

## Acoustic Events in the Solar Atmosphere from *Hinode*/SOT NFI Observations

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Received: 8 June 2011 / Accepted: 12 February 2012 / Published online: 15 March 2012  
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**Abstract** We investigate the properties of acoustic events (AEs), defined as spatially concentrated and short duration energy flux, in the quiet Sun, using observations of a 2D field of view (FOV) with high spatial and temporal resolution provided by the Solar Optical Telescope (SOT) onboard *Hinode*. Line profiles of Fe I 557.6 nm were recorded by the Narrow-band Filter Imager (NFI) on a  $82'' \times 82''$  FOV during 75 min with a time step of 28.75 s and  $0.08''$  pixel size. Vertical velocities were computed at three atmospheric levels (80, 130, and 180 km) using the bisector technique, allowing the determination of energy flux to be made in the range 3–10 mHz using two complementary methods (Hilbert transform and Fourier power spectrum). Horizontal velocities were computed using local correlation tracking (LCT) of continuum intensities providing divergences. We found that the net energy flux is upward. In the range 3–10 mHz, a full FOV space and time averaged flux of  $2700 \text{ W m}^{-2}$  (lower layer 80–130 km) and  $2000 \text{ W m}^{-2}$  (upper layer 130–180 km) is concentrated in less than 1 % of the solar surface in the form of narrow ( $0.3''$ ) AE. Their total duration (including rise and decay) is of the order of  $10^3$  s. Inside each AE, the mean flux is

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**Electronic supplementary material** The online version of this article (doi:[10.1007/s11207-012-9954-3](https://doi.org/10.1007/s11207-012-9954-3)) contains supplementary material, which is available to authorized users.

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$1.6 \times 10^5 \text{ W m}^{-2}$  (lower layer) and  $1.2 \times 10^5 \text{ W m}^{-2}$  (upper). Each event carries an average energy (flux integrated over space and time) of  $2.5 \times 10^{19} \text{ J}$  (lower layer) to  $1.9 \times 10^{19} \text{ J}$  (upper). More than  $10^6$  events could exist permanently on the Sun, with a birth and decay rate of  $3500 \text{ s}^{-1}$ . Most events occur in intergranular lanes, downward velocity regions, and areas of converging motions.

**Keywords** Acoustic waves · Granulation, dynamics · Photosphere

## 1. Introduction

Oscillations appear all over the Sun and are the second major component of the photospheric velocity field. 5-min oscillations have been very closely studied in recent years particularly to probe the physical properties of the solar interior.

Solar pressure waves (and oscillations) are believed to be excited by turbulent convection around 200 km below the surface (Goode, Gough, and Kosovichev, 1992), where velocities take maximum values. Recent numerical simulations of acoustic wave propagation and dispersion (Shelyag, Erdélyi, and Thompson, 2006) suggest a possible location of the flux source 2000 km below the solar surface.

The mechanism of excitation of oscillations is generally understood from a theoretical perspective. Observational verifications and investigations need to be done. The question arises whether such excitation occurs all over the surface or whether localized sources of enhanced generation exist.

Wave amplitude and phase diagnosis have been applied to detect acoustic events (AEs) as sources of enhanced acoustic wave generation at high spatial resolution (Brown, 1991). AEs (defined as sub-arcsec spatially concentrated and short duration energy flux) have been first detected on high-resolution spectra from ground based observations (Rimmele *et al.*, 1995; Strous, Goode, and Rimmele, 2000) and are now well studied by 2D spectrometers using line scans (Bello González *et al.*, 2009, 2010a, 2010b). AEs (or seismic events) are visible in the photosphere but could be the counterpart of the localized events which excite solar oscillations beneath the photosphere, transferring mechanical energy into oscillations. The strongest events appear to be located in the intergranular lanes, where downflows are often detected. They may be excited by some cooling mechanism (Rimmele *et al.*, 1995). Strous, Goode, and Rimmele (2000) suggest that AEs could generate an appreciable part of the energy necessary to sustain the whole *p*-mode spectrum. More recently, Bello González *et al.* (2010b), using the SunRise experiment, found that the energy of acoustic waves above 5 mHz could compensate partly energy losses of the chromosphere and originates mainly from small and localized regions.

Convective motions produce temporally varying stress and entropy fluctuations which can act as sources of acoustic waves. Theoretical work shows that downflowing plumes (cooling events; see Rast, 1999) can locally excite acoustic oscillations. 3D numerical simulations (Skartlien, Stein, and Nordlund, 2000) suggest that compressed granules at meso-granular boundaries could generate upward-propagating waves. *p*-mode excitation is suspected to occur preferentially close to the top of the convection zone in the superadiabatic layer, where turbulent velocities and entropy fluctuations are the largest (Stein *et al.*, 2004).

Acoustic wave dissipation is also assumed to be an important heating source for at least the lower chromosphere. In a recent study, Rutten, van Veelen, and Sütterlin (2008) observed that acoustic grains (Ca II H2v and K2v lines) in the chromosphere could be caused by AEs. Their photospheric diagnosis suggested that the Ca II grains could be the signature of

acoustic excitation by downdrafts. They also showed that exploding granules could explain oscillation amplitude enhancements, which could modulate the H $\alpha$  line core intensity above.

In this paper, we present high spatial resolution Doppler measurements at several altitudes in the photosphere in order to detect AEs. We take benefit of observations carried out on 4 September 2009, in complete absence of atmospheric effects and outstanding spatial resolution in a large 2D field of view (FOV). This provides a better statistics than before at unprecedented spatial resolution. We investigate the location of AEs, their temporal behavior, dynamical and energetic properties in the range 3–10 mHz and the relationships to the granular or intergranular pattern.

## 2. Observations and Data Reduction

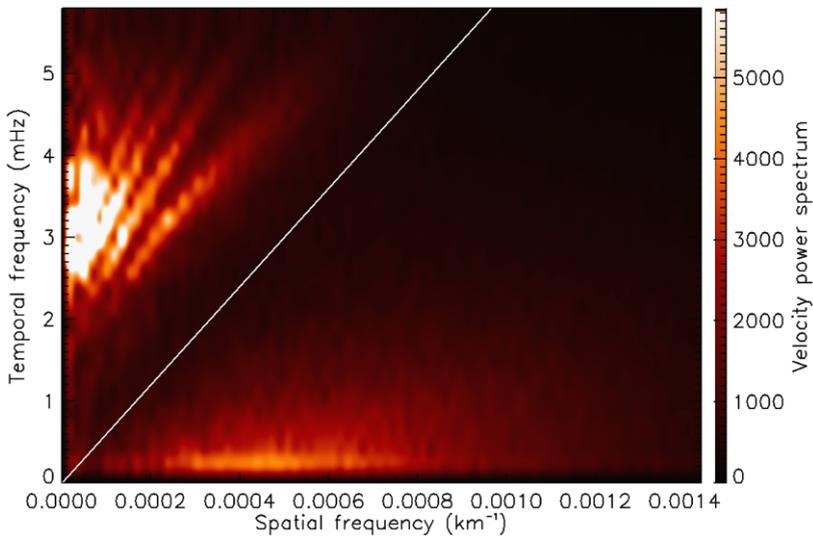
We used multi-wavelength data sets of the Solar Optical Telescope (SOT) onboard *Hinode* (e.g. Ichimoto *et al.*, 2005; Suematsu *et al.*, 2008). The SOT has a 0.50 m primary mirror aperture with a spatial resolution of about 0.28'' at 550 nm. Observations were performed at disk center, so that vertical velocities produce Dopplershifts, whereas horizontal velocities can be derived from the proper motions of granules.

We used the Narrow-band Filter Imager (NFI) to scan profiles of the magnetically insensitive 557.6 nm Fe I line with a spatial resolution of 0.28''. The full width at half maximum of the filter is 60 mÅ. The spectral line was scanned using nine wavelengths along the line profile in the following order, with respect to the line center: –160, –120, –80, –40, 0, +40, +80, +120, +160 mÅ. The observations were recorded continuously on 4 September 2009, from 21:07:59 to 22:23:13 UT. The solar rotation was compensated. Each line scan took 28.75 s for a total observing time of 75 min, so that we have 158 consecutive times of observations corresponding to  $9 \times 158 = 1422$  images. The FOV was 82''  $\times$  82'' (1024  $\times$  1024 pixels) with a pixel sampling of 0.08''.

We first aligned images corresponding to the blue wing of the line at –160 mÅ apart from line center (blue continuum) using cross correlation of four quadrants and detected the maximum of the cross correlation functions at a fraction of pixel using 2D paraboloid interpolation. Then we aligned together the nine consecutive spectral images (–160 to +160 mÅ) covering the line and belonging to the same scan of 28.75 s duration by correlating two successive images spectrally separated by 40 mÅ. The procedure reduced the FOV to 80.5''  $\times$  80.8'' (1006  $\times$  1010 pixels), showing that the tracking of *Hinode* with solar rotation compensation is excellent.

Using a narrow-band filter has the advantage of a large 2D FOV, but the resulting counterpart is that wavelengths scanned along the line profile are not simultaneous. In order to correct this effect, which can induce errors in deriving radial velocities from line profiles, we applied a phase correction to the temporal Fourier transform (FT) of the set of data, for each wavelength, with respect to the first wavelength of the line scan (blue continuum). After computation of the fast Fourier transform (FFT), a phase correction of the form  $\exp(2i\pi u \Delta t)$  was applied ( $u$  is the temporal frequency,  $\Delta t$  with  $0 \leq \Delta t \leq 28.75$  s is the time lag between the blue continuum and the current wavelength), and corrected data were obtained from the inverse FFT.

In order to improve the image quality, we computed the modulation transfer function (MTF) of the telescope taking into account the characteristics of the primary mirror, the central occultation, and the three branches of the secondary mirror, together with the geometry of square pixels of the CCD device. Each intensity image of the series was deconvolved with the MTF of the telescope and the CCD array.



**Figure 1**  $k$ - $\omega$  diagram of radial (vertical) velocities at the altitude of 130 km. The abscissa and ordinate represent the spatial and temporal frequencies in  $\text{km}^{-1}$  and in Hz, respectively. The line of  $\omega/k = C_s = 6 \text{ km s}^{-1}$  is also shown.

We detected small transmission fluctuations in the filter (a few percent) at constant wavelength. This effect was corrected with respect to the mean value of the light curve calculated on the overall FOV for each wavelength position.

We computed horizontal velocities from proper motions of granules observed in the continuum (average between blue and red wings at  $-160 \text{ m\AA}$  and  $+160 \text{ m\AA}$  apart from the line center). We first had to remove the effects of oscillations before the detection of granular motions; for that purpose, we applied a subsonic Fourier filter in  $k$ - $\omega$  space, where  $k$  and  $\omega$  are, respectively, the wave number and the frequency. This filter is defined by a region of high frequencies set at zero in  $k$ - $\omega$  space. A 3D FFT transform was computed in the 2D space + time, and only Fourier components such that  $\omega/k \leq C_s = 6 \text{ km s}^{-1}$  (where  $k = \sqrt{k_x^2 + k_y^2}$ ) were retained (Figure 1) to keep only the convective contribution in the final data (Title *et al.*, 1989).

We used the local correlation tracking (LCT) as described by November and Simon (1988) in order to compute horizontal velocities  $v_x$  and  $v_y$  as a function of space and time, from proper motions of the granulation in the nearby continuum of the line. Horizontal motions were necessary to calculate the horizontal divergence ( $\partial v_x / \partial x + \partial v_y / \partial y$ ) of the flow, as a function of space and time.

Then we computed radial velocities and intensities at different depths in the line profile using the bisector technique. We defined three bisectors (chords) whose widths are  $80 \text{ m\AA}$  (line core),  $120 \text{ m\AA}$  (inflection points) and  $160 \text{ m\AA}$  (line wings). The line chord of  $160 \text{ m\AA}$  was used to sample a layer around an altitude of  $80 \text{ km}$  (Altrock *et al.*, 1975; Berilli *et al.*, 2002), while chords of  $120 \text{ m\AA}$  and  $80 \text{ m\AA}$ , deeper in the line, were used, respectively, to study atmospheric levels at about  $130 \text{ km}$  and  $180 \text{ km}$ . For each time, a mean line profile was computed over the whole FOV, defining a wavelength and intensity reference for the three chords of the bisector. We applied the same method to individual profiles of the 2D FOV and computed for the three chords Dopplershifts and intensity fluctuations by reference to the

mean profile. Dopplershifts provided the vertical component of the velocity  $v_z$  as a function of space and time at three different altitudes ( $z = 80, 130,$  and  $180$  km, upward/downward velocities, respectively, positive/negative).

### 3. Temporal Behavior and Energy Flux of Acoustic Events from Hilbert Transform

From radial velocities at different heights, we derived phases and amplitudes of vertically traveling waves and the acoustic flux as a function of time, spatial position in the FOV and altitude in the photosphere.

Following Rimmele *et al.* (1995) and Strous, Goode, and Rimmele (2000), the acoustic flux  $e$  per unit of surface ( $\text{W m}^{-2}$ ) can be approximated by the product of the volumic energy density and the group velocity, assuming that the density  $\rho$  is constant:

$$e \propto \rho v_z^2 v_g,$$

where  $|v_z|$  is the amplitude and  $v_g$  is the group velocity of the wave.

The group velocity cannot be derived directly from observations, contrary to the phase velocity. For sonic waves, we used the relation  $v_g v_\phi = C_s^2$ , where  $v_\phi$  is the phase velocity and  $C_s = \sqrt{\gamma P/\rho}$  is the adiabatic sound speed ( $P$ : pressure,  $\gamma = 5/3$ ). This approximation is valid for vertically propagating waves in a plane parallel isothermal atmosphere (no magnetic field) with the dispersion relation  $\omega^2 = C_s^2 k^2 + N_s^2$ . With  $P = 4000$  Pa and  $\rho = 1.23 \times 10^{-4} \text{ kg m}^{-3}$  (altitude 150 km, HSRA; Gingerich *et al.*, 1971), we find  $C_s = 7.4 \text{ km s}^{-1}$ . The cutoff frequency  $N_s = \gamma g/(2C_s)$  ( $g$  solar gravity) is of the order of 4.9 mHz in this simplified model.

The phase velocity  $v_\phi$  was derived from observations by

$$v_\phi = \omega/k_z \quad \text{with } k_z = \Delta\varphi/\Delta z,$$

where  $\omega$  is the frequency of the assumed quasi monochromatic wave,  $\Delta\varphi$  is the phase lag between the two heights of observation and  $\Delta z$  is the thickness of the layer. The group velocity is directly related to the phase lag  $\Delta\varphi$  by the relation:

$$v_g = \Delta\varphi \frac{C_s^2}{\omega \Delta z}.$$

Numerically, for 5-min oscillations with  $\Delta z = 50$  km,  $v_g = 0.9 \Delta\varphi$  with  $v_g$  in  $\text{km s}^{-1}$  and  $\Delta\varphi$  in degrees (typically  $|\Delta\varphi| \leq 10$  deg so that  $|v_g| \leq C_s$ ).

The energy flux is given by the relation

$$e \propto v_z^2 (\gamma P/\omega) (\Delta\varphi/\Delta z) \quad \text{in } \text{W m}^{-2}.$$

We had to derive the velocity amplitude  $|v_z|$  and phase lag  $\Delta\varphi$  from measurements at two different levels. We used a mathematical method consisting of extending the observed vertical velocity  $v_z(t) = v(t)$  to the complex quantity  $V(t)$  such that

$$V(t) = v(t) + i\underline{v}(t),$$

where  $\underline{v}(t)$  is the Hilbert transform (HT) of  $v(t)$  (see the Appendix). We used the velocity data at two altitudes,  $z_1$  and  $z_2$ , in order to build complex velocities  $V_1(t) = v_1(t) + i\underline{v}_1(t)$  and  $V_2(t) = v_2(t) + i\underline{v}_2(t)$ , from which we derived the phase lag  $\Delta\varphi = \varphi_2 - \varphi_1 = \arg(V_2) - \arg(V_1)$  and the average amplitude  $A = (|V_1| + |V_2|)/2$ .

As the method is valid only for quasi monochromatic signals, we filtered data to isolate temporal frequencies  $u$  using the following narrow-band pass filter (full width at half maximum FWHM of 1.2 mHz):

- i)  $u \leq u_0 - 1.0$  mHz, filter null,
- ii)  $u_0 - 1.0$  mHz  $\leq u \leq u_0 - 0.2$  mHz,  $\cos^2$  ramp,
- iii)  $u_0 - 0.2$  mHz  $\leq u \leq u_0 + 0.2$  mHz, filter at 1,
- iv)  $u_0 + 0.2$  mHz  $\leq u \leq u_0 + 1.0$  mHz,  $\cos^2$  ramp,
- v)  $u \geq u_0 + 1.0$  mHz, filter null,

where  $u_0$  is the central frequency. We have chosen six different central frequencies: 3.3, 4.5, 5.7, 6.9, 8.1, and 9.3 mHz (for the frequency 3.3 mHz, we also used a second filter of 1.8 mHz FWHM to produce images and movies).

The phase lag and velocity group calculations were done inside two different layers (80–130 km and 130–180 km) for which the average pressure is, respectively, 5700 Pa and 4000 Pa (according to the HSRA model atmosphere; Gingerich *et al.*, 1971).

#### 4. Energy Flux Derived from the Fourier Power Spectra

Following Bello González *et al.* (2009), we used a complementary method to compute the mean energy flux from the Fourier power spectra (FPS)  $P_v$  of velocities, defined as the absolute value of the FT of  $v^2(t)$ . The energy flux is now defined by

$$e \propto \rho P_v \Delta v v_g,$$

where  $\Delta v$  is the frequency bandwidth (we chose 1.2 mHz) and  $v_g$  is the group velocity. This method is the most accurate for determining the average energy flux (as it does not require any frequency filtering), but on the contrary it does not provide temporal evolution of the flux and the group velocity is not determined from observations. We used the theoretical value provided by the simple plane parallel model:

$$v_g = C_s \frac{\sqrt{\omega^2 - N_s^2}}{\omega},$$

so that it is constant and uniform over the FOV and there is no energy flux for frequencies below 4.9 mHz. Computations have been performed for four frequencies (5.7, 6.9, 8.1, and 9.3 mHz) and for three different altitudes (80, 130, and 180 km) for which the corresponding pressure and volumic mass are, respectively: 7400 Pa,  $2.1 \times 10^{-4}$  kg m<sup>-3</sup>; 4800 Pa,  $1.45 \times 10^{-4}$  kg m<sup>-3</sup>; 3100 Pa,  $9.8 \times 10^{-5}$  kg m<sup>-3</sup> (according to the HSRA model atmosphere, Gingerich *et al.*, 1971).

Contrarily to the first method based on HT, the energy flux is now proportional to the volumic mass instead of the pressure.

#### 5. Granulation, Dynamics and Acoustic Events

We built several video movies using the 158 time steps that show the full temporal sequence (75 min) of granulation images with AEs (layer 130–180 km) and other quantities overlaid. Energy flux was computed for movies at 3.3 mHz (FWHM 1.8 mHz). The movies can be consulted in reduced size (central part of the FOV with 640 × 640 pixels) in standard MPEG1 format (5 Mbytes) or in full size (1006 × 1010 pixels) as MPEG4 (20 Mbytes) or non compressed JavaScript (40 Mbytes) at <http://www.lesia.obspm.fr/perso/jean-marie-malherbe/Hinode2010/index.html>.

Movie 0 summarizes the sequence of raw data processed here.

**Figure 2** Acoustic flux (3.3 mHz, 1.8 mHz FWHM) between 130 and 180 km from chords 80 and 120 mÅ, amplitude and phase lag. AEs are indicated by white dots. Green color represents velocity amplitude, and blue and red indicate positive and negative phase lags, respectively. FOV = 80'' × 80''.

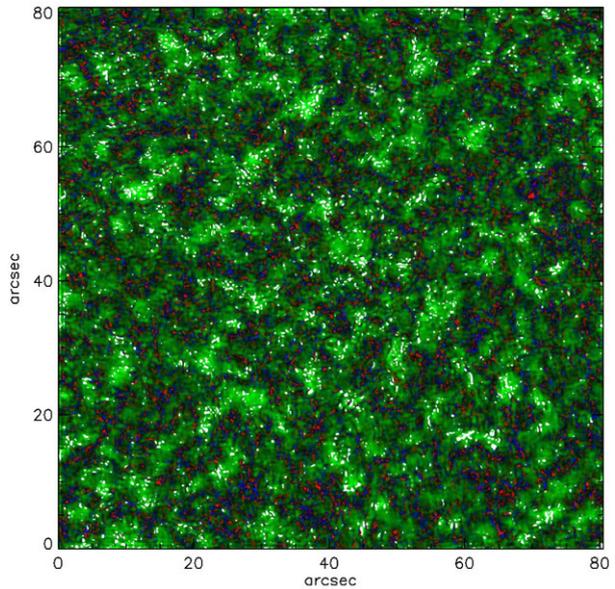


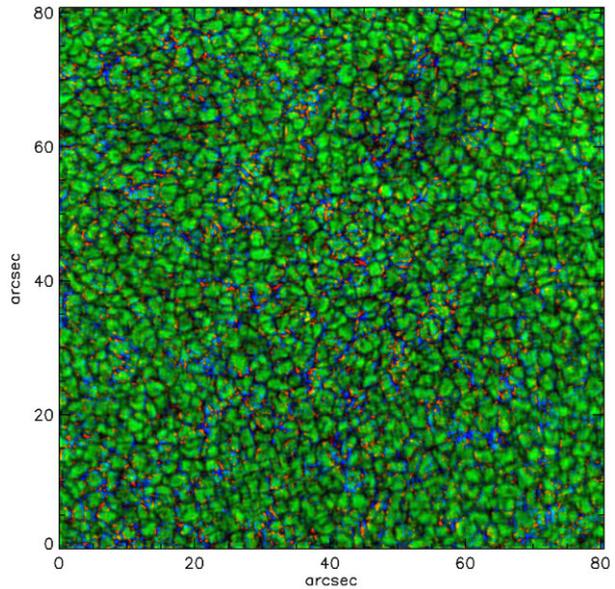
Figure 2 (and movie 1) shows the unsigned vertical acoustic flux in the middle of the sequence (image 76). The flux is spatially concentrated over a few pixels (1 pixel = 0.08''). AEs (flux proportional to the square of velocity amplitudes and phase lags) are characterized by high velocity amplitudes combined to moderate phase lags between both levels of observation (typically a few deg or a few  $\text{km s}^{-1}$  for the group velocity). In regions of low amplitude, phase lags become noisy (this is a limitation of the HT), generating small but noisy flux. The mean temporal evolution of a typical AE is detailed in Section 6.

Figure 3 (and movie 2) shows the signed vertical acoustic flux in the middle of the sequence with respect to the granulation pattern observed in the continuum, defined as the average of the wing intensities at  $-160 \text{ mÅ}$  and  $+160 \text{ mÅ}$ . Continuum images were generated after removal of high frequencies in the  $(k-\omega)$  diagram. In the  $(k_x, k_y, \omega)$ -space, we filtered all frequencies (oscillations) corresponding to  $\omega \geq C_s k$ , where  $C_s = 6 \text{ km s}^{-1}$  is the sound speed, and  $k = \sqrt{k_x^2 + k_y^2}$ , in order to keep only permanent convective flows. This figure, together with the movie, shows that AEs are spatially concentrated in intergranular lanes, and that upward-propagating flux is dominant.

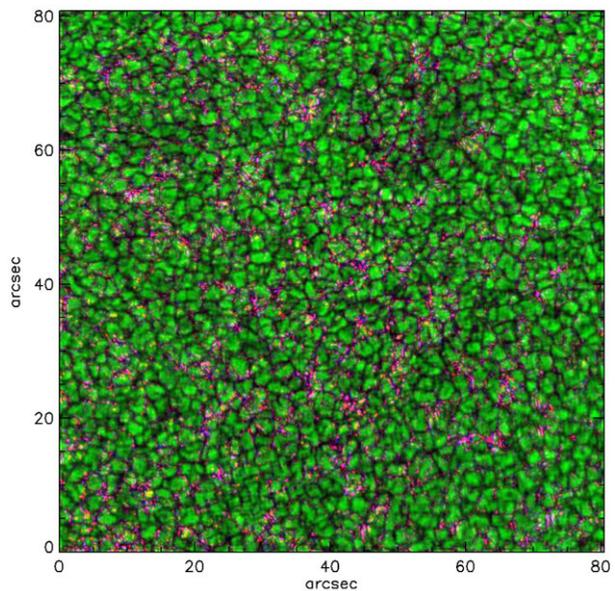
The acoustic flux was computed for layers 80–130 km and 130–180 km. Figure 4 (and movie 3) shows the unsigned flux in the two different layers (middle of the sequence) with respect to the granulation pattern observed in the continuum, defined as the average of the wing intensities and suppressing high frequencies in the  $(k-\omega)$  diagram to eliminate oscillations. The flux in the two different layers, when perfectly superimposed, appears as magenta; we notice that this is the case for most AEs, suggesting a good correlation (numerically 0.83) between both layers and propagation along 100 km for 97.3 % of observed events.

We studied the location of AEs not only with respect to the granulation pattern, but also with respect to vertical motions. For that purpose, Figure 5 (see also movie 4) shows the convective vertical velocities at 130 km together with AEs (layer 130–180 km) in the middle of the sequence superimposed to the granulation pattern observed in the continuum. Both vertical velocities and continuum intensities were suppressed at high frequencies ( $\omega \geq C_s k$ , where  $C_s = 6 \text{ km s}^{-1}$ ). The sequence confirms that intergranular lanes are associated with

**Figure 3** Acoustic flux (3.3 mHz, 1.8 mHz FWHM) between 130 and 180 km from chords 80 and 120 mÅ. Green color represents continuum intensity, and blue and red points indicate upward and downward concentrations of acoustic flux, respectively. FOV =  $80'' \times 80''$ .



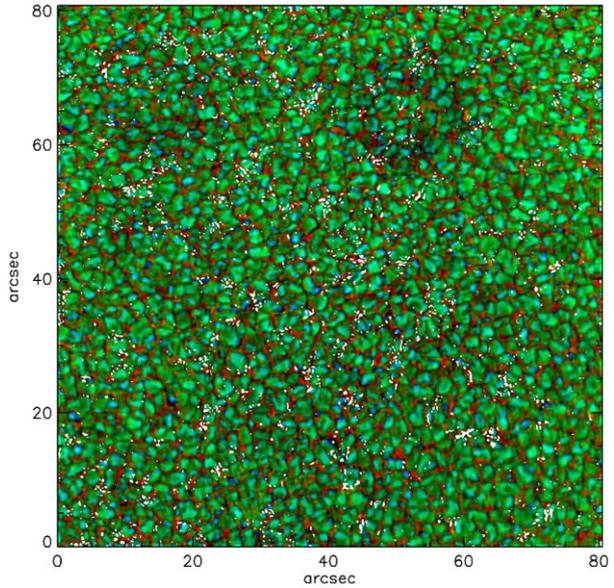
**Figure 4** Unsigned acoustic flux (3.3 mHz, 1.8 mHz FWHM) in two different layers with respect to the granulation pattern. Green color represents continuum intensity, and blue and red points indicate acoustic flux in height ranges 80–130 km and 130–180 km, respectively. FOV =  $80'' \times 80''$ .



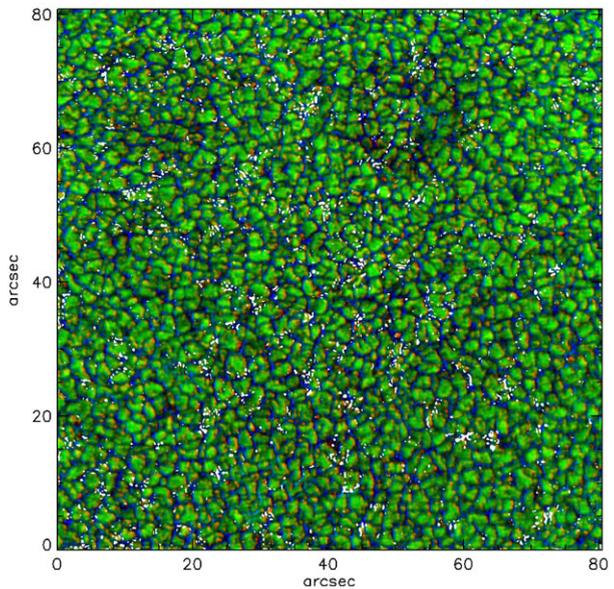
downflows, while granules are associated to upflows. It also shows that AEs mostly occur in intergranular lanes together with downdrafts.

Our multilevel velocity data allowed us to analyze the vertical velocity gradient, defined as the difference of radial velocities (positive upwards) between altitudes of 180 and 130 km. A positive gradient means increasing (signed) velocities with height. Figure 6 (and movie 5) shows the vertical gradient of convective velocities together with AEs in the middle of the sequence with respect to the granulation pattern. The gradient is mostly positive (which

**Figure 5** Vertical convective velocities and AEs with respect to the granulation pattern. AEs are indicated by white dots. Green color represents continuum intensity, and blue and red indicate upward and downward velocities, respectively. FOV =  $80'' \times 80''$ .



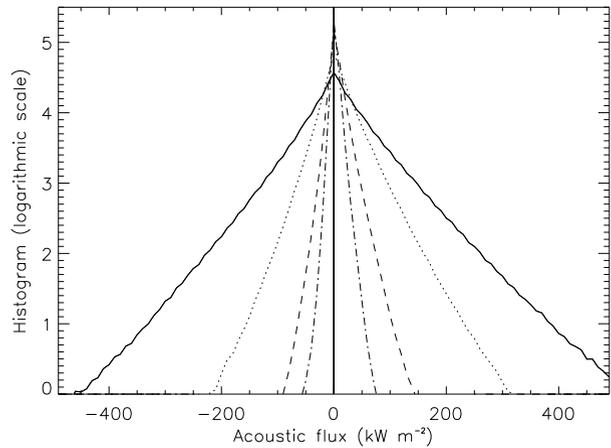
**Figure 6** Vertical gradient of convective velocities and AEs with respect to the granulation pattern. AEs are indicated by white dots. Green color represents continuum intensity, and blue and red indicate increasing and decreasing vertical velocities with height, respectively. FOV =  $80'' \times 80''$ .



means increasing velocity with height) in intergranular lanes. In absolute value, it means that the velocity decreases with height above intergranules. On the contrary, the gradient is almost zero or slightly negative above granules.

Histograms (not shown) of the continuum intensity as a function of vertical velocities or velocity gradients computed over the whole FOV and over the total duration of the sequence confirmed a strong correlation between dark regions (intergranules) and down-drafts, as well as bright regions (granules) and upward velocities. Flows are in the range

**Figure 7** Histogram of acoustic flux between 130 and 180 km (logarithmic scale) over the whole FOV for 3.3 mHz (solid line), 4.5 mHz (dotted line), 5.7 mHz (dashed line) and 6.9 mHz (dash-dot). The fluxes are summed over a FWHM of 1.2 mHz.



$-1 \text{ km s}^{-1}$  to  $+1 \text{ km s}^{-1}$ . Dark lanes (intergranules) are also related to positive velocity gradients ( $+0.2 \text{ km s}^{-1}$  typically).

## 6. Mean Properties and Temporal Evolution of Acoustic Events and Energy Flux

### 6.1. Energy Distribution of Acoustic Flux

The distribution of seismic flux derived from the full FOV is displayed in Figure 7. It is qualitatively comparable at 3.3 mHz to the one obtained by Strous, Goode, and Rimmele (2000), except that this is not the same spectral line (different altitude) and bandwidth. In the HT method, the acoustic flux is sensitive to a multiplicative parameter, the pressure. We have taken 4000 Pa, which represents a realistic order of magnitude for the layer 130–180 km according to Stebbins and Goode (1987) and from the HSRA model. It is also inversely sensitive to the thickness of the layer (50 km). The flux distribution is asymmetric, as upward flux dominates.

### 6.2. Number of Acoustic Events and Their Birth Rate

We labeled all AEs (detected at 3.3 mHz) with flux averaged over the whole temporal sequence above  $3\sigma$  ( $75 \text{ kW m}^{-2}$ ). This spatial criterion allows us to select energetic AEs covering less than 1 % of the surface. We used the binarization technique described by Roudier *et al.* (2003) to count and recognize pixels belonging to the same event. We found that the number of AEs is almost constant as a function of time within our  $80'' \times 80''$  FOV: 1250 events permanently above  $3\sigma$ , corresponding to  $2.2 \times 10^6$  events on the whole surface of the Sun. With a typical lifetime of 600 s at half maximum flux, we found a birth rate of  $3500 \text{ s}^{-1}$  over the full Sun, or  $5.7 \times 10^{-16} \text{ s}^{-1} \text{ m}^{-2}$ . This result is not far from the one ( $8 \times 10^{-16} \text{ s}^{-1} \text{ m}^{-2}$ ) obtained by Strous, Goode, and Rimmele (2000).

### 6.3. Energy Flux of Acoustic Events in Granules and Intergranules

We investigated the temporal behavior of the total acoustic flux measured in AEs at 3.3 mHz, as a function of time, in intergranules (negative continuum) as well as in granules (positive

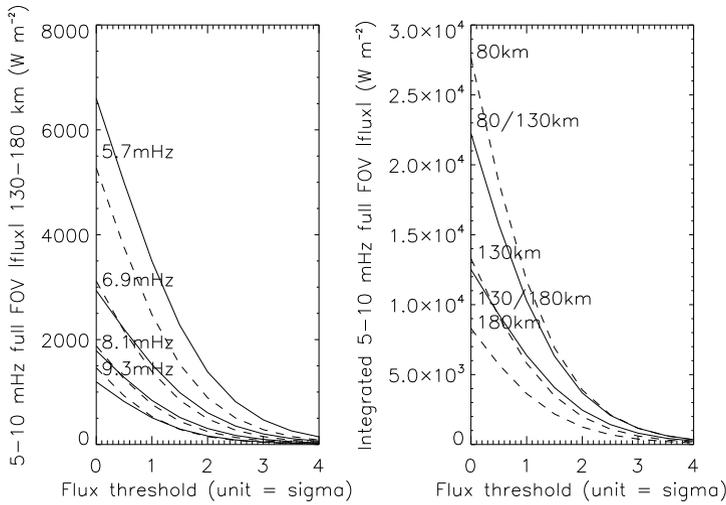
continuum). AEs were selected in terms of energy flux above  $3\sigma$  (covering less than 1 % of the surface). The net total flux of AEs (downward + upward) dominates in intergranules (four times larger than in granules), is upward and remains approximately constant in time, indicating that there exists a permanent renewal of a large number of events during the sequence.

#### 6.4. Power and Energy of Acoustic Events

We have computed, using the HT, the net acoustic flux (balance between upward and downward flux) in the range 3–10 mHz (1.2 mHz FWHM), layers 130–180 km and 80–130 km, as a function of the strength of AEs. We considered them as significant when the time averaged energy flux over the whole sequence duration is spatially above  $3\sigma$  or  $75 \text{ kW m}^{-2}$ , to cover less than 1 % of the surface. In the upper layer, the full FOV averaged flux (above  $3\sigma$ ) was  $2000 \text{ W m}^{-2}$  ( $2700 \text{ W m}^{-2}$  in the lower layer). But the flux averaged only over the area of AEs in the upper layer was  $1.2 \times 10^5 \text{ W m}^{-2}$  in the range 3–10 mHz and  $2.8 \times 10^4 \text{ W m}^{-2}$  in 5–10 mHz. In the lower layer, we got  $1.6 \times 10^5 \text{ W m}^{-2}$  in the interval 3–10 mHz and  $3.6 \times 10^4 \text{ W m}^{-2}$  in 5–10 mHz. The mean energy (flux integrated over space and time) carried out by each AE in the upper layer was  $1.9 \times 10^{19} \text{ J}$  in 3–10 mHz and  $4 \times 10^{18} \text{ J}$  in 5–10 mHz. These values are of the same order of magnitude than those found by Strous, Goode, and Rimmele (2000). In the lower layer, we got  $2.5 \times 10^{19} \text{ J}$  for 3–10 mHz and  $5 \times 10^{18} \text{ J}$  for 5–10 mHz. The mean area of AE is about 12 pixels of  $0.08''$  (corresponding approximately to the resolving power of the telescope).

Figure 8 allows one to compare results in the 5–10 mHz range over the full FOV obtained from the HT (allowing the determination to be made of time dependent group velocity and signed flux inside the layers 130–180 and 80–130 km) and those (unsigned) got from classical FPS with uniform and constant group velocity ( $v_g = C_s \frac{\sqrt{\omega^2 - N_s^2}}{\omega}$ ) at three altitudes (80, 130, 180 km). In order to facilitate the comparison, we have taken the absolute value of the flux provided by the HT; and we computed the average value of the flux between 130–180 km (upper layer) and 80–130 km (lower layer) of the FPS. The plot for four frequencies (5.7, 6.9, 8.1, 9.3 mHz, each band having 1.2 mHz FWHM) shows that there is a good agreement between space and time averaged results derived from the two approaches. This result indicates that the group velocity, derived from observations by the HT, is close in average to the one used in the FPS, emphasizing the stochastic character of the large number of acoustic events.

We also computed (Figure 8) the flux integrated over the frequency band of 5–10 mHz inside the upper and lower layers (HT), and at 80, 130, and 180 km (FPS). Here again, the agreement is good. We find for the three altitudes, respectively,  $27\,000 \text{ W m}^{-2}$ ,  $12\,000 \text{ W m}^{-2}$  and  $8000 \text{ W m}^{-2}$  over the full FOV (without any flux threshold). Bello González *et al.* (2009) found  $2000 \text{ W m}^{-2}$  in the same spectral line at 250 km and in Fe I 543.4 nm at 500 km (Bello González *et al.*, 2010a); they also got results (Bello González *et al.*, 2010b) with SunRise (no atmospheric effects) in the range  $7000 \text{ W m}^{-2}$  (wavelet) to  $12\,000 \text{ W m}^{-2}$  (Fourier) in Fe I 525.02 nm at 250 km which could be compatible with our results ( $8000 \text{ W m}^{-2}$  at 180 km). Concerning the contribution of AEs to the total flux over the whole FOV, we found that events selected above  $3\sigma$  (1 % of the surface) have a contribution of less than 10 % in the 5–10 mHz interval.



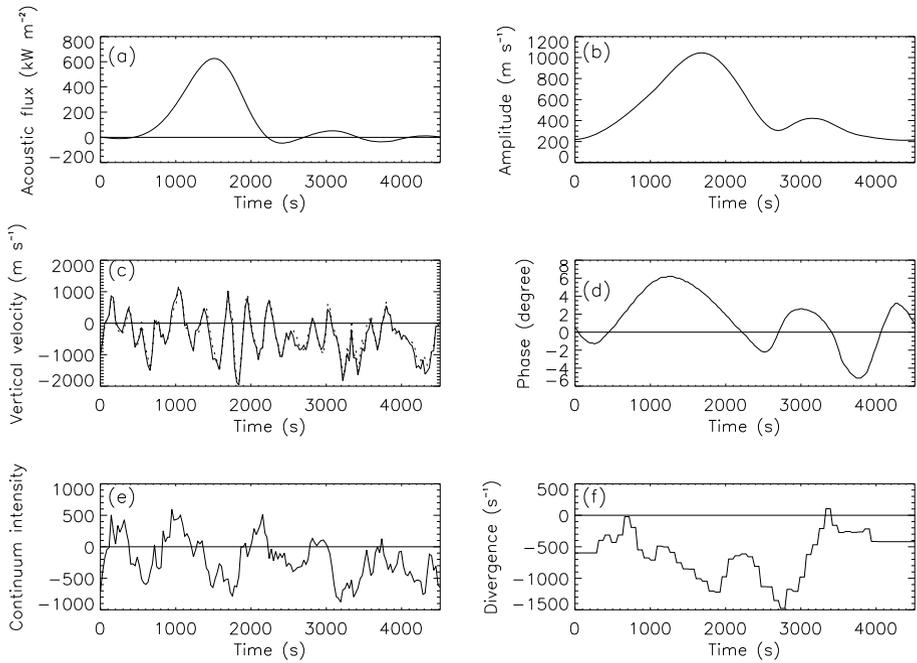
**Figure 8** Left: Unsigned acoustic flux ( $W m^{-2}$ ) in the 130–180 km layer averaged in time and space for frequencies 5.7, 6.9, 8.1, and 9.3 mHz. The solid and the dashed lines indicate results from HT and FPS, respectively. Right: Integrated 5–10 mHz unsigned flux ( $W m^{-2}$ ) for layers 130–180 and 80–130 km for HT (solid lines). Similarly the dashed lines indicate the results from FPS at altitudes 80, 130, and 180 km. The flux above  $2\sigma$ ,  $3\sigma$ , and  $4\sigma$  cover 6%, 1%, and 0.15% of the solar surface, respectively.

### 6.5. Temporal Evolution of Acoustic Events—Amplitude, Phase, and Divergence

AEs are energetic phenomena concentrated in space and time. Thanks to the HT, it is possible to study the temporal evolution and the sign of the energy flux for specific frequencies and heights.

First, Figure 9 shows the temporal behavior of a typical AE during the full duration of the sequence (75 min).

Then we isolated all AEs of the sequence and analyzed their average properties and in particular their mean temporal behavior in the 130–180 km layer, according to the strength of acoustic flux. For that purpose, we used different spatial thresholds in terms of time averaged energy flux over the whole sequence duration at  $2\sigma$ ,  $3\sigma$ , and  $4\sigma$  (respectively, 50, 75, and  $100 \text{ kW m}^{-2}$ ). This criterion selects events covering, respectively, 6%, 1%, and 0.15% of the surface. We shifted in time events belonging to these three classes after detection of their maxima, superimposed them peak to peak, and made an average. The result is shown in Figure 10. The mean evolution time of AEs measured at half maximum lies around 600 s with a full duration up to 1200 s. There is a time lag between maximum amplitudes and phases of about 500 s (300 s for Strous, Goode, and Rimmele (2000)). Phase lags lie around 3 to 4 degrees (corresponding to group velocities of 3 to  $4 \text{ km s}^{-1}$ ) and velocity amplitudes are in the range  $0.8$  to  $1.0 \text{ km s}^{-1}$  at maximum. The strength of the flux is strongly related to velocity amplitudes. Acoustic flux occurs essentially in intergranules, with downward motions ( $-0.2 \text{ km s}^{-1}$ ) and negative continuum intensity (dark regions); both quantities are correlated (darkest lanes and fastest downflows) with the flux strength. AEs appear also related to regions of converging flows, but the convergence (negative divergence) seems to be maximum 200 s prior to the flux maximum. Velocity amplitudes, downward flows, convergences and intergranular darkness are largest for the most intense AEs.

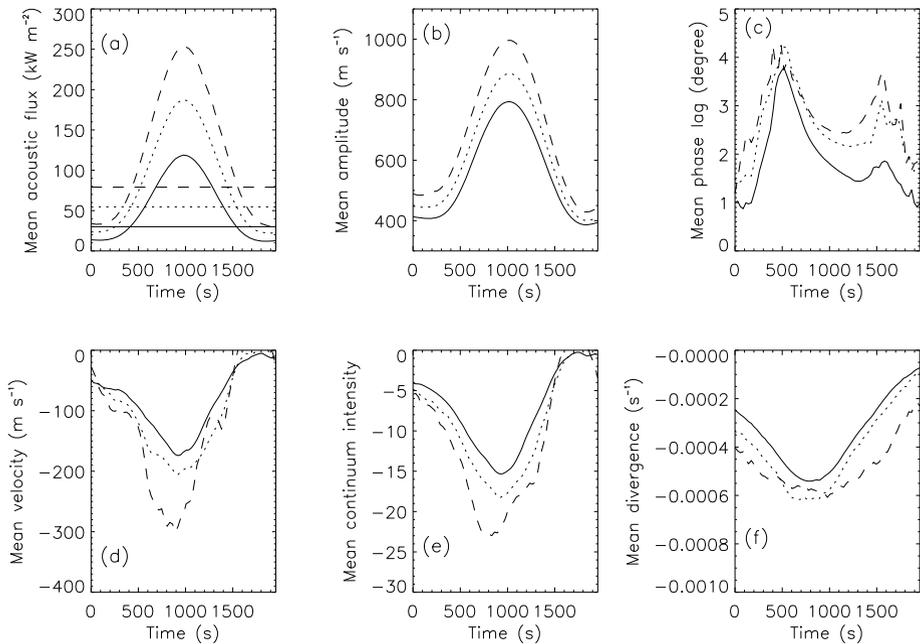


**Figure 9** Time evolution of a typical AE in the layer 130–180 km. (a) Acoustic flux ( $\text{kW m}^{-2}$ ) at 3.3 mHz (FWHM 1.2 mHz); (b) velocity amplitude ( $\text{m s}^{-1}$ ); (c) vertical velocity ( $\text{m s}^{-1}$ ) at 130 and 180 km; (d) phase lag (deg); (e) continuum intensity (arbitrary unit, dark is negative); (f) horizontal velocity divergence ( $\text{s}^{-1}$ , negative for converging flows).

## 7. Discussion and Conclusions

AEs, defined as time averaged energy flux over the whole sequence duration above  $3\sigma$  or  $75 \text{ kW m}^{-2}$  (spatial criterion selecting less than 1 % of the surface), were evidenced from the SOT/NFI onboard *Hinode* with outstanding spatial resolution and FOV using the non magnetic Fe I 557.6 nm line. Velocities were computed at three altitudes, corresponding to different chords in the line profiles, using the bisector technique. We used two methods to determine acoustic flux. The first one, based on the HT, after temporal frequency filtering, allowed us to determine velocity amplitudes and phase lags as a function of time in two layers (130–180 and 80–130 km). The group velocity is proportional to phase lags and was used to derive the signed energy flux. The second method (avoiding filtering) was based on FPS at three altitudes (80, 130, and 180 km) using a constant and uniform group velocity taken from models, but did not provide flux sign nor temporal evolution. Both methods delivered complementary results mutually in agreement in the range 5–10 mHz.

In the 3–10 mHz range, the contribution of AEs is  $2000 \text{ W m}^{-2}$  (upper layer 130–180 km) and  $2700 \text{ W m}^{-2}$  (lower layer 80–130 km), with more flux in the 3–5 mHz than in the 5–10 mHz domain. AEs are spatially concentrated ( $0.3''$  typical, some are probably below the resolving power of the telescope). Their average duration is about 600 s at half maximum (1200 s including rise and decay phases) and they carry energy mainly upwards. Each event carries in the range 3–10 mHz an average flux of  $1.2 \times 10^5 \text{ W m}^{-2}$  (upper layer) and  $1.6 \times 10^5 \text{ W m}^{-2}$  (lower layer), and a total energy of about  $1.9 \times 10^{19} \text{ J}$  (upper



**Figure 10** Properties of AEs averaged in space in the layer 130–180 km as a function of time. Solid, dotted, and dashed lines indicate weak, medium, and intense AEs with flux above  $2\sigma$ ,  $3\sigma$ , and  $4\sigma$  levels, respectively. The statistics is strongly reduced for intense events ( $4\sigma$ ). (a) Acoustic flux ( $\text{kW m}^{-2}$ ) at 3.3 mHz (FWHM 1.2 mHz); (b) velocity amplitude ( $\text{m s}^{-1}$ ); (c) phase lag (deg); (d) convective velocity ( $\text{m s}^{-1}$ ); (e) continuum intensity (arbitrary unit, dark is negative); (f) divergence ( $\text{s}^{-1}$ , negative for converging flows).

layer) or  $2.5 \times 10^{19}$  J (lower layer). More than  $10^6$  events exist at any instant on the Sun, with a mean birth rate of  $3500 \text{ s}^{-1}$ . Most occur in intergranular lanes, downward velocity regions, and areas of converging motions. The peak of velocity amplitude ( $0.8$  to  $1 \text{ km s}^{-1}$ ) occurs after the maximum phase lag, which indicates an energy propagation speed of several  $\text{km s}^{-1}$ . Just before the time of peak flux, converging flows seem to intensify. The strength of AEs is correlated to the strength of convective flows, converging horizontal motions, and also to the darkness of intergranules. Regions with fastest downward motions and strongest convergences, as well as darkest structures, produce the most energetic AEs.

From a theoretical point of view, the details of the excitation mechanism are suspected to be stress and entropy fluctuations. Analysis of observations and numerical simulations show that the sources of the solar oscillations are associated with downdrafts in dark intergranular lanes (Rimmele *et al.*, 1995), and near the boundaries of granules (Stein and Nordlund, 2001), as we found here. It will be of great interest to locate AEs with respect to families of granules which are formed from the evolution of trees of fragmenting granules, and which are related to larger scales as the mesogranulation and supergranulation (Roudier *et al.*, 2003). This aim can be reached using a much longer observing run (6 h) than the present one. Such a run was performed (14 April 2010) and results will be presented in a future paper.

**Acknowledgements** We are grateful to the anonymous referee for helpful comments and suggestions and to R. Stein for useful hints. We are also indebted to the *Hinode* team for the possibility to use their data.

*Hinode* is a Japanese mission developed and launched by ISAS/JAXA, collaborating with NAOJ as a domestic partner, NASA and STFC (UK) as international partners. Scientific operation of the *Hinode* mission is conducted by the *Hinode* science team organized at ISAS/JAXA. This team mainly consists of scientists from institutes in the partner countries. Support for the post-launch operation is provided by JAXA and NAOJ (Japan), STFC (U.K.), NASA, ESA, and NSC (Norway).

This work was supported by the Centre National de la Recherche Scientifique (C.N.R.S., UMR 8109 and 5572) and by the Programme National Soleil Terre (P.N.S.T.), France.

## Appendix

In order to compute the complex signal  $V(t) = v(t) + i\underline{v}(t)$ , we used the temporal FFT together with the following properties of the Hilbert transform (HT). Given an observed signal  $v(t)$ , the HT  $\underline{v}(t)$  is given by

$$\underline{v}(t) = h(t) \star v(t),$$

where  $\star$  denotes the convolution product and  $h(t) = \frac{1}{\pi t}$ .

For a sinusoidal signal of the form  $v(t) \propto \cos(\omega t + \varphi)$ , the HT is simply  $\underline{v}(t) \propto \sin(\omega t + \varphi)$ , so that in this case  $V(t) \propto \exp[i(\omega t + \varphi)]$ .

The easiest way to get  $\underline{v}(t)$  is to use the Fourier transform (FT with  $u$  denoting the temporal frequency):

$$\text{FT}_{\underline{v}}(u) = \text{FT}_h(u)\text{FT}_v(u).$$

It can easily be shown that

$$\text{FT}_h(u) = -i \operatorname{sgn}(u),$$

where  $\operatorname{sgn}(u)$  is the sign function,  $+1$  for  $u > 0$ ,  $0$  for  $u = 0$  and  $-1$  for  $u < 0$ .

As a consequence, the FT of the complex signal  $V(t) = v(t) + i\underline{v}(t)$  is given by

$$\text{FT}_V(u) = \text{FT}_v(u) + i\text{FT}_h(u)\text{FT}_v(u) = \text{FT}_v(u)(1 + \operatorname{sgn}(u)).$$

This expression reduces simply to

- i)  $u < 0$ ,  $\text{FT}_V(u) = 0$ ,
- ii)  $u = 0$ ,  $\text{FT}_V(u) = \text{FT}_v(u)$ ,
- iii)  $u > 0$ ,  $\text{FT}_V(u) = 2\text{FT}_v(u)$ .

We first computed the temporal FT of the observed signal  $v(t)$ ; in order to get the FT of the complex velocity  $V(t) = v(t) + i\underline{v}(t)$ , values corresponding to negative frequencies were eliminated and values corresponding to positive frequencies were doubled. Finally, the complex velocity  $V(t) = v(t) + i\underline{v}(t)$  was derived from the inverse FT.

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