QUASI-REGULAR STRUCTURES OF THE SOLAR PHOTOSPHERE

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ABSTRACT

As we already reported, the simple procedure of time averaging, when applied to the photospheric brightness field, reveals quasi-regular structures of the photospheric and subphotospheric flows. Our analysis presented here shows that the decrease in the rms contrast of the averaged images with the increase of the averaging time τ is slower compared to the $\sqrt{\tau}$ law, which argues for the real persistence of the revealed structures as physical entities. The procedure of running-average-based correlation is suggested to seek coherence between the brightness variations at the points of emergence and sinking of granules. Some results of the correlation analysis confirm the notion that granules are overheated blobs of material carried by the convective circulation.

Key words: solar photosphere; granulation; convection patterns.

INTRODUCTION

We already reported our observations of quasi-regular structures in time-averaged images of the solar photosphere (Getling & Brandt, 2002). To analyse the granular field, we used the sequence of images of a 118.7×87.9 Mm^2 area of the solar photosphere obtained by Brandt, Scharmer, and Simon (Simon et al., 1994) on 5 June 1993 with the Swedish Vacuum Solar Telescope (La Palma, Canary Islands). This series still remains unsurpassed in terms of duration (11 h), continuity (a constant, 21-s frame cadence), and quality (rms contrast varying between 6 and 10.6%). In our study, we dealt with a sub-set of this series, which covered a 43.5×43.5 Mm^2 area ($60'' \times 60''$) and an 8-h interval. Here, we present tentative results of our correlation analysis of the brightness-variation curves taken at some selected locations within the area studied, as well as some additional considerations concerning the brightness contrast of the averaged images.

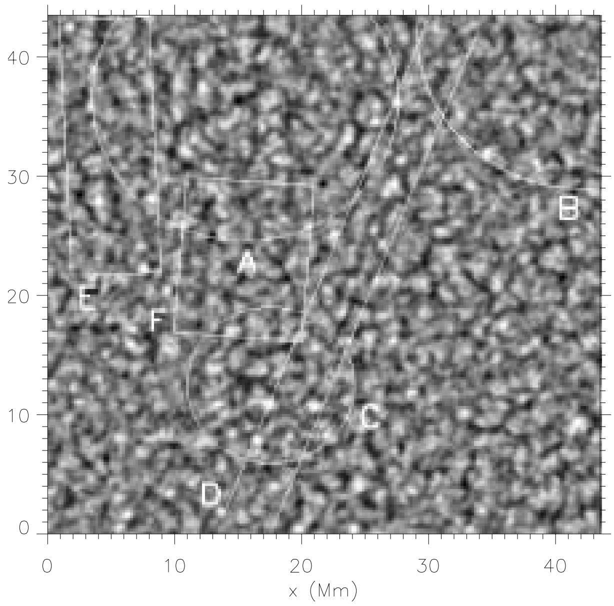

Figure 1. Granulation pattern averaged over a 2-h timespan of the data sub-set (14:26:43–16:29:03 UT). The rms intensity contrast is 2.92%

The images of the Sun were obtained in the 10-nm-wide spectral band centred at a wavelength of 468 nm. The primary data reduction included the alignment of contiguous images, destretching based on the procedure of local correlation tracking (November, 1986), and subsonic Fourier filtering (Title et al., 1989), which eliminated fast time variations (the cutoff phase speed was 4 km/s). For a more detailed description of the data acquisition technique see Simon et al. (1994).

First, we found that the averaged images are far from completely smeared and contain a multitude of bright, granular-sized blotches even if the averaging period is as long as 8 h. This suggests that granules prefer to originate at certain sites, where they

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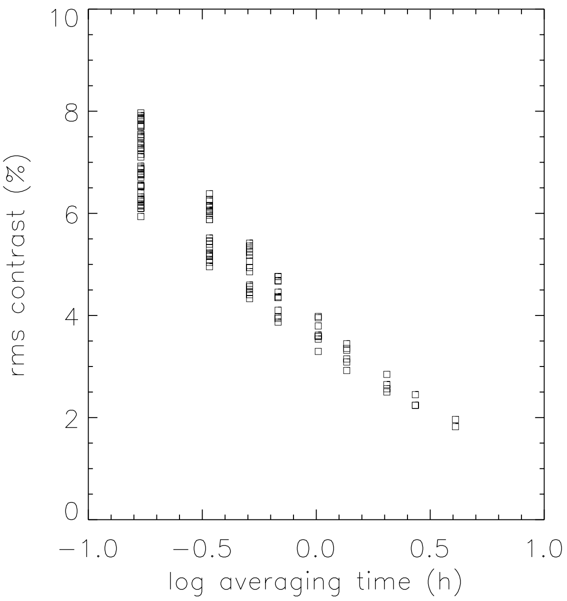

Figure 2. The rms intensity contrast of the averaged images as a function of the averaging time.

emerge repeatedly, and the granular field demonstrates a sort of persistence for many hours. Second, the resulting patterns display relatively regular structures, which can be revealed only if the averaging period is sufficiently long (the optimum seems to lie between 2 and 3 h). The averaged brightness relief is "trenched" (Fig. 1): it comprises systems of concentric rings and arcs (some of them are marked with surrounding circles A, B, and C in the figure) as well as systems of parallel linear features (enclosed in boxes D, E, and F). Such structures are families of parallel chains of bright and of dark blotches. We shall call them ridges and trenches, respectively. The trenching patterns resemble the so-called target patterns observed in experiments on Rayleigh–Bénard convection. Third, in some cases, the brightness values at a local averaged-field maximum and at a nearby minimum were found to exhibit a distinct tendency to vary in antiphase (this, however, was stated based on an immediate impression rather than quantitative analysis). Thus, a previously unknown type of self-organization is manifest in the solar atmosphere, and our findings support the suggestion that granules are associated with overheated blobs carried by the convective circulation (Getling, 2000).

CONTRAST OF AVERAGED IMAGES

A criterion for the reality of the granular-field persistence is the behaviour of the rms averaged-image contrast with the increase of the averaging time τ. Indeed, if we average images with completely random distributions of granules, the rms contrast can be expected to vary as $1/\sqrt{N}$, where N is the number of images averaged, or $1/\sqrt{\tau}$. In the presence of persistent, quasi-regular structures, the contrast should obviously decline more slowly than $1/\sqrt{\tau}$ does. Thus, comparisons with the $1/\sqrt{\tau}$ law provide a test for the deterministic nature of the structures that can be seen in the averaged images.

The contrast of the images at hand is strongly affected by seeing conditions, which introduce random fluctuations in contrast from one frame to another. These fluctuations are responsible for the spread in the contrast values, which can be clearly seen in Fig. 2. Let us also note the substantial decrease in this spread with increasing τ, which could naturally be expected.

In our case, however, comparisons of the τ dependences of the rms contrast with the $1/\sqrt{\tau}$ law are of limited significance, because the τ range where such comparisons could be warranted is extremely narrow. Indeed, within the range $0 < \tau \lesssim 1$ h, the averaging time covers very few granular lifetimes, and the statistical laws are not applicable here. Moreover, the spread in contrast values is very large for this range; therefore, the mean contrast values for small τ may not be representative. Beyond $\tau \approx 3$ h, as our findings suggest, the regularities valid for smaller τ may fail because of the disruption of the large-scale structures under study (and the behaviour of the rms contrast may really approach the $1/\sqrt{\tau}$ law, due to the physics of the process). Therefore, the contrast reduction rates are worth analysing only in the range $0.1 < \log\tau < 0.4$, which corresponds to no more than a doubling of τ. In our data, the mean contrast drops over this range by a factor of 1.34, while $\sqrt{2} = 1.41$. Thus, we can note an appreciable difference, although the noise level is obviously high in the solar images even if large-scale structures are present. The contrast reduction rate is also less than that of the random field artificially constructed by Rast (2002) and endowed with some properties of the real granulation. Therefore, despite the fairly narrow τ range appropriate for comparisons, our analysis of the contrast reduction rate supports our suggestion that long-lived, quasi-regular structures do really exist.

RUNNING-AVERAGE-BASED CORRELATIONS

As thermal convection takes place in a horizontal fluid layer heated from below, the horizontal temperature distribution at a given height reproduces, to a first approximation, the horizontal distribution of the vertical velocity component at the same height. There are good reasons to believe (Getling, 2000) that, under solar conditions, the convective circulation permanently carries blobs of overheated material to the photospheric surface from lower layers, and these blobs are observed as granules. In this case, the temperature and vertical-velocity distributions over the photospheric surface should be similar only when averaged over time. Similarly, we can expect the time-averaged field of the vertical velocity component to be mainly represented by the time-averaged brightness field. Thus, the steady convective updrafts and downdrafts will appear bright and dark in time-averaged images, respectively.

Let us consider the temporal brightness variations at some “bright” point and a nearby “dark” point. Assume that overheated blobs are disposed, in one way or another, along a closed streamline of the circulating material. The circulation of these blobs will result in a brightness correlation between the points of their emergence and sinking. The lag between the brightness variations at the two points will correspond to the time taken by a blob to traverse the distance between these points. If the characteristic lifetime of blobs is larger than the circulation period, the correlation curve may exhibit additional correlation peaks separated from the main peak by this period (and, generally, its multiples). Similarly, moving temperature minima associated with cool material and situated between the hot blobs will manifest themselves as negative correlation extrema at the lags between the passage of a hot blob through one point and a cool blob through the other.

Actually, on the solar surface, we observe a superposition of features that have different characteristic times and scales. As a result, the pattern of brightness variations related to the convective circulation on a given scale is substantially smeared, and a special algorithm is needed to select this pattern from the entire spatiotemporal spectrum. To this end, we suggest using our technique of running-average-based correlations.

Let $x_j = (x_0, ..., x_{N-1})$ and $y_j = (y_0, ..., y_{N-1})$ be two data arrays with elements corresponding to N moments of time $t_j = j\Delta t$, $j = 0, ..., N-1$. If we introduce a moving window of halfwidth $n\Delta t$, the running average of x_j will be

$$\overline{x}_{i,n} = \begin{cases} \dfrac{\sum\limits_{j=i-n}^{i+n} x_j}{2n+1} & \text{for } n \leq i \leq N-1-n, \\ \overline{x}_{n,n} & \text{for } 0 \leq i < n, \\ \overline{x}_{i,n} = \overline{x}_{N-1-n,n} & \text{for} \\ & N-1-n < i \leq N-1 \end{cases}$$

and similarly for y_j. We shall consider the running-average-based correlations between x_j and y_j defined as follows:

$$P_{xy,n}(L) = \begin{cases} \dfrac{\sum\limits_{k=0}^{N-L-1} (x_{k+|L|} - \overline{x}_{k+|L|,n})(y_k - \overline{y}_{k,n})}{\sqrt{\sum\limits_{k=0}^{N-1} (x_k - \overline{x}_{k,n})^2 \sum\limits_{k=0}^{N-1} (y_k - \overline{y}_{k,n})^2}} \\ \hfill \text{for } L < 0, \\ \dfrac{\sum\limits_{k=0}^{N-L-1} (x_k - \overline{x}_{k,n})(y_{k+L} - \overline{y}_{k+L,n})}{\sqrt{\sum\limits_{k=0}^{N-1} (x_k - \overline{x}_{k,n})^2 \sum\limits_{k=0}^{N-1} (y_k - \overline{y}_{k,n})^2}} \\ \hfill \text{for } L > 0. \end{cases}$$

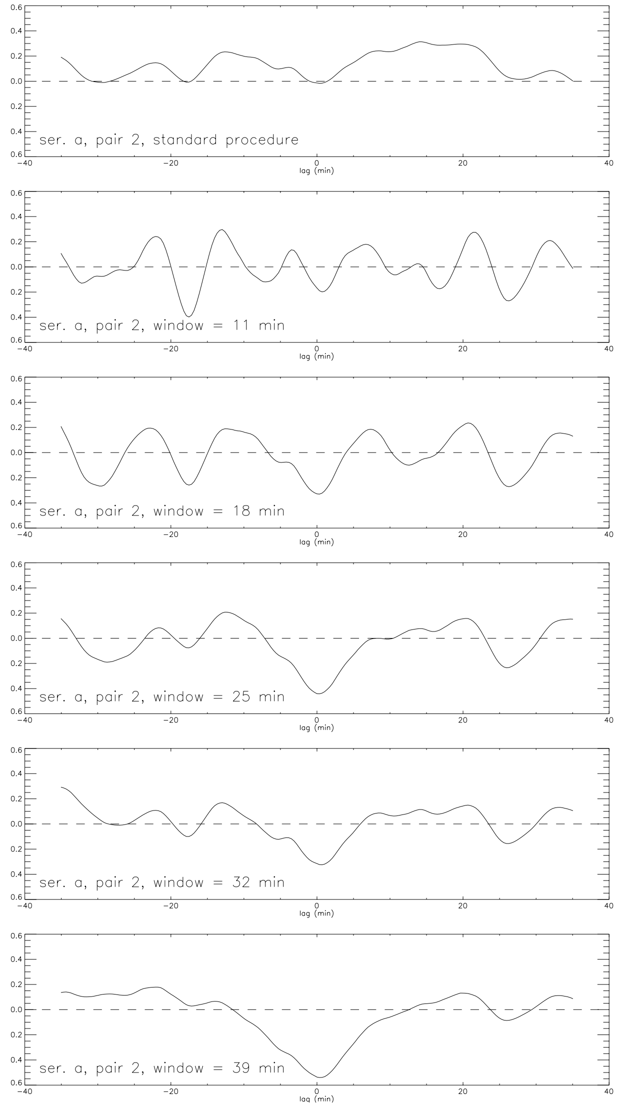

Figure 3. Correlation curves obtained for a pair of points in system A using the standard technique and with various running windows.

Obviously, the replacement

$$\overline{x}_{i,n} \rightarrow \overline{x} \equiv \frac{\sum\limits_{j=0}^{N-1} x_j}{N}, \quad \overline{y}_{i,n} \rightarrow \overline{y} \equiv \frac{\sum\limits_{j=0}^{N-1} y_j}{N}$$

for any i and n (which equalizes the full width of the window to the length of sample) reduces the running-average-based correlations to cross correlations defined in a standard way.

If we use running averages in our analysis, then, as fluctuations of the variables, we correlate the departures of these variables from the mean values computed with a given running window. Thus, we single out short-term fluctuations against the background of longer term variations and compare the behaviour of the short-term fluctuations in time. The longer term variations, even if they are correlated, do not contribute to the resulting correlation coefficients.

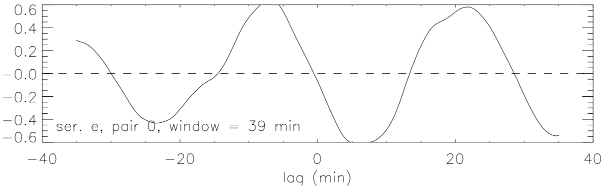

Figure 4. Correlation curve obtained for a pair of points in system A with a 39-min window.

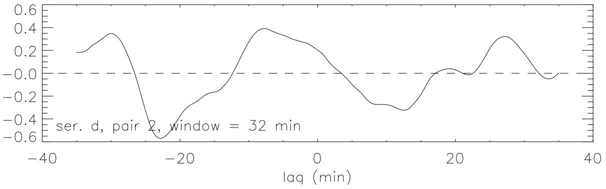

Figure 5. Correlation curve obtained for a pair of points in system A with a 32-min window.

Since the spatial and temporal scales of fluctuations are usually interrelated, our procedure actually makes it possible to study correlations associated with the convective circulation of interest, eliminating the effects of larger scale processes (which coherently affect both the “bright” and the “dark” point).

We present here three characteristic examples of correlation curves computed using the running-average technique. All of them refer to “bright”−“dark” point pairs chosen in the concentric-ring system denoted as A in Fig. 1. In each case, the “bright” point corresponds to a local intensity maximum on a ridge in the 2-h-averaged image and the “dark” point is a nearby minimum in a trench next to the ridge. In view of the aforesaid, these correlation curves admit a clear physical interpretation.

Figure 3 illustrates the result of applying the running-average technique. While the correlation curve obtained in a standard manner (top) does not contain any remarkable features and can only be attributed to virtually independent brightness variations, the selection of short-term variations using windows as long as 39 min reveals a strong anticorrelation between the “bright” and the “dark” point with a nearly zero lag. This may correspond to the simplest case where a hot blob emerges and a cool blob sinks simultaneously, and vice versa. No other hot blobs are present at the same streamline, and the situation resembles the so-called one-blob instability of convection rolls, known in the theory of convection (Bolton et al., 1986); see Getling (2000) for discussion.

Other two examples of remarkable correlation curves are given in Figs. 4 and 5. In both cases, the window widths (39 and 32 min, respectively) were chosen so as to reach maximum absolute extremum values of the correlation. It can be seen that the two correlation functions are qualitatively similar. The first one resembles a periodic function and exhibits fairly large extremum correlation values, while the second one is less regular. However, both have a negative extremum near a lag of −23 min and a positive one between −7 and −8 min. The appearance of these two curves suggests that they reflect the repeated emergence of hot blobs. If our interpretation is correct, the first curve makes it possible to accurately determine the circulation period, which proves to be 29–30 min. In the second case, such a determination is less definite, and the period may lie between 22 and 35 min.

Of course, the correlation curves are not always as regular as in the above examples. It should be kept in mind, however, that the selection of point pairs was, at this stage of investigation, fairly arbitrary. In some cases, the points of a pair we have selected may belong to different circulation systems (convection cells); in some others, they may not lie at close streamlines of the same system; finally, the circulation may locally be disturbed. However, the very existence of pairs that demonstrate such patterns of brightness correlation supports our notion that granules are carried by the convective circulation and can even repeatedly emerge.

CONCLUSION

We have found that the rms intensity contrast of the averaged images decreases with the averaging time more slowly than $1/\sqrt{\tau}$ does, although the τ range in which such comparisons are warranted is fairly narrow. Thus, the large-scale structures present in the averaged images are not accidentally composed of bright and dark blotches and can be regarded as physical entities. The running-average-based correlation technique suggested here reveals some remarkable features of correlations between local average-intensity maxima and nearby minima. They can naturally be interpreted in terms of our notion that granules are blobs of overheated material carried by the convective circulation. We have also reported a tentative determination of the period of such circulation. More complete analyses of the correlation pattern and the underlying flow structure remain to be done.

REFERENCES

Bolton E.W., Busse F.H., and Clever R.M. (1986): J. Fluid. Mech. 164, 469.

Getling A.V. (2000): AZh 77, 64 (Astron. Rep., 44, 56).

Getling A.V. and Brandt P.N. (2002): A&A 382, L5.

November L.J. (1986): Appl. Opt. 25, 392.

Rast M.P. (2002): A&A Letter (in press)

Simon G.W., Brandt P.N., November L.J. et al. (1994): in Solar Surface Magnetism, ed. R.J. Rutten, & C.J. Schrijver (Kluwer, Dordrecht) 261.

Title A.M., Tarbell T.D., Topka K.P., et al. (1989): ApJ 336, 475.