Mapping of large-scale photospheric velocity fields

M. Švanda[1,2], M. Klvaňa[1], M. Sobotka[1]

[1] Astronomical Institute, Academy of Sciences, Fričova 298, CZ-251 65 Ondřejov, Czech Republic
[2] Astronomical Institute, Charles University, V Holešovičkách 2, CZ-180 00 Praha 8, Czech Republic

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.

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. An attempt to describe the differential rotation by a parabolic dependence did not make for clear results. It follows from the arguments above that there exists a temporally variable large-scale streaming of the plasma on the surface of the Sun, that can be roughly described by the differential rotation. 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 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, the large-scale photospheric velocity fields have to be almost horizontal. Then, the tracer-type measurement should be sufficient for mapping such velocities. 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, 1988) and later used for mapping of the motions of granules in the series of white-light images (November & Simon, 1986). 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 onboard the SoHO observatory. Properties of supergranular cells were described in many papers (e. g. Wang & Zirin, 1989, DeRosa et al., 2000) and they make the supergranulation an excellent tracer. 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.

Address for correspondence: svanda@asu.cas.cz

The method

A recent experience with the application of the suggested method to observed data (e. g. Švanda, 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 method of calculation of horizontal velocity fields consist of six steps that are schematically shown in Fig. 2. Let us just write some comments:

- The weighted average suppress more than five hundred times the *p*-modes in the frequency band 2–4 mHz (see Hathaway, 1988).
- As the input to the data processing we take one-day observation that contains 96 full-disc dopplergrams in 15minutes sampling. The data series is "derotated" using Carrington rotation rate, so that the heliographic longitude of the central meridian is equal in all frames. 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.
- The noise coming from the evolutionary changes of the shape of individual supergranules is suppressed by the k-ω filter in the Fourier domain (see Title et al., 1989, Hirzberger et al., 1997). The cut-off velocity is set to 1 500 ms^{-1}.
- 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 60". In one observational day 80 pairs of velocity maps are calculated and averaged.
- The magnitudes of the calculated vector field are corrected using the formula:

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

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.

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 ms^{-1}.

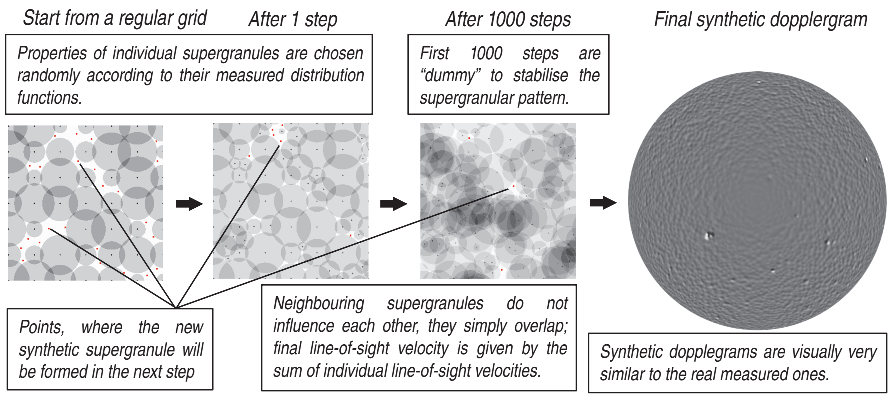

Fig. 4. Main principles of the SISOID code, which computes a synthetic supergranulation.

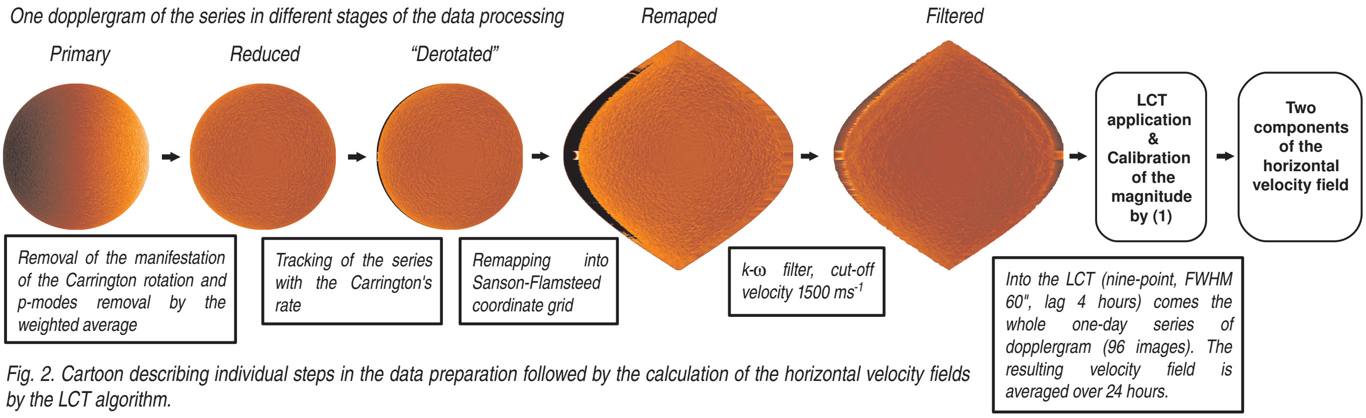

Fig. 2. Cartoon describing individual steps in the data preparation followed by the calculation of the horizontal velocity fields by the LCT algorithm.

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. 3. 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 ms^{-1}. Along the equator the zonal flow from the east to the west slightly prevails with the magnitude 80–100 ms^{-1}. In the areas of middle latitudes no direction of flows is preferred, the magnitudes of the velocity vectors are typically under 50 ms^{-1} 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 ms^{-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. 3 right); 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 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. 4). The shapes of both curves correspond to types mentioned in the literature 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., 2003).

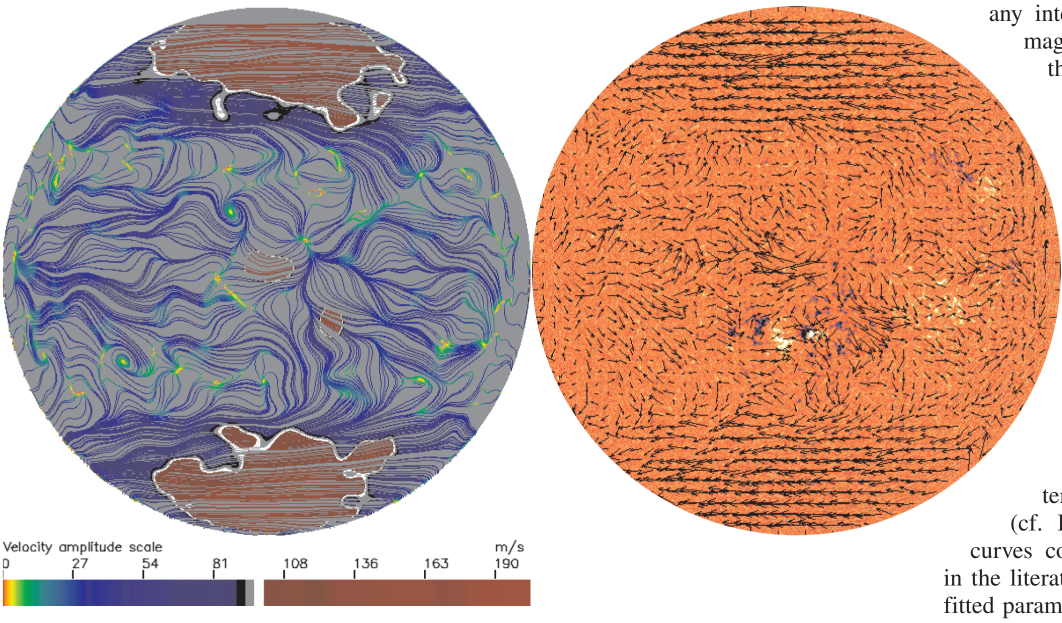

Fig. 3. Example of measured velocity field in the Carrington coordinate system: Horizontal velocities on July 7th, 1996, one-day average. Left – visualisation by streamlines (the velocity field was smoothed by a Gaussian with FWHM 65" before the calculation of streamlines). Right – visualisation with arrows (the MDI dopplergram in the background, dark (bright) tones signify the negative (positive) polarity of the magnetic field).

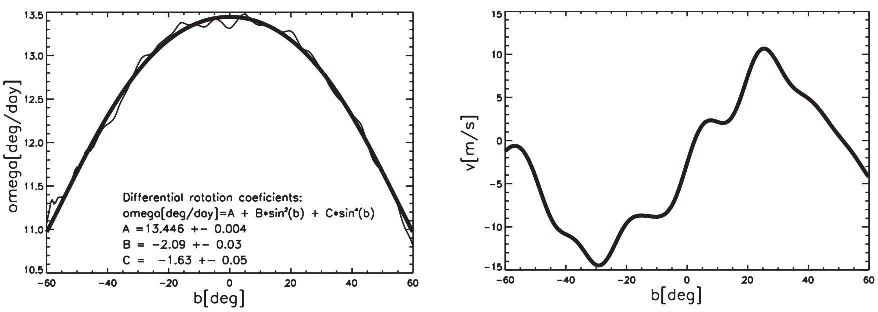

Fig. 4. Integral curves calculated from the horizontal velocity field obtained for July 7th 1996. Left – synodic differential rotation, right – meridional circulation curve.

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