Local 5-min Oscillations above Solar Granules and Intergranular Space

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Abstract—A time series of granulation spectral images with high spatial (<0.7") and temporal (9.3 s) resolutions has been obtained with the German vacuum tower telescope (VTT) on the Canary Islands in an effort to study the local 5-min solar oscillations. Observations were carried out with a CCD array in the Fe I λ532.4185-nm line. The 5-min intensity and velocity fluctuations near the temperature minimum, where this line originates, are shown to respond differently to the fine photospheric structure. The most energetic velocity fluctuations occur above the regions where the convective velocities are at a maximum; the main power of the velocity fluctuations above granules concentrates at lower frequencies than that in intergranular space. The amplitude of the intensity fluctuations in the λ532.4185-nm emission above granules is, on the average, approximately a factor of 2 smaller.

INTRODUCTION

More than 35 years has elapsed since Leighton et al. (1962) discovered the 5-min oscillations in the solar atmosphere, but intense debates about the excitation mechanism of these oscillations have continued to the present day. The initial assumption that rising granules were responsible for the generation of waves (Evans and Michard 1962; Schmidt and Zirker 1963; Meyer and Schmidt 1967; Stix 1970) was not confirmed experimentally (Frazier 1968; Musman 1974). At present, the prevailing view is that the solar p-modes are powered by the stochastic processes attributable to turbulent convection immediately beneath the photosphere. Goldreich and Keeley (1977) and Goldreich and Kumar (1988) were the first to draw this conclusion from theoretical calculations. Subsequently, this idea was further developed by Kumar and Goldreich (1989), Goldreich and Kumar (1990), Goldreich et al. (1994), Balmforth (1992), Bi and Li (1998), and Goode et al. (1998). On the other hand, Libbrecht et al. (1986) pointed out that the proposed mechanism ran into difficulties when explaining oscillations with high powers of the angular number l.

Since the acoustic energy is proportional to the eighth power of the Mach number (Goldreich and Keeley 1977), the most energetic oscillations, according to Brown (1991), must be generated in those regions where the convective velocities are at a maximum, i.e., the bulk of the acoustic energy must come from isolated sources which occupy a relatively small part of the space. Indeed, having measured the Doppler shifts near sunspot groups, Brown et al. (1992) found that a small fraction of the solar surface emits a disproportionately large amount of acoustic energy in the frequency range 5.5–7.5 mHz.

A similar excitation mechanism for the 5-min oscillations was proposed by Goode et al. (1992), who provided evidence for the location of the excitation sources at 200 km below the photosphere. Having compared the observed velocity fluctuations at different heights in the solar photosphere (which can be both positive and negative) with the observations by Stebbins and Goode (1987), the authors concluded that the excitation sources of the 5-min oscillations are “isolated expansive events” attributable to granular motions. Restaino et al. (1993) holds the same point of view.

The relation between the local 5-min oscillations and granular motions appears to have been investigated in greatest detail by Espagnet et al. (1996). Having analyzed the time sequence of the granulation pattern in white light and spectral observations in the Na I D2 line, the authors concluded that the most energetic oscillations were actually separated in space and time, in agreement with the theoretical predictions of Brown (1991). According to Espagnet et al. (1996), however, these oscillations occur only in intergranules, where the downflow velocities are at a maximum, and are absent in granules, in conflict with the mechanism proposed by Goode et al. (1992). The study by Rimmele et al. (1995) also suggests that the oscillation excitation sources preferentially lie in intergranular space, in the regions with enhanced turbulence. This enhanced turbulence in intergranules may be caused by the appreciable velocity gradient at the boundaries of large granules which was observed by Nesis et al. (1992, 1997) and Solanki et al. (1996).

On the other hand, the thorough studies of granule filtergrams in the G band by Hoekzema et al. (1998) and Hoekzema and Rutten (1998) did not confirm the results of Espagnet et al. (1996). The 5-min oscillations
turned out to be insensitive to the fine photospheric structure, or, in other words, the above authors failed to
detect any differences between the oscillations above
granules and intergranules. As regards the p-mode
sources, they apparently lie considerably deeper than

We thus conclude that the available studies are con-
tradictory and cannot be used to elucidate the relation
between the local 5-min oscillations and granulation.
The observations, especially those obtained with high
spatial and temporal resolutions, should be analyzed
further. Here, we make an attempt to use such observa-
tions to solve this problem. We hope that our results
will help to better understand the excitation mechanism
of the 5-min oscillations.

OBSERVATIONS

The observations were performed by N. Shchukina
in August 1996 with the 70-cm German vacuum tower
telescope (VTT) at the Del Teide Observatory of the
Institute of Astrophysics on the Canary Islands (Teneri-
ife Island). A description of the telescope and the spec-
trograph can be found in Schröter et al. (1985).

The Fe I λ532.4185-nm line with the lower-level
excitation potential EPL = 3.21 eV was chosen for the
observations. Its central residual intensity in the atmo-
spheric spectrum of the quiet Sun, which was measured
relative to the local continuum, is \( r_\lambda = 0.139 \) (Delbouille et al. 1973), and the formation region, as calcu-
lated by Shchukina and Trujillo Bueno (1998) with
allowance for departures from local thermodynamic
equilibrium, lies near the temperature minimum (\( T =
500 \) km). Thus, the emission at the line center origi-
nates high in the photosphere, where one might expect
significant intensity and velocity fluctuations attribut-
able to wave motions.

The observations were carried out near the center of
the solar disk. Using narrow-band H\( \alpha \) and Ca II K filters,
we chose an undisturbed region on the solar sur-
face. The spectrograph dispersion near a wavelength of
600 nm was \( \lambda = 0.01 \) nm mm\(^{-1}\). The detector was a CCD
camera with 1024 \times 1024 pixels connected in pairs 2 \times 2
(512 spectral “tracks”, each included 512 discrete val-
ues of the spectrum). The extent of the region recorded
by the CCD array was \( \lambda = 0.2 \) nm. The size of one dual
pixel corresponded to 0.″ 174 on the solar surface. The
entrance slit width of the spectrograph was 80 \( \mu \)m or
0.″ 38 on the solar disk. Thus, the telescope field of view
was 0.″ 38 \times 89″. The Fe I λ532.4185 line was exposed
at intervals of 9.3 s over 31 min. The duration of a sin-
gle exposure was 5.7 s, and their total number was 200.
During the observations, the tremor of the solar surface
at the spectrograph entrance slit due to atmospheric
seeing and guiding errors did not exceed 0.″ 35, which

is comparable to the diffraction-limited spatial resolu-
tion of the telescope (0.″ 20).

DATA REDUCTION

All 200 images were corrected for dark current and
flat-fielded following the standard procedure (see, e.g.,
Kiselman 1994). The calibration images which were
used as flat fields were exposed immediately after the
spectrum was taken at the same wavelength near the
solar-disk center by averaging the spatial structure on
the solar surface. The latter was achieved by rocking
the telescope’s additional mirror. The resulting calibra-
tion image was obtained by averaging over 50 expo-
sures. A close examination of the finally reduced observa-
tional data shows that 0.″ 4–0.″ 5 features are clearly
distinguished in the spectrograms. Recall that the tem-
poral resolution was 9.3 s.

For each spectral track \( i \) (\( i = 1–512 \)) and for each
individual image \( j \) (\( j = 1–200 \)) of the solar surface
0.″ 38 \times 89″ in size, we measured three parameters: the
line central residual intensity \( I_0(i,j) \) (the minimum in
the line core), the wavelength position \( P(i,j) \) of this
minimum in pixels, and the continuum intensity \( I_c(i,j) \).
The values of \( I_0(i,j) \) were calculated by averaging over
20 pixels at a distance of 0.11 nm from the line center.
According to the atlas by Delbouille et al. (1973), the
residual intensity at this wavelength for the spatially
averaged solar spectrum is 98%. Since we are inter-
ested only in the relative variations of these three line
parameters, we ignore the effects of the spectrograph
instrumental profile.

Figures 1a–1c show typical variations in the above
line parameters along the slit (over the solar surface) for
a single exposure (image \( j = 15 \)). The variations in
\( P \) were transformed to velocity variations \( \delta V \); the posi-
tion of the intensity minimum in the average image
spectrum was used as the reference point. This spec-
trum was obtained by averaging over 512 spectral
tracks for a given exposure. Note that in this and the fol-
lowing figures, positive values of \( \delta V \) correspond to
flows toward the observer (upward-directed velocities).

The spatial intensity variations \( \delta I_0(i,j) = I_0(i,j) - I_0(j) \)
at the line center were measured relative to their mean
\( I_0(j) = \frac{1}{512} \sum I_0(i,j) \) for a given image \( j \). The contin-
um intensity variations \( \delta I_c(i,j) \) were determined in a
similar way. As we see from Fig. 1, the velocity fluctua-
tions \( \delta V(i,j) \) for one instant of time reach \( \pm 1 \) km s\(^{-1}\),
while the intensities in the continuum and at the line
center vary within \( \pm 8 \) and \( \pm 2% \), respectively.

Figures 1d-1f show variations of the line parameters
under study with time in one of the spectral tracks (\( i = 7 \)).
Note that when \( \delta V(i,j) \) was determined, the position
of the line center in the time-averaged spectrum of the \( i = 7 \)
track served as the reference point in these panels,
Fig. 1. (a)–(c) Spatial variations (along the spectrograph slit) in velocity $\delta V$ (a), central residual intensity $\delta I_0$ (b), and continuum intensity $\delta I_c$ (c) observed in the Fe I $\lambda 532.4185$-nm line for one instant of time. The region on the solar surface is $0.838 \times 89''$ in size; (d)–(f) variations of the same parameters with time for one position on the solar disk ($0.738 \times 0.74''$ region); (g)–(j) examples of separating the velocity field $\delta V$ (dot-dashed lines) observed near the temperature minimum into the wave $\delta V_w$ (solid lines) and convective ($\delta V_c$, dashed lines) components, the dots represent continuum intensity variations $\delta I_c$ with time (the variations $\delta V, \delta V_w, \delta V_c$, and $\delta I_c$ are given in arbitrary units). The regions with $\delta I_c > 0$ and $\delta I_c < 0$ correspond to granules and intergranules, respectively.

while the line and continuum intensity variations were measured relative to their time-averaged values $\langle I_{\Delta \lambda}(i) \rangle = \sum_{j} I_{\Delta \lambda}(i, j)/200$, where the subscripts $\Delta \lambda = 0$ and $c$ mean the line center and the continuum, respectively. It follows from Fig. 1 that the observed temporal variations $\delta V$ and $\delta I_0$ in the Fe I $\lambda 532.4185$ line are comparable to the spatial variations, while the continuum variations with time $\delta I_c$ are approximately a factor of 2 smaller.
RESULTS AND DISCUSSION

The variations in the Fe I λ532.4185 parameters under study are mainly attributable to convective and wave motions. By convective motions we mean the individual motions of granules and intergranules. In order to separate the granular and wave components of the velocity field, we constructed a diagnostic $k$–$\omega$ diagram (Fig. 2) in which the power of the velocity variations is plotted against temporal ($\omega$) and spatial ($k$) frequencies. In this diagram, the oscillations and convective motions are clearly separated by the minimum at $\omega = 1.9$ mHz ($T = 530$ s). Based on the diagram, we limited the wave and convective motions to the temporal frequencies $\omega = 1.8$–5.7 mHz ($T = 170$–560 s) and $< 2.2$ mHz ($T > 450$ s), respectively. The wave motions were separated in spatial frequency from the convective motions at $k = 0.18$ by using the corresponding high- and low-pass filters. The wave and convective components of the intensity fluctuations were separated in a similar way.

Examples of separating the general velocity field $\delta V(i, j)$ into the wave $\delta V_\omega(i, j)$ and convective $\delta V_k(i, j)$ components for several spectral tracks ($i = 7, 108, 210, \text{and} 450$) are shown in Figs. 1g–1j. To compare the patterns of temporal variations in the velocity field at the formation height of the Fe I λ532.4185-nm center and in the continuum intensity field, the same figures show temporal variations in the continuum intensity $\delta I_c$ (the convective component alone). For this reason, the velocities and intensities are given in arbitrary units. Note that in contrast to Figs. 1a–1f, in Figs. 1g–1j and in all the figures that follow, the shifts of the line center were measured relative to its position in the spectrum averaged over time and space, while the intensities $I_\delta(i, j)$ and $I_c(i, j)$ were measured relative to their mean values $\langle I_\delta \rangle = \sum_i \sum_j I_\delta(i, j)/(512 \times 200)$.

The oscillation arcs in Figs. 1g, 1i, and 1j have velocity amplitudes $\delta V_\omega(i, j)$ at maximum that are appreciably higher than the means. Considerably more frequently, each $0'' 38 \times 0'' 174$ surface element oscillates with smaller amplitudes (see Fig. 1h). Interestingly, in contrast to Espagnet et al. (1996), we found no preferential locations of the strong trains of velocity oscillations above expanding intergranular regions. Oscillations of this kind occur with almost the same probability both above intergranules and above granules.

Recall that the goal of our study is to analyze the spatial and temporal relation between the granulation and the local oscillations, in particular, the pattern of wave motions above granules and intergranules. Since the granule mean lifetime is $\approx 10$ min (Title et al. 1989), i.e., about two periods of the 5-min oscillations, we, unfortunately, cannot apply the techniques of spectral analysis of oscillations to such short series. However, it seems appropriate to artificially "prolong the time of
Mean characteristics for the field of wave ($\langle \delta V_w \rangle$, $\langle \delta I_c \rangle$) and convective ($\langle \delta V_k \rangle$, $\langle \delta I_k \rangle$) motions in the upper solar photosphere ($H = 500$ km) above granules and intergranules of different contrast $\delta I_c$, which occupy area $S$

<table>
<thead>
<tr>
<th>$N$</th>
<th>$\delta I_c$, %</th>
<th>$\langle \delta I_c \rangle$, %</th>
<th>$S$, %</th>
<th>$\langle \delta V_w \rangle$, m s$^{-1}$</th>
<th>$\langle \delta I_w \rangle$, %</th>
<th>$\langle \delta V_k \rangle$, m s$^{-1}$</th>
<th>$\langle \delta I_k \rangle$, %</th>
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<td>52.2</td>
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<td>0.21</td>
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<tr>
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<td>2.1</td>
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<td>0.12</td>
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<tr>
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<td>3.0</td>
<td>35.3</td>
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<tr>
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<td>3.9</td>
<td>24.6</td>
<td>45</td>
<td>0.17</td>
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<td>-0.27</td>
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<tr>
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<td>4.7</td>
<td>16.2</td>
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<td>0.18</td>
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oscillations” above granules and intergranules. We proceeded as follows. For each instant of time $j$ within one image, we divided the spectral tracks into two classes by using the continuum intensity averaged over space and time $\langle I_c \rangle$ as the criterion. We assumed that any individual track $i$ represents the granule spectrum if the continuum intensity in this track is higher than the mean, i.e., if the contrast $\delta I_c(i, j) = I_c(i, j) - \langle I_c \rangle > 0$. The tracks with $\delta I_c(i, j) < 0$ were considered as the intergranule spectra. The granules were found to occupy only 47.8% of the total area of the observed region. This result is in good agreement with the recent results (47-48%) of Hirzberger et al. (1997) and Hoeckzema et al. (1998). Note also that the mean contrasts $\langle \delta I_c \rangle$ for granules and intergranules were +2.1 and -2.1%, respectively. Having averaged separately the spectra of the tracks with positive and negative contrasts in each image, we obtained two time sequences, one of which contained only the average granule spectra and the other contained only the average intergranule spectra. For each of these sequences, we then determined the variations in line central intensity $\delta I_0(j)$, in continuum intensity $\delta I_c(j)$, and in velocity $\delta V(j)$.

Figures 3a–3d (the curves with mean contrasts of +2.1 and -2.1%) show how the wave $\langle \delta V_w \rangle$ and convective $\langle \delta V_k \rangle$ velocity components (Figs 3a, 3b), as well as the wave $\langle \delta I_w \rangle$ and convective $\langle \delta I_k \rangle$ components of the iron-line central intensity (Figs. 3c, 3d), vary with time above granules and intergranules in the upper photosphere. These curves are analyzed below. Note only that the oscillations above granules and intergranules in the Fe I λ532.4185-nm formation region differ in pattern.

In order to find out whether the pattern of wave motions depends only on the sign of contrast in the continuum or if it also depends on its magnitude, we made a finer classification of the granulation by intensity. For this purpose, all spectra separately for granules and intergranules in each image were subdivided into six subclasses. In the case of granules, we attributed the spectral tracks to the same subclass, if their contrast $\delta I_c(i, j)$ was larger than some threshold value. In the case of intergranules, the contrast in each subclass was smaller. The threshold contrasts for granules and intergranules and for their subclasses are given in the table (column 2). Also given here are their mean contrasts (column 3) and the fraction of the area $S$ occupied by them (column 4).

The results of our calculations for granules and intergranules of various intensities are shown in Fig. 3 and are given in columns 5–8 of the table. Note that Fig. 3 presents the results only for 8 of the 14 types of intensity from the table (even numbers $N$ for granules and odd numbers for intergranules). This is done in order not to overload the figure.

An analysis of the time dependences in Fig. 3 and the data in the table leads us to the following conclu-
Fig. 3. (a)–(d) Temporal variations in wave (left) and convective (right) velocity components \( \delta \bar{V}_w \), \( \delta \bar{V}_k \) and in central residual intensity (\( \delta \bar{I}_w \), \( \delta \bar{I}_k \)) in the upper photosphere above granules (solid lines) and intergranules (dot-dashed lines) with various mean contrasts (\( \delta \bar{I}_e \)) (the numbers beside the curves). Other characteristics of the granulation classes are given in the table. The wave velocity component \( \delta \bar{V}_w \) for each intensity class is displaced from zero point by the mean (for a given class) convective velocity (\( \delta \bar{V}_k \)) (see column 7 in the table). Similarly for the wave intensity component \( \delta \bar{I}_w \); the shift (\( \delta \bar{I}_e \)) for each intensity class is given in column 8 of the table; (e) the velocities of oscillatory motions obtained by averaging the spectra of randomly selected regions on the solar surface. The granulation pattern was disregarded. The total area \( S \) of the regions was 5.9% for the solid line and 52.2% for the dot-dashed line; (f) the velocities of oscillatory motions for the same averaging areas but the granule and intergranule spectra were summed separately. The mean contrasts of granules and intergranules are, respectively, 5.9 and –2.1% (intensity classes \( N = 13 \) and 7 in the table). For a convenient comparison, the mean velocities in (e) and (f) were reduced to a common zero point.
Fig. 4. Power spectrum of the fluctuations in velocity $\delta \bar{V}_w$ (a), (b) and line intensity $\delta \bar{I}_w$ (c), (d) above granules and intergranules with different contrasts $\langle \delta I_\lambda \rangle$: for all the frequencies studies (left) and for the frequencies at which the greatest power concentrates (right). The oscillation power is in arbitrary units.

sions. First, as the absolute value of the mean contrast increased from 2.1 to 6.5%, the mean amplitude of the fluctuations in velocity $\langle \delta \bar{V}_w \rangle$ and intensity $\langle \delta \bar{I}_w \rangle$ doubled both above granules and above intergranules (columns 5 and 6 in the table). Second, for the same contrast, these amplitudes above intergranules are larger than those above granules. Third, the oscillations above granules with different contrasts are in phase, and there is only a small trend; the same is true for intergranules. Fourth, the oscillations above granules and intergranules have different periods. This can be easily verified by performing a spectral analysis of the oscillations above granules and intergranules.

Figure 4a shows a $B-\omega$ diagram in which the power of the velocity fluctuations $\delta \bar{V}_w$ is plotted against frequency $\omega$ and mean contrast $B = \langle \delta \bar{I}_\lambda \rangle$. It follows from the diagram that the greatest power of the local 5-min velocity fluctuations concentrates at two frequencies: $\omega = 3.73 \pm 0.26$ and $3.21 \pm 0.26$ mHz (the periods $T$ are 268 and 312 s, respectively); the matter above granules oscillates with the period 312 s, while the matter above intergranules oscillates mainly with $T = 268$ s. This conclusion is more clearly demonstrated in Fig. 4b. The power of the oscillations above intergranules rapidly increases with contrast both for $T = 268$ s and for $T = 312$ s. Above granules, as the contrast increases, the oscillation power decreases for $T = 268$ s and increases for $T = 312$. These results differ markedly from those of Espagnet et al. (1996), who argue that the most energetic velocity fluctuations occur only above intergranules. The reason for the disagreement is difficult to establish, especially since the formation height of the central intensity of the Na I D$_2$ line ($H = 550$ km), with which Espagnet et al. (1996) carried out the observations, is close to the formation height of the Fe I $\lambda 532.4185$-nm line ($H \approx 500$ km) used in our studies. One possible reason is that the duration of the spectroscopic observations by these authors is a factor of 2 shorter (~16 min).

The power of the intensity fluctuations $\delta \bar{I}_w$ has a different distribution (Figs. 4c, 4d). The power of the oscillations with the 268- and 312-s periods increases with contrast both above granules and above intergranules, but the most energetic intensity fluctuations occur only above intergranules. Unfortunately, we cannot compare these results with those of Espagnet et al.
(1996), because the authors do not provide the corresponding data.

We make several more remarks on the convective velocity and line intensity components. As we see from Fig. 3b and from column 7 of the table, where the mean convective velocities $\langle \delta V_k \rangle$ are given, the matter generally rises above granules ($\langle \delta I_c \rangle > 0$) and sinks above intergranules ($\langle \delta I_c \rangle < 0$) near the temperature minimum ($H = 500$ km); the higher the contrast of the continuum structure, the higher the rise and sink velocity. As the mean contrast (in absolute value) increases from 2.1 to 6.5%, the relative convective velocities (the velocities of granules relative to intergranules) increase from 300 to 670 m s$^{-1}$, with the variations in central residual intensity being small (Fig. 3d, column 8 in the table). In particular, it follows from the table that the means $\langle \delta I_c \rangle$ lie in the range 0.33 to 0.79%. According to Espagnet et al. (1995), for granules of different sizes, the convective velocities at the formation height of the Na I D$_2$ line range from 320 to 720 m s$^{-1}$, while the variations in its central intensity range from 0.4 to 0.9%, which is seen to essentially match our results. Note that for comparison, we chose the study of these authors, because, first, as was noted above, the iron and Na I D$_2$ lines are formed at close heights, and, second, the results of Espagnet et al. (1995) are among the few that, like our results, were corrected for wave motions.

Our method of studying the wave motions above granules and intergranules may also have drawbacks. The observed oscillation amplitude is known (Tanenbaum et al. 1969; Snider et al. 1974) to decrease with increasing aperture. Thus, it is likely that the increase in the oscillation amplitude with contrast (see Figs. 3a, 3c) is attributable not to the peculiar behavior of the matter above different granules but to the decrease of the surface area above which the spectra were averaged from 52 to 4%. Even within one narrow contrast range, the unequal number of spectral tracks $i$ are averaged at different times $j$. In other words, by changing the contrast, we may pass to the observations of oscillations with a different angular number $l$.

In order to check whether these features are inherent in our method, we repeated calculations but without separating the continuum intensity field into granules and intergranules. We only used the condition that the emergent radiation at each instant of time $j$ was summed over the same number of tracks $i$ as in the case of allowance for the granulation pattern, but this time arranged "quasi-stochastically" along the spectrograph slit. For clarity, Fig. 5a shows the arrangement in space and time of those cells in which the radiation above granules with $\delta I_c > 5\%$ (the mean contrast is 5.9%) was summed. In Fig. 5b, we show the positions of the same number of cells with the granulation pattern ignored.

The amplitude of the velocity fluctuations computed for the latter case turned out to be virtually independent of the averaging area. Figure 3e, in which the results of our calculations are presented for two limiting areas ($S = 5.9$ and 52.2%), shows that the greatest difference between the mean velocity amplitudes of the wave motions was a mere 2 m s$^{-1}$ (or 5% of the mean). Note that neither the amplitude nor the period and power of the oscillations depend on the averaging area for the quasi-stochastic arrangement of cells. The velocities of the oscillatory motions for the same averaging areas but computed separately from the spectra of granules and intergranules of the corresponding contrast are shown in Fig. 3f. It follows from its comparison with Fig. 3e that the increase in the oscillation amplitude with photospheric contrast is real. We made this sure again when we chose the contrast ranges in such a way that the averaging areas were approximately equal. We derived dependences similar to those in Fig. 3a.

Finally, in order to be completely sure that our results are reliable, we extracted four granules and three intergranules from the observational data with a lifetime ~30 min and computed the oscillation power spectrum for them separately. Our conclusions did not...
change: the matter mainly oscillates with $T = 312$ s above granules and with $T = 268$ s above intergranules. Thus, the dependences in Figs. 3 and 4 are real and are not attributable to the peculiar features of our method.

CONCLUSION

The observations with high spatial (<0.5") and temporal (9.3 s) resolutions and the new method have allowed us to investigate in detail the pattern of local 5-min oscillations above granules and intergranules. In the upper photosphere at a height ~500 km, the amplitudes of the velocity fluctuations above granules and intergranules are approximately equal. In this case, the higher the contrast of these structures and, hence, the higher the convective velocities at the continuum formation level, the larger the amplitudes [according to Espagnet et al. (1995), the coherence between the intensity and the velocity is close to unity at a height ~0 km]. The main power of the velocity fluctuations above granules and intergranules concentrates at the frequencies $\omega = 3.21 \pm 0.26$ mHz ($T = 312$ s) and $3.73 \pm 0.26$ mHz ($T = 268$ s).

The amplitudes of the intensity fluctuations also increase with contrast, but above intergranules they are twice as large as those above granules. The main power of the intensity fluctuations concentrates only at $\omega = 3.73 \pm 0.26$ mHz, and above intergranules it is a factor of 3 higher than that above granules.

We have revealed the patterns of propagation of the local 5-min oscillations above granules and intergranules by statistically analyzing the observational data. Like other authors (Frazier 1968; Musman 1974), we have found no significant correlation between the occurrence of a certain granule or intergranule and the train of oscillations. We support the assumption that the excitation of 5-min oscillations by turbulent convection is stochastic in nature. In addition, our studies, in close agreement with the theoretical studies by Brown (1991) and Goode et al. (1992), show that the most intense trains of oscillations in the upper photosphere (~500 km) are produced in those regions where the upflow and downflow velocities in the lower photosphere (~0 km) are at a maximum.

It seems natural that the main power of the velocity fluctuations above granules, where upflows dominate, and intergranules with preferential downflows concentrate in different periods. The conclusion that the central-intensity fluctuations above bright granules and dark intergranules occur with the same period but with a different power also seems quite natural. However, for the period and the power to be estimated quantitatively, in addition to knowledge of the relative convective velocities, we need detailed calculations of such parameters as the temperature and the scale height (in density) for various photospheric structures.

The characteristics of convective motions in the upper photosphere (see the table) are in good agreement with the results of previous studies (Espagnet et al. 1995) which were obtained by a completely different method.

In summary, we formulate the main conclusion.

1. The local 5-min intensity and velocity fluctuations at the heights near the temperature minimum, where the Fe I λ532.4185-nm line originates, respond differently to the fine structure of the lower photosphere.

2. The amplitudes of the intensity fluctuations above intergranules are almost twice those above granules. The amplitudes of the velocity fluctuations above granules and intergranules of the same contrast are approximately equal. The most energetic oscillations are observed above the regions with a maximum convective velocity.

3. Above granules and intergranules, the matter oscillates with different periods, although the period difference is at the limit of the accuracy of our observations.

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REFERENCES


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