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Do Long-Lived Features Really Exist in the Solar Photosphere?
II. Contrast of Time-Averaged Granulation Images

P.N. Brandt[1] **and A.V. Getling**[2]

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Abstract The decrease in the rms contrast of time-averaged images with the averaging time is compared between four datasets: (1) a series of solar granulation images recorded at La Palma in 1993; (2) a series of artificial granulation images obtained in numerical simulations by Rieutord *et al.* (2002); (3) a similar series computed by Steffen and his colleagues (see Wedemeyer *et al.*, 2004); (4) a random field with some parameters typical of the granulation, constructed by Rast (2002). In addition, (5) a sequence of images was obtained from real granulation images using a temporal and spatial shuffling procedure, and the contrast of the average of n images from this sequence as a function of n is analysed. The series (1) of real granulation images exhibits a considerably slower contrast decrease than do both the series (3) of simulated granulation images and the series (4) of random fields. Starting from some relatively short averaging times t, the behaviour of the contrast in series (3) and (4) resembles the $t^{-1/2}$ statistical law, while the shuffled series (5) obeys the $n^{-1/2}$ law from $n = 2$ on. Series (2) demonstrates a peculiarly slow decline of contrast, which could be attributed to particular properties of the boundary conditions used in the simulations. Comparisons between the analysed contrast-variation laws indicate quite definitely that the brightness field of solar granulation contains a long-lived component, which could be associated with locally persistent dark intergranular holes and/or with the presence of quasi-regular structures. The suggestion that the random field (4) successfully reproduces the contrast-variation law for the real granulation (Rast, 2002) can be dismissed.

Keywords: Sun: photosphere, Sun: granulation

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[1] Kiepenheuer-Institut für Sonnenphysik, Schöneckstrasse 6,
79104 Freiburg, Germany
email: pnb@kis.uni-freiburg.de
[2] Institute of Nuclear Physics, Lomonosov Moscow State
University, 119991 Moscow, Russia
email: A.Getling@mail.ru

1. Introduction

As reported previously by a number of researchers, the brightness field of solar granulation bears evidence for the presence of features with lifetimes far exceeding those of granules. In particular, Roudier *et al.* (1997) detected dark "intergranular holes" — singularities in the network of intergranular lanes, which could be observed for more than 45 minutes and whose diameters range from 180 to 330 km. Similar features, which persisted over up to 2.5 hours, were also observed by Hoekzema, Brandt, and Rutten (1998) and Hoekzema and Brandt (2000).

A different form of long-term persistence, closely related to spatial structuring, was revealed in granulation images averaged over intervals of one to two hours. As noted by Getling and Brandt (2002) and Getling (2006, Paper I), averaged brightness fields consist of bright, nearly granular-sized blotches against a darker background; they may form long-lived, quasi-regular systems of concentric rings or parallel strips — "ridges" and "trenches" in the relief of the brightness field. Later, algorithmic treatment showed that patterns of alternating bright and dark lanes (varying in the degree of their regularity) are virtually ubiquitous in averaged granulation images (Getling and Buchnev, 2007). Since the material upflows in the visible layers of the solar atmosphere are brighter than the downflows, such patterns should reflect the presence (and, possibly, widespread occurrence) of roll convection in the upper convection zone. In particular, roll systems could form the fine structure of larger-scale, supergranular and/or mesogranular, convective flows.

Some other indications of a long-term spatial organisation in the granulation field have also been revealed. Dialetis *et al.* (1988) found that granules with longer lifetimes exhibit a tendency to form mesogranular-scaled clusters. Muller, Roudier, and Vigneau (1990) also detected such clustering in the spatial arrangement of large granules; they emphasised a plausible relationship between the clusters and mesogranules. Roudier *et al.* (2003) reported their observations of a specific collective behaviour of families ("trees") of fragmenting granules. Such families can persist for up to eight hours and appear to be related to mesogranular flows. An imprint of the supergranular structure can also be traced in the granulation pattern (Baudin, Molowny-Horas, and Koutchmy, 1997).

As a particular argument for the presence of long-lived features, we noted (Getling and Brandt, 2002) a conspicuously slow decrease in the rms contrast of the averaged images with the averaging time.

In his comment on our original paper (Getling and Brandt, 2002), Rast (2002) suggested that the quasi-regular structures detected in the granulation patterns are merely of statistical nature and do not reflect the structure of real flows. He artificially constructed a series of random fields with some characteristic parameters typical of the solar granulation (claiming nevertheless that this series "is not an attempt to model solar granulation" and represents "a completely random and changing flow pattern") and found that the law of contrast variation with the averaging time does not change substantially if the real images are replaced by such fields. On this basis, Rast (2002) raised doubts on the real presence of a long-term component in the granulation dynamics.

In view of attributing the features of regularity in the averaged images to statistical effects, Rast (2002) also put forward some other arguments. Getling (Paper I) discussed them in detail and has shown that the reasoning by Rast (2002) does not contest the possibility of a physical origin of the quasi-regular structures. At the same time, the particular issue of the contrast variation with the averaging time was reserved for a special consideration.

This paper continues the publication of our study whose first part was presented in Paper I and addresses precisely the contrast-variation laws for various series of images.

Generally, the less variable the pattern, the slower the contrast decline with the length of the averaged sequence of images. Thus, the direct implication of a slow decrease in the contrast of averaged images is the presence of persistent features in the brightness field under study. The contrast-variation law itself does not reflect the degree of spatial order in this field; however, if the regularity is associated with temporal persistence, the presence of regular structures will flatten the contrast-variation curve. For these reasons, we extend here the conceivable range of interpretation of our results compared to that discussed in Paper I. Accordingly, we have slightly modified the main title of the paper ("Do quasi-regular structures really exist in the solar photosphere?"), which was originally intended to be common for both parts.

We compare here the laws of contrast variation with the averaging time for real granulation images, images obtained by numerical simulation of convection on a granular scale, the artificial fields constructed by Rast (2002), and a series of "shuffled" images (obtained as subfields of the original series of granulation images taken at random positions in both spatial coordinates and at random times). Our results confirm the presence of a long-lived component in the granulation field, while the counterargument by Rast (2002) based on the contrast variation can be dismissed.

2. The Data

By the real granulation images, we mean the images of the La Palma series obtained by Brandt, Scharmer, and Simon (see Simon *et al.*, 1994) on 5 June 1993 using the Swedish Vacuum Solar Telescope (La Palma, Canary Islands). We analysed a seven-hour subset of this series; the frame cadence was 21.03 s, and a 43.5 × 43.5 Mm^2 subfield (480 × 480 pixels with a pixel size of $0.125''$, or 90.6 km) was cut out of the original images. In Paper I, we already described some details of the technique of data acquisition and pre-processing employed by Simon *et al.* (1994).

The random fields constructed by Rast (2002) are additive superpositions of 192^2 randomly disposed two-dimensional Gaussians that vary randomly in amplitude and radius around given mean values. These values and the time scale of the evolution were chosen so as to mimic the corresponding parameters of the solar granulation. The sequence of such fields represents a continuous time evolution with the persistent emergence of "new" Gaussian peaks and disappearance of "old" ones. The resulting images contain 192 × 192 pixels. In the language of the numerical correspondence between the parameters of the random field and those of the granulation patterns, the images follow at a time step of 20 s over a period of 8.25 hours.

Another sequence of random fields was prepared from a series of real (speckle-reconstructed) granulation images obtained with the Dutch Open Telescope (DOT), La Palma, on 19 October 2001. This series comprised 198 frames of $14.7 \pm 0.1\,\%$ rms contrast, measuring 1040×864 pixels with a pixel size of 0.071 arcsec and taken in the 432 nm continuum with a time lag of 30 s between frames. To generate randomised fields, the images were subject to the following shuffling procedure. Three series of random numbers ranging between 0.0 and 1.0 were generated by an appropriate standard computer program. The numbers in two of these series were used to extract randomly-shifted subfields of 400×400 pixels from the original field. The shifts were taken as the above-mentioned random numbers multiplied by the maximum shifts, 600 pixels in x and 400 in y. The third random number served to compose a new sequence of 198 frames by randomly shuffling the sequence number of the selected frames, from which the random subfield was extracted.

In addition to the La Palma granulation images, the random fields constructed by Rast (2002), and the sequence of shuffled granulation images, we consider here two series of artificial granulation patterns obtained by numerical simulation of granular-scaled convection. The first one was prepared by Rieutord *et al.* (2002). An image of this set is made of 315×315 pixels (a single pixel being 95.24 km) and covers a 30×30 Mm^2 area. The interval between images corresponds to 20 s of real time. The second series was computed by M. Steffen, B. Freytag, and H.-G. Ludwig (see Wedemeyer *et al.*, 2004) for an 11.2×11.2 Mm^2 area; each image is represented by 200×200 pixels with a pixel size of 56 km and the interval between frames is 30 s.

3. Contrast of Averaged Images

We note that the rms contrast of the individual images in the La Palma series varies widely, and even the averaged images exhibit a large spread in the contrast values, depending on the central time of the averaging interval. This raises considerable difficulties as the laws of contrast variation with the averaging time are compared between the real granulation, the artificial field (Rast 2002), and simulated granulation (as noted in the Introduction, it is on such comparisons that Rast (2002) largely based his criticism on the inferences of the original paper by Getling and Brandt (2002)).

For this reason, to obtain unambiguous results, we normalize both the mean intensity and the rms intensity contrast of each image to a standard value for either of these two quantities. We apply this procedure to the four above-mentioned data series (the normalisation of the DOT series was part of the speckling technique). In addition, we remove the residual mean-intensity gradient within each frame (such gradients were noticeable in the images of the La Palma series).

For the data series so normalised, we compute the variation in the rms contrast with the averaging time t (at a fixed mid-time of the averaging interval and with a maximum averaging time of about 7 hours). In the case of the shuffled images, we calculate the average of n images, from the first to the n-th one, the contrast of this average, and the coefficient of correlation between the first and the n-th image; we represent both the contrast and the correlation coefficient as a function of n.

The resulting contrast-variation curves are plotted in Figure 1, on both linear (Figure 1a) and log–log (Figure 1b) scales. The rms contrast of an individual image is set to unity in all cases; in this sense, the contrast values presented here can be called normalised. For comparison, in Figure 1b, we also show a straight line that corresponds to the statistical $n^{-1/2}$ law of decrease in the rms contrast of n averaged completely random fields with n, or, in other words, to the $t^{-1/2}$ law of contrast decrease with the averaging time t.

It can be seen that the curve for the real solar images runs well above the other three curves. It diverges most widely with the curve for the random field constructed by Rast (2002), while the curves for the numerically simulated granulation remain in

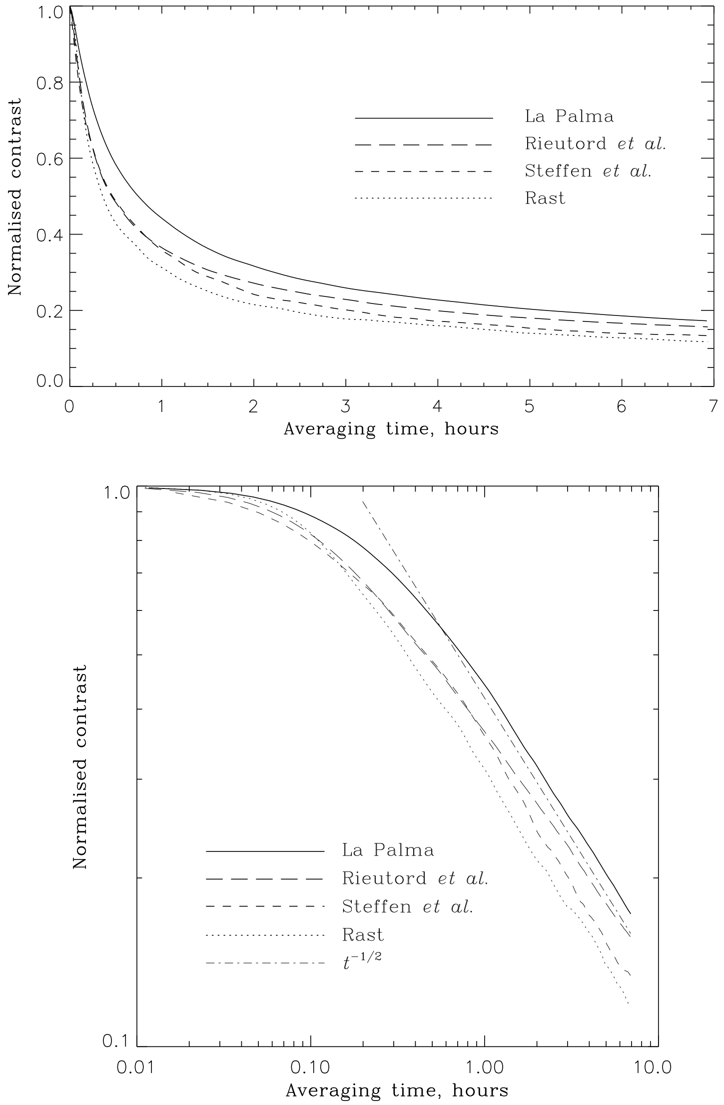

Figure 1. Contrast of the averaged images as a function of the averaging time t for the La Palma granulation images, numerically simulated granulation patterns, and the random field constructed by Rast (2002), on a linear (*top*) and log–log (*bottom*) scales. In the bottom graph, a $t^{-1/2}$ law of variation is also shown for comparison.

between these extremes. Although the differences in the slope are most pronounced in the region of $t \lesssim 1$ h, they remain quite appreciable over the entire range of averaging times.

Most instructive are comparisons of the slopes of the contrast-variation curves with the slope of the $t^{-1/2}$ straight line in Figure 1b. The contrast of the real granulation images decreases with t more slowly than according to the $t^{-1/2}$ law

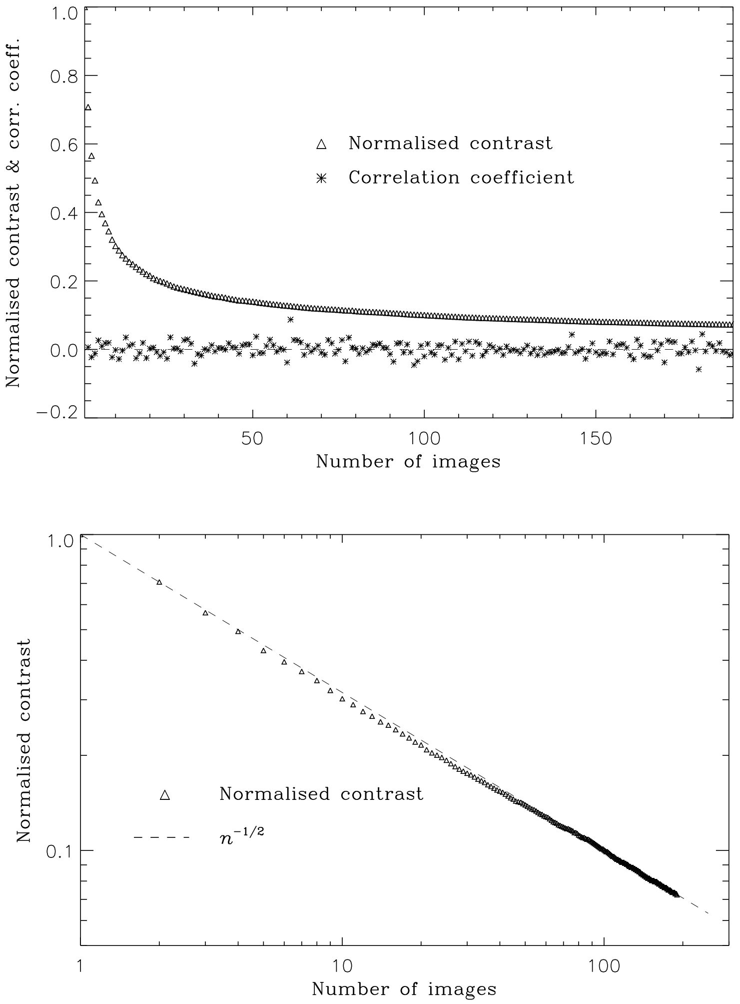

Figure 2. *Top*: contrast of the averaged sequence of n shuffled granulation images and the coefficient of correlation between the first and last images in this sequence as a function of the number n on a linear scale. *Bottom*: same contrast as a function of n but on a log–log scale and an $n^{-1/2}$ law of variation.

even in the rightmost part of the graph, at averaging times of several hours. At the same time, the curve for the field constructed by Rast (2002) is nearly parallel to the $t^{-1/2}$ line for $t \gtrsim 0.3$ hours. A similarly rapid decline can also be noted for one of the series of simulated images (Wedemeyer *et al.* 2004); it is virtually consistent with the statistical law in the region of $t \gtrsim 1$ hour. As for the images obtained by Rieutord *et al.* (2002) in their simulations, the corresponding curve also runs well below that of the La Palma series, although, among the four curves in Figure 1, it exhibits the slowest decline at $t \gtrsim 0.8$ hours, even approaching the La Palma curve at large t.

The fact that the relatively slow decline in the contrast values should obviously be associated with the presence of some long-lived component in the granulation field is additionally illustrated by Figure 2, which shows the variation in the rms contrast of averaged sequences of n shuffled granulation images as a function of the number n. This variation is plotted on a linear scale in Figure 2a and on a log–log scale in Figure 2b. In addition, Figure 2a presents the coefficient of correlation between the first and the nth frame in the sequence as a function of n. A straight line corresponding to the statistical $n^{-1/2}$ law is also plotted for comparison in Figure 2b.

Two remarkable features can be noted immediately. First, the correlation coefficient of the shuffled images is very small even at very small n (*e.g.*, $n = 2$) and does not exhibit any systematic trend, fluctuating about zero throughout the entire interval of n. This means that the shuffled images can be considered to be completely uncorrelated. Second, in agreement with the first property, they follow very closely the $n^{-1/2}$ over the whole interval of n, again starting from small n, such as $n = 2$ (the very small depression of the curve in the range $10 \lesssim n \lesssim 30$ can be attributed to the incomplete validity of the statistical law at such moderate values of n). It is noteworthy that the field constructed by Rast (2002), as noted above, follows the $n^{-1/2}$ law only from averaging times of about 0.3 hours, while it exhibits a slower contrast decline at shorter averaging times; obviously, this effect results from the finite lifetimes of the brightness peaks in the field constructed by Rast (2002), which makes the images within these lifetimes correlated rather than statistically independent. In contrast, the shuffling procedure appears to completely destroy any long-lived features that might be present in the original series.

4. Discussion and Conclusion

We see that the contrast of the averaged images of solar granulation decreases with the averaging time considerably more slowly than does the contrast of the averages of either a random field similar to the granulation in some of its parameters (Rast, 2002), or sequences of shuffled granulation images, or the granulation pattern numerically simulated by Steffen and his colleagues (see Wedemeyer *et al.* (2004)). This difference is especially pronounced at short to moderate averaging times.

The artificial granulation pattern obtained in simulations by Rieutord *et al.* (2002) differs markedly from the other computed pattern (Wedemeyer *et al.* 2004) in the behaviour of the contrast of averaged images. The former series of images exhibits, at $t \gtrsim 0.8$ hours, the slowest decline in the rms contrast with the averaging time t (among all the five datasets considered here) and thus appears to contain a persistent component, while the latter demonstrates a contrast variation consistent with the statistical $t^{-1/2}$ law at sufficiently large t. This fact remains currently unexplained. In principle, effects of the sort could be attributed to an implicit, uncontrolled influence of the boundary conditions used in the simulations; these conditions can favour the persistence of some features in the simulated velocity field. However, checking this conjecture would require a highly scrupulous analysis of the numerical model. In the context of the adequacy of the so-called realistic simulations of solar convection, it would be worth doing such an analysis in the future.

The results of our comparative analysis of the contrast-variation laws indicate quite definitely that the brightness field of solar granulation contains a long-lived component. Our approach cannot distinguish between particular forms of this component. One of us (P.N.B) adheres to the point of view that it is formed by locally persistent dark intergranular holes (Roudier *et al.*, 1997; Hoekzema *et al.*, 1998; Hoekzema and Brandt, 2000). The other author of this paper (A.V.G.) is inclined to attribute the observed contrast-variation law to the presence of quasi-regular structures (first reported by Getling and Brandt (2002) and discussed in detail by Getling in Paper I). Most likely, it should not be assumed that these two interpretations contradict each other, since features similar to intergranular holes can naturally be present in quasi-regular structures.

Our comparison between the contrast-variation curves for the real granulation and the random field constructed by Rast (2002) completes the discussion in Paper I concerning the critical comments by Rast (2002) on our original paper (Getling and Brandt, 2002). Based on all our reasoning, we can dismiss the suggestion by Rast (2002) on the purely statistical nature of the quasi-regular structures in the granulation field.

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