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MOTIONS OF SUPERGRANULAR STRUCTURES ON THE SOLAR SURFACE

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Abstract. We present a method used to study motions of supergranular structures in the solar photosphere. It is based on the local correlation tracking method applied to full-disk dopplergrams measured by SoHO/MDI. In primary dopplergrams, there is a plenty of noise originating mostly from oscillations and morphological changes of the shape of supergranules. We describe a method used to suppress such noise. To demonstrate the suggested technique and properties of computed velocity fields, we processed a few-day period during the time of minimum of solar activity. The obtained vector velocity fields are drawn using streamlines in the Carrington's coordinate system. We discuss the reproductivity of the obtained results and the connection of the velocity field we found to the large-scale velocity field in the upper part of the convection zone.

Key words: Solar photosphere – supergranulation – horizontal velocity field

1. Introduction

Motions of the mass and structures in the solar photosphere remain an open question, in spite of tens years of intensive studies. Their manifestations are known in various types of observations, but we have only a scarce knowledge about the physics of photospheric flows and about their connections to the subphotospherical convection and magnetic fields.

A really interesting velocity structure in the photosphere is the supergranulation, an exhibition of a convective mode represented by cells with a size of about 30 Mm and with a mean lifetime approx. 20 hours (e.g., Wang and Zirin, 1989). Velocity field in supergranules is predominantly horizontal with the amplitude of 300–500 $\mathrm{m\,s^{-1}}$ (e.g., Leighton *et al.*, 1962; Worden and Simon, 1976; Hathaway *et al.*, 2002), while the vertical component is lower by an order (Hathaway *et al.*, 2002). We used the facts that supergranules are well defined almost at the full disk of the Sun and that they have a large temporal stability, to map their motions. In this study we assume that supergranules are carried by velocity field of large scales.

If we pass over the studies of the velocity structures on the largest scales – studies of the differential rotation (e.g. Snodgrass, 1984) can be mentioned here – there are not many works inquired into the large-scale photospheric velocity fields. Ambrož (2001a, 2001b, 2002) inferred the large-scale velocity field from the low-resolution magnetic synoptic maps acquired on the Wilcox observatory of the Stanford University. His studies in the period of solar minimum have shown long-living structures with a dominant zonal component. Some other studies using the data from MDI/SoHO were published by Beck and Schou (2000).

2. Data Processing

The MDI instrument onboard the SoHO observatory acquired in certain periods of its operation (the Dynamics program) the full-disk dopplergrams at a high cadence – one observation per minute. These campaigns was originally designed for the studies of the high-frequency oscillations. In the dopplergrams the pattern of supergranulation can be found almost on the whole disk. We cannot use these primary data directly for the ongoing processing, because they contain too much noise and other disturbing effects.

Even though the quality of the data series from MDI is very good, there are some wrong measurements. Such errors like missing measurements or missing parts of frames we correct using linear interpolation between two error-free neighbouring frames to get an uninterrupted data sequence. By now, we have processed a series of one-minute cadence dopplergrams covering the time interval from May 25th to June 25th 1996, that means, 46 080 primary dopplergrams with resolution 2" per pixel. From these, the line-of-sight component of the Carrington's rotation is subtracted and the calibration error of MDI (Hathaway *et al.*, 2002) is compensated.

In the next step we remove the high-frequency solar oscillations using a weighted average (see Hathaway, 1988). The weights have a Gaussian form

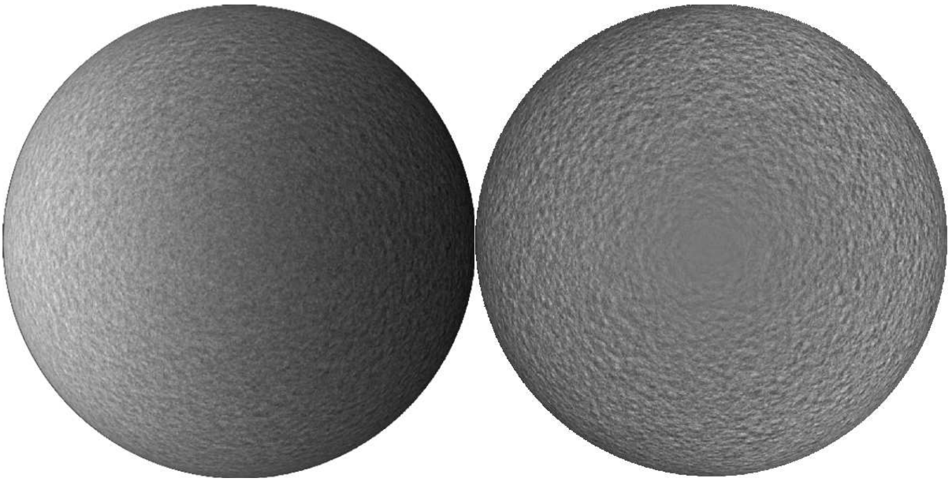

Figure 1: Comparison of the primary dopplergram (left) and the reduced one (right). Velocity structure formed by supergranular cells is enhanced after data processing.

given by the formula:

$$w(\Delta t) = e^{\frac{(\Delta t)^2}{2a^2}} - e^{\frac{b^2}{2a^2}} \left(1 + \frac{b^2 - (\Delta t)^2}{2a^2}\right), \qquad (1)$$

where Δt is a time distance of a given frame from the central one (in minutes), $b = 16$ and $a = 8$. We sample averaged images in the interval of 15 minutes. The filter suppresses more than five hundred times the solar oscillations in the 2–4 mHz frequency band.

The averaged images in a sequence of a chosen length are transformed to the system of synodic heliographic coordinates latitude/longitude, so that the longitude of the central meridian is equal in all frames. Then, the data in the frames are resampled changing the spherical coordinate system to the Cartesian one to compensate geometrical distortions of supergranules far from the disk centre. The noise in horizontal displacements coming from the individual evolutionary changes of supergranules is suppressed by the $k - \omega$ filter in the Fourier domain (see Hirzberger *et al.*, 1997 for details) with the cut-off phase velocity 700 $\mathrm{m\,s^{-1}}$. This way, the velocity structure formed by supergranular cells is enhanced (Fig. 1). These data are directly used to track supergranules and to compute the horizontal velocity fields.

3. Calculation of the Velocity Fields and their Visualisation

We used the local correlation tracking (LCT) method (November and Simon, 1988) to compute the horizontal velocity field from the sequence of reduced dopplergrams. This method works on the principle of the best match – the local displacements in the frames are determined for each position using the correlation between a pair of sub-frames limited by a pre-defined spatial window (correlation window) and the velocities of these displacements are calculated. To determine of the sub-pixel vector of the displacement we use the nine-point method based on fitting of the biquadratic surface (Darvann, 1991).

Because we have studied large-scale flows, we used the correlation window with FWHM of 200" and 100" and the time lag between a pair of images was 4 hours. We averaged the computed velocity field over 24 hours and the results were sampled each 12 hours.

The existence of the differential rotation complicates the tracking of the large-scale velocity field, because the amplitudes and directions of velocities of the processed velocity field have a significant dispersion. This is the reason, why the data before the Fourier filtration are transformed to the coordinate system that rotates with the angular velocity with respect to the observer, which is given by:

$$\omega = A + B \sin^2 b + C \sin^4 b, \tag{2}$$

where ω is the synodic angular velocity in degrees per day, b is the heliographic latitude, $A = 13.064$, $B = -1.69$ and $C = -2.35$; the coefficients of the equation (2) were determined spectroscopically from the plasma rotation by Snodgrass (1984). If we remove the differential rotation, we lower the maximum values of the velocity field and the shifts, which are evaluated by the LCT technique – this improves the sensitivity of the method and the results.

After the application of the LCT method we again add the differential rotation profile (2) to the zonal component of the determined velocity field and we transform the resulting velocity field to the synodic Carrington's coordinate system.

The computed velocity field we visualise by double-directional streamlines (Klvaňa *et al.*, 2004). The streamlines are drawn with the constant step 1 pixel (3.2"). The amplitude of the velocity in each part of the stream-

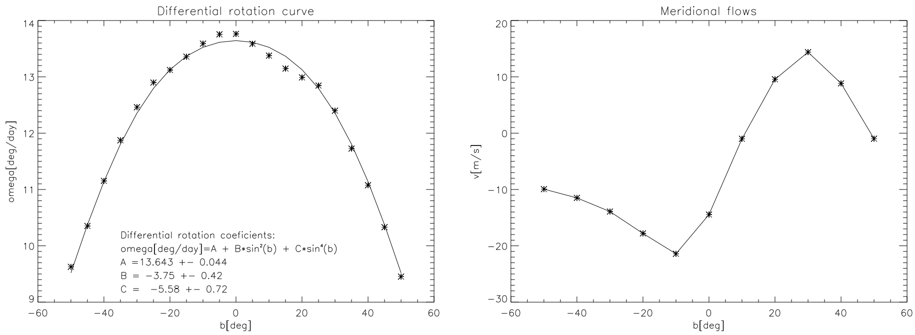

Figure 2: The integral curves of the differential rotation and the meridional circulation computed for May 25th, 1996, using the correlation window with FWHM 100". Curves, obtained in the other day of the processed series, are quite similar in shape and other parameters. The shape and parameters of the integral curves indicate neglectable dependency on the size of the correlation window.

line is represented by a shade of grey. The length of each streamline is 1000 steps in both directions and the starting points are situated on concentric circles and generate the grid of equilateral triangles with the length of each side approximately 30 pixels (96").

4. Properties of the Obtained Velocity Fields

From the obtained velocity fields, their integral characteristics can clearly be inferred: The differential rotation and the meridional circulation (Fig. 2). The shapes of both curves correspond to types mentioned in the literature (e.g., Gizon, 2003b), both for the values of the fitted parameters B, C and for the velocity of meridional flow. The value of the coefficient A of the curve (2) is somewhat larger (by about 0.5 ° per day). This can be a manifestation of surface low-frequency waves, recently detected in the supergranulation (see the review by Gizon, 2003b). According to Gizon *et al.* (2003a), the supergranulation supports pro-grade surface waves, which have an effect of motion with the amplitude of about 60 $\mathrm{m\,s^{-1}}$ – this corresponds to 0.43 ° per day on the equator.

We analyse the topology of horizontal velocities using the streamlines calculated from the velocity field inferred with the correlation window with FWHM = 200" (Fig. 3). Streamlines representing plasma motions in the Carrington's coordinate system clearly show laminar flows predominantly

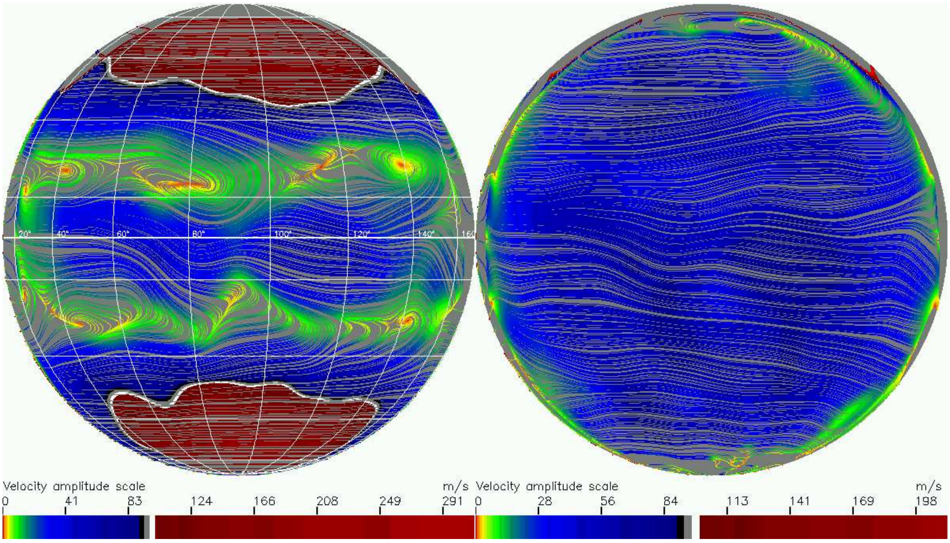

Figure 3: *Left* – Horizontal velocity field in the Carrington coordinate system (FWHM 200"). *Right* – Residual horizontal velocity field relative to the differential rotation described by the curve (2).

in the zonal direction – in polar areas from the west to the east and in the equatorial area in the opposite direction.

A significant inclination of the zonal flow from the equator to the poles in the equatorial area can be observed, as well as an opposite inclination in the polar areas. This inclination toward the meridional direction is better visible in streamlines where the differential rotation was subtracted. It confirms the existence of meridional flow from the solar equator to the solar poles (Fig. 3 right). The dividing line between both directions does not coincide with the equator, but it intersects the equator in several places. The image of the laminar flow is partially reproducible in time. If we follow the temporal evolution of laminar structures, we can notice two superimposed and topologically different components. The first one is moving across the solar disc and it is evidently related to the solar rotation. The second one stays on the solar disc without significant motion in the 30-days series. For a deeper analysis of both structures we need to process longer series of observations.

The vorticity structures in areas near +40 and −40 degrees depict areas with small values of velocities. In these areas, the signal-to-noise ratio

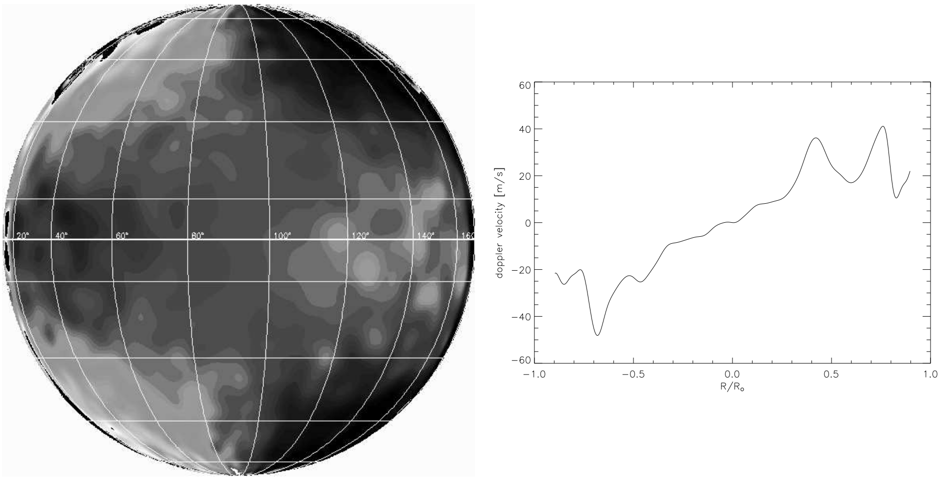

Figure 4: *Left* – Doppler component of the horizontal velocity determined by means of LCT with FWHM 100", with Carrington's rotation removed. There is an indication of large-scale compact velocity structures on the whole disk excepting the central area of the disc. Dark shades represent motions to the observer. Effects of different rotational velocities in different heliographic latitudes can also be seen. *Right* – Equatorial cut through the Doppler component of the horizontal velocity field. Compact velocity structures with size of about 300 Mm and with an internal, mostly horizontal velocity field are detected.

decreases, so that the noise in the velocity field becomes more significant. This noise has its origin in the Fourier-smoothed morphological changes of supergranules. Considering that changes in a shape of supergranules are associated with the evolution, they have a short-term character in comparison to the supergranular lifetime. Taking into account that streamlines are strongly sensitive to the local changes, even small such changes induce fast variations of the vorticity structures. Although this vorticity structures act in a very suggestive way, they probably do not describe any physical process and probably they are consequences of short-lived morphological structures and of the used mathematical technique.

Result of the LCT method is a horizontal velocity field with two components – zonal velocity v_φ and meridional velocity v_ϑ. We can use simple formula to get Doppler component $v_{\rm dop}$:

$$v_{\rm dop} = v_\varphi \sin\varphi + v_\vartheta \sin\vartheta, \qquad (3)$$

where φ and ϑ are heliographic longitude and latitude measured from the centre of the solar disc. Such "dopplergrams" are transformed from the

Cartesian coordinate system to the spherical one. In these images (Fig. 4 left) we found areas, whose internal velocity is larger than the velocity of the surrounding photosphere. These structures generate a cellular-like pattern. From the equatorial cut (Fig. 4 right) we can estimate the size and the velocity pattern of these structures: The size is of about 300 Mm, the internal velocity in the cells has the horizontal component of 20 $\mathrm{m\,s^{-1}}$ and vertical of 2 $\mathrm{m\,s^{-1}}$. We can follow slow changes and motions in this compact persistent pattern from day to day with a very good reproducibility.

5. Conclusion

On the basis of the motions of supergranular structures in the one-month period during the solar minimum we obtained a picture of the global velocity field in the solar photosphere, with significant zonal and meridional components. These components do not show a uniform pattern, they are structured. This means that the approximation of the differential rotation by means of a smooth curve is a statistical artifact, so that the coefficients of analytical approximation strongly depend on many circumstances (in agreement with Ambrož, 2002). In our example, maximum values of the zonal and meridional components in the equatorial area are around 100 $\mathrm{m\,s^{-1}}$ in the E-W direction and 30 $\mathrm{m\,s^{-1}}$ in the direction from the equator to the poles.

The dividing line between the meridional flows on both hemispheres is not bound to the equator but it intersects the equator in several locations. This means that we can find flows across the equator.

We found maximum zonal velocities larger than 250 $\mathrm{m\,s^{-1}}$ in the polar areas. Meridional components were much fainter here.

6. Acknowledgements

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GIBANJA SUPERGRANULARNIH STRUKTURA NA SUNČEVOJ POVRŠINI

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Izlaganje sa znanstvenog skupa

Sažetak. Prikazuje se metoda izučavanja gibanja supergranularnih struktura u Sunčevoj fotosferi temeljena na traganju lokalnom korelacijom primjenjenom na dopplergrame cijelog diska Sunca dobivene SoHO/MDI instrumentom. U izvornim dopplergramima nalazi se mnogo smetnji koje uglavnom potiću od oscilacija i morfoloških promjena oblika supergranula. Opisuje se metoda potiskivanja tih smetnji. Da se prikaže korišćena tehnika i svojstva proračunatih polja brzina, obradili smo period od nekoliko dana za vrijeme minimuma Sunčeve aktivnosti. Dobivena vektorska polja brzina su nacrtana koristeći strujnice u Carringtonovu koordinatnom sustavu. Diskutira se reproducibilnost dobivenih rezultata i veza dobivenog polja brzina s poljem brzina velikih razmjera u gornjem dijelu konvektivnog sloja.

Ključne riječi: Sunčeva fotosfera – supergranulacija – horizontalno polje brzina