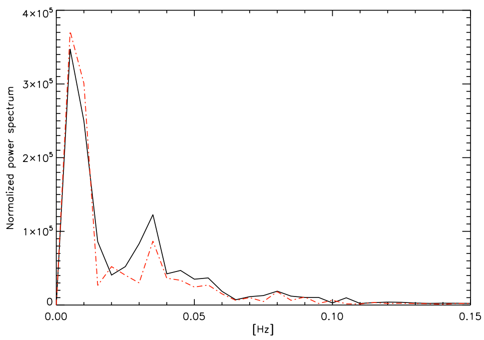

Fig. 5. Power spectrum of the signals integrated in a slab of 130 km of thickness. The continuous line represents the signal coming from 150 km and the dash-dot line represents the signal measured at 300 km.

5. Conclusions

We have investigated the influence of the interference between acoustic sources in the high frequency signal in the solar atmosphere.

We have shown that the cooperation between different wavefronts can lead to intensity or velocity signals whose frequencies can be associated to the characteristic spatial and temporal scales of the sources generating the pulses in the photosphere.

Fig. 6 shows a schematic picture of the process. Two sources are emitting the same pulse with a waiting time T_1. Along the LoS1 the observer sees the same frequency as the emitting source, while along the LoS2 the observer measures a higher frequency signal since the time lag between the wavefronts is $T2 < T1$. We have found that the characteristic scale length of the sources, which can be associated to the granulation scale, can significantly enhance the power in the high frequency range of the spectrum.

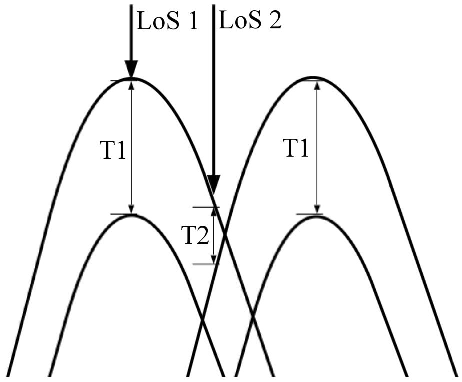

Fig. 6. Schematic picture of the cooperation process between the sources. The waiting time between two wavefronts is shorter along the LoS 2 thus producing an higher frequency signal as seen from an observer.

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