MAPPING OF LARGE-SCALE PHOTOSPHERIC VELOCITY FIELDS

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ABSTRACT

We present a technique utilized for mapping of large-scale velocity fields. This technique is based on the local correlation tracking (LCT) method. We use supergranular structures in the full-disc dopplergrams as tracers, assuming that the supergranules are carried by a larger-scale velocity field under study. The described technique was applied to measurements acquired by the MDI/SoHO instrument in the period of the solar minimum and to full-disc dopplergrams obtained by a simple numerical simulation. Before the application of LCT, the dopplergrams undergo a complex reduction procedure. We obtained some information about the reliability of the proposed approach by application of the described technique to simulated data. The properties of calculated velocity fields are discussed.

Key words: Solar photosphere; velocity fields; local correlation tracking.

1. INTRODUCTION

Solar photosphere is a very dynamic layer of the solar atmosphere. It is strongly influenced by the underlying convective zone. Despite years of intensive studies, velocity fields in the solar photosphere remain not so well known. The evidence about the vigorous and sometimes chaotic character of motions of observed structures in the photosphere came already from the first systematic studies made in 19th century. Let us mention at least the discovery of the solar differential rotation (Carrington, 1859). Motions in the photosphere are strongly coupled with magnetic field.

An attempt to describe the differential rotation by a parabolic dependence did not make for clear results. Coefficients of the parabola differed according to traced objects and time (reviewed e. g. by Schröter, 1985). The character of the differential rotation was never in doubt. It follows from the arguments above that there exists a temporally variable large-scale streaming of plasma on the surface of the Sun, that can be roughly described by the differential rotation. Large-scale plasma motions were recently studied on the basis of tracking the magnetic structures (e. g. Ambrož, 2001a, 2001b). The long-term high-cadence Doppler measurements done by the MDI instrument on board the SoHO observatory made it possible to develop the described method of the calculation of large-scale velocities in the solar photosphere. The knowledge of the behaviour of velocities in various periods of the solar activity cycle could contribute to the understanding of the coupling between the velocity and magnetic fields and of the solar dynamo function.

Since the photosphere is a very thin layer (0.04 % of the solar radius), the large-scale photospheric velocity fields have to be almost horizontal. Then, the tracer-type measurement should be sufficient for mapping such velocities. Tracer-type measurement provides generaly two (horizontal) components of the velocity vector. From the various techniques utilised for tracking the local correlation tracking (LCT) method is very useful. The method was originally designed for the removal of the seeing-induced distortions in image sequences (November, 1986) and later used for mapping of the motions of granules in the series of white-light images (November & Simon, 1988). The method works on the principle of the best match of two frames that record the tracked structures at two different instants. For each pixel in the first frame a small correlation window is chosen and this window is compared with a somewhat displaced window of the same size in the second frame. A vector of displacement is then defined as a difference of coordinates of centres of both windows when the best match is found. From this displacement and the time lag between correlated frames the velocity vector is calculated.

The method needs a tracer – a significant structure recorded in both frames, lifetime of which is much longer than the time lag between the correlated frames. We decided to use the supergranulation pattern in the full-disc dopplergrams, acquired by the MDI instrument on-board the SoHO observatory. Properties of supergranular cells (size, life-time, velocity field, etc.) were described in many papers (e. g. Leighton, 1964, Sýkora, 1970, Wang & Zirin, 1989, DeRosa et al., 2000, Hathaway et al., 2002). We assume that supergranules are carried as objects by the large-scale velocity field. This velocity field is probably located beneath the photosphere, so that the results will describe the dynamics in both the photospheric and subphotospheric layers. Existence of the supergranulation on almost the whole solar disc (in contrast to magnetic structures) and its large temporal stabil-

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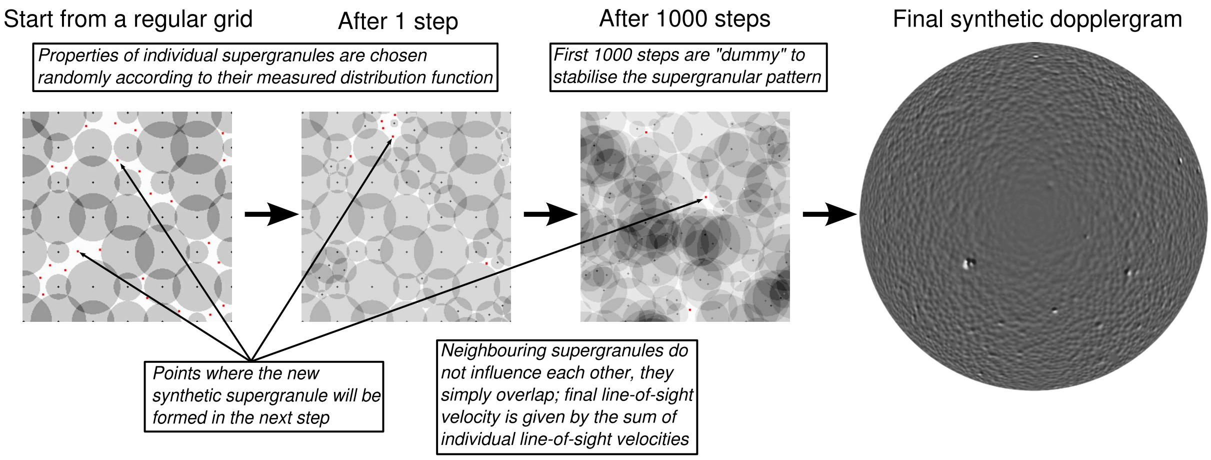

Figure 1. Main principles of the SISOID code for calculation of synthetic dopplergrams.

ity makes the supergranulation an excellent tracer.

2. THE METHOD

A recent experience with the application of the suggested method to observed data (e. g. Švanda et al., 2005) has shown that for the proper setting of the parameters and for tuning of the method, synthetic (model) data with known properties are needed. The synthetic data for the analysis come from a simple simulation (SISOID code = *SI*mulated *S*upergranulation as *O*bserved *I*n *D*opplergrams), with the help of which we can reproduce the supergranulation pattern in full-disc dopplergrams. The main principles of the work of the SISOID code are symbolized in Fig. 1.

The SISOID code is not based on physical principles taking place in the origin and evolution of supergranulation. It is based on a reproduction of known parametres that describe the supergranulation. Individual synthetic supergranules are characterised as centrically symmetric features described by their position, lifetime, maximal diameter and characteristic values of their internal horizontal and vertical velocity components; all these quantities are chosen randomly according to the corresponding measured distribution functions. The SISOID simulation is done in the pseudocylindrical Sanson-Flamsteed coordinate grid (Calabretta & Greissen, 2002); in each step an appropriate part of the simulated supergranular field is transformed into heliographic coordinates. The output of the program is a series of synthetic dopplergrams of the solar hemisphere in the orthographical projection to the disc. The model velocity field is introduced according to the assumption of the velocity analysis: The supergranules are carried by a velocity field of a larger scale. In the simulation only the position of individual supergranules is influenced. For one day of the real solar time, 96 dopplergrams are calculated.

The method of calculation of horizontal velocity fields consists of the following steps:

1. Although the synthetic data have properties very similar to the real observed data, there is one big difference – presence of the noise in the real data, especially high-frequency oscillations (p-modes). First, from the frames the manifestation of the solar rotation is removed under the assumption of the rigid solar rotation. In the next step we remove the high-frequency solar oscillations using a weighted average (Hathaway, 1988). As the input to the data processing we take one-day observation that contains 96 full-disc dopplergrams in 15minutes sampling.

2. The data series is “derotated” using Carrington rotation rate, so that the heliographic longitude of the central meridian is equal in all frames and equals to the heliographic longitude of the central meridian of the central frame of the series.

3. Then the data series is transformed to the Sanson-Flamsteed coordinate system to remove the geometrical distortions caused by the projection of the sphere to the disc.

4. The noise coming from the evolutionary changes of the shape of individual supergranules is suppressed by the k-ω filter in the Fourier domain (Title et al., 1989, Hirzberger et al., 1997). The cut-off velocity is set to $1\,500$ $\mathrm{m\,s^{-1}}$ and has been chosen on the basis of the empirical experience.

5. The LCT (nine point) method is applied with the lag between correlated frames equal to 16 frames (equals to 4 hours in the solar time) and the correlation window with FWHM 30 pixels (equals to $60''$ on the solar disc in the linear scale). In one observational day 80 pairs of velocity maps are calculated and averaged.

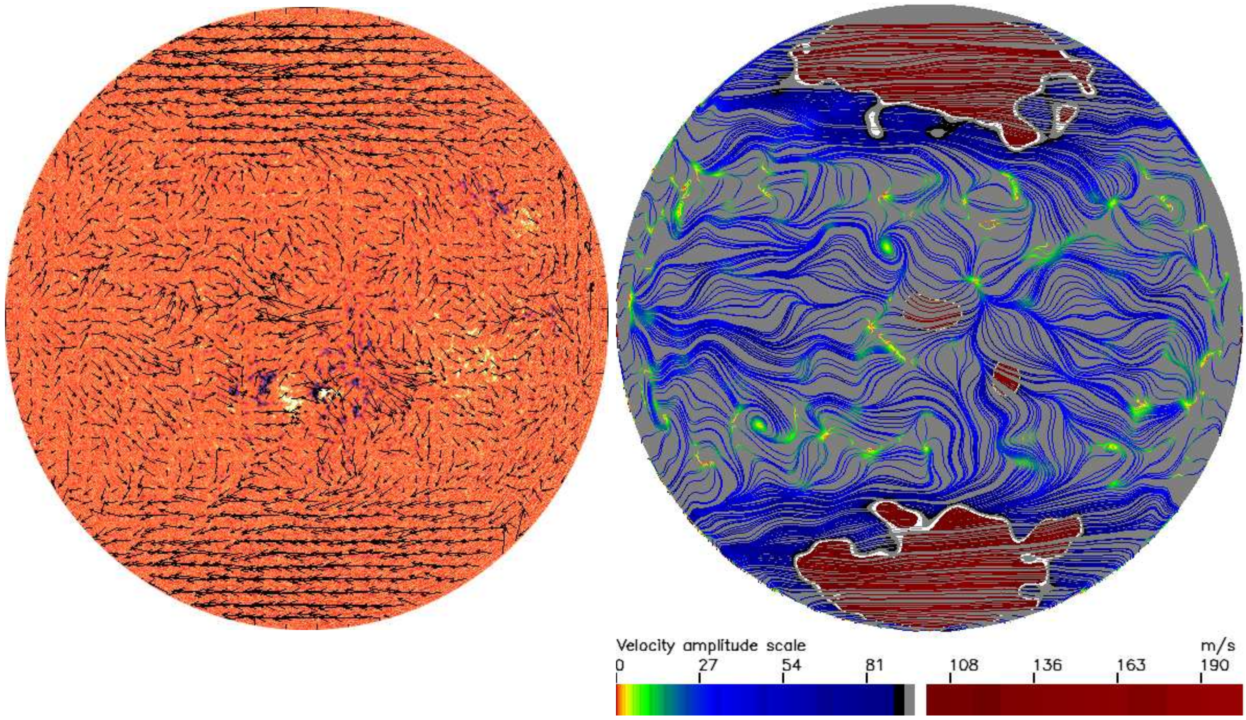

Figure 2. Example of measured velocity fields in the Carrington coordinate system: Horizontal velocities on July 7th, 1996, one-day average. Left – visualisation with arrows (the MDI magnetogram in the background, blue (yellow) tones signify the negative (positive) polarity of the magnetic field). Right – visualisation by streamlines (the velocity field was smoothed by a Gaussian with FWHM 56″ before the calculation of streamlines).

6. The magnitudes of the calculated vector field are corrected using the formula

$$v_{\mathrm{cor}} = \frac{v_{\mathrm{calc}}}{0.61 + 0.36\,c\,v_{\mathrm{calc}}}, \qquad (1)$$

   which came from the comparison with the synthetic data (v_{calc} is the magnitude of velocities calculated by LCT and v_{cor} is the corrected magnitude; directions of the vectors before and after the correction are the same; c is a constant related to the choice of units, $c = 1$ when both v_{calc} and v_{cor} are used in units of “px/lag”, $c = 0.009\,93$ when $\mathrm{m\,s^{-1}}$ units are used).

It follows from the tests on the synthetic data that the described method provides sufficiently reliable results for the mapping of the large-scale velocity fields from the motions of supergranules with the spatial resolution of 60″ and with an accuracy of 10 $\mathrm{m\,s^{-1}}$.

3. RESULTS

The described method was applied to the sixty-day series of the measured dopplergrams covering the interval May 25th – July 24th 1996; the one-day-averaged horizontal velocity fields in the Carrington coordinate system were sampled each 12 hours. An example can be seen in Fig. 2. The velocities can be topologically divided in three parts. In the polar areas the plasma flows from the west to the east with the mean velocity of approx. 110 $\mathrm{m\,s^{-1}}$. Along the equator the zonal flow from the east to the west slightly prevails with the magnitude 80–100 $\mathrm{m\,s^{-1}}$. In the areas of middle latitudes no direction of flows is preferred, the magnitudes of the velocity vectors are typically under 50 $\mathrm{m\,s^{-1}}$ here. Since the accuracy of the calculation is 10 $\mathrm{m\,s^{-1}}$, the signal-to-noise ratio is the lowest here, so that the very small velocities (under 15 $\mathrm{m\,s^{-1}}$) have to be treated as unreliable here.

The visual analysis of the movie of the processed series indicate an existence of long-lived large-scale structures in the computed velocities, positions and shapes of which are partially reproducible in time. These structures form cellular like pattern. From the cut along the solar equator the parametres of the cells were estimated: size approx. 200 Mm, predominantly horizontal velocity field with magnitudes about 20–40 $\mathrm{m\,s^{-1}}$. Detailed properties and behaviour of this pattern will be studied later.

On one day from the processed series (July 7th 1996), the velocities were studied closer for the sake of possible influence by a photospheric magnetic field. Qualitatively there has not been found any interference with the underlying magnetic field (cf. Fig. 2 left); the velocity vectors seem to have the same character in areas occupied by the magnetic field and areas without the magnetic field. Since this contribution has a preliminary character, the coupling

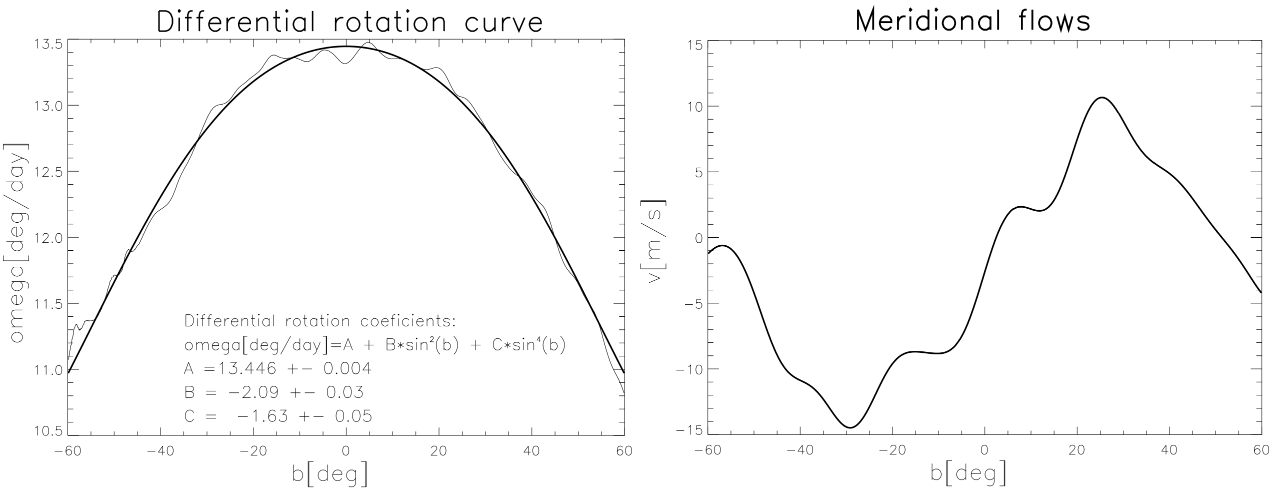

Figure 3. Integral curves calculated from the horizontal velocity field obtained for July 7th 1996. Left – synodic differential rotation curve, right – meridional circulation curve.

between the calculated velocities and the magnetic field in the photosphere will be studied later in more detail.

From the calculated velocity fields their integral characteristic can be simply inferred (cf. Fig. 3). 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 somewhat larger value of the coefficient A could be a manifestation of the surface low-frequency waves, recently detected in the supergranulation (Gizon et al., 2003a).

4. CONCLUSION

We have developed the method useful for the mapping of the large-scale horizontal velocity fields in the solar photosphere. The method is based on the local correlation tracking algorithm and provides results with the spatial resolution $60''$ (43.5 Mm) on the solar disc and with the accuracy of 10 m s^{-1}. The method was applied to the real dopplergrams measured by the MDI instrument onboard the SoHO observatory in the period of the minimum of solar activity cycle. From the results the integral characteristics can be clearly inferred. For the closer studied day (July 7th, 1996) we did not detect any influence of the photospheric magnetic field to the calculated velocity fields. This topis will be studied later in more detail.

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