

## Transport of Supergranules and their Vertical Coherence

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**Abstract.** In recent papers, we have introduced a method for measuring the photospheric flow field that is based on the tracking of supergranular structures. Here, in combination with helioseismic data, we are able to estimate the depth in the solar convection envelope to which the detected large-scale flow field is coherent. We show that the upper 10 Mm in the convection zone depicts similar features in horizontal velocity. Our interpretation of this observation is that the supergranulation is a coherent structure 10 Mm deep and is subject to large-scale transport by the underlying velocity field.

### 1 Introduction

The supergranulation is a surface pattern that has remained a puzzle since its discovery. There are many papers published examining the parametric properties of supergranular cells. Typical values of the size are 20–30 Mm, with a lifetime of 24 hours (see, e.g., DeRosa & Toomre 2004, and references herein). Classically, the supergranules are interpreted as cells of convective origin. Many authors doubt this interpretation. The surface properties of supergranules may be also explained as a non-linear interaction between granules (e.g. Rieutord et al. 2000). Wave-like properties of the supergranulation have also been discussed (e.g. Gizon et al. 2003).

The supergranules are readily visible on the whole disk of the Sun in Dopplergrams. Assuming that supergranules are carried by the flow field on larger scales, they can be tracked and reveal the underlying large-scale flow field. Recently, we developed a method based on this idea (for details see Švanda et al. 2006). The method uses local correlation tracking (LCT) to measure displacements of supergranular structures in the series of processed SOHO/MDI (Scherer et al. 1995) Dopplergrams and interpret them as the large-scale velocity fields in the solar photosphere. By this alone, we cannot establish in which depths of the subphotospheric layers the measured velocity fields are located. With the use of the data provided by time-distance helioseismology (Duvall et al. 1993) we can determine this unknown parameter.

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## 2 Data and Method

For a comparison between the data obtained by our method and the results of time-distance helioseismology, we used high-cadence full-disk Dopplergrams recorded in March and April of 2001. From 46 maps of the region around NOAA 9393/9433 we used six examples on six different days (March 3rd, 28th, 29th, 30th, 31st, and April 25th). On these days the data were also suitable for our method, and the field of view was far from the solar limb. One-day series of full-disk Dopplergrams were processed following the procedure introduced by Švanda *et al.* (2006), with a few modifications. Postel projection was used instead of Sanson-Flamsteed projection. Due to the small field of view we assumed rigid solar rotation for the reference frame of the flows. The results of the analysis consist of 24-hour-averaged large-scale velocity field maps with a  $60''$  correlation window. The helioseismic flow maps were smoothed to match this resolution, which filters out the internal flow in supergranulation.

All the datasets were aligned with the center of the field of view on Carrington coordinates  $L = 148.5^\circ$  and  $B = 19^\circ$ . For each depth in the helioseismic datacube we calculated its similarity to the flow map obtained by tracking of supergranular structures using the magnitude-weighted cosine of the direction difference. This quantity is robust to the presence of noise. We investigate the similarities separately for the regions occupied by the magnetic field and the regions of quiet Sun, which were distinguished using MDI magnetograms.

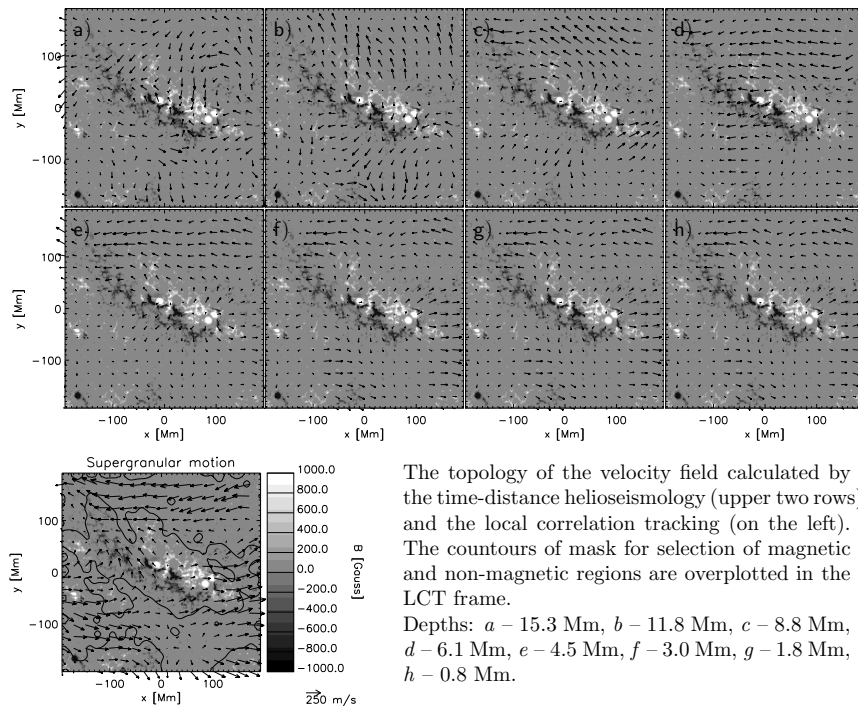


Figure 1. A mosaic of the flows at various depths in the vicinity of NOAA 9433 on April 25th 2001.

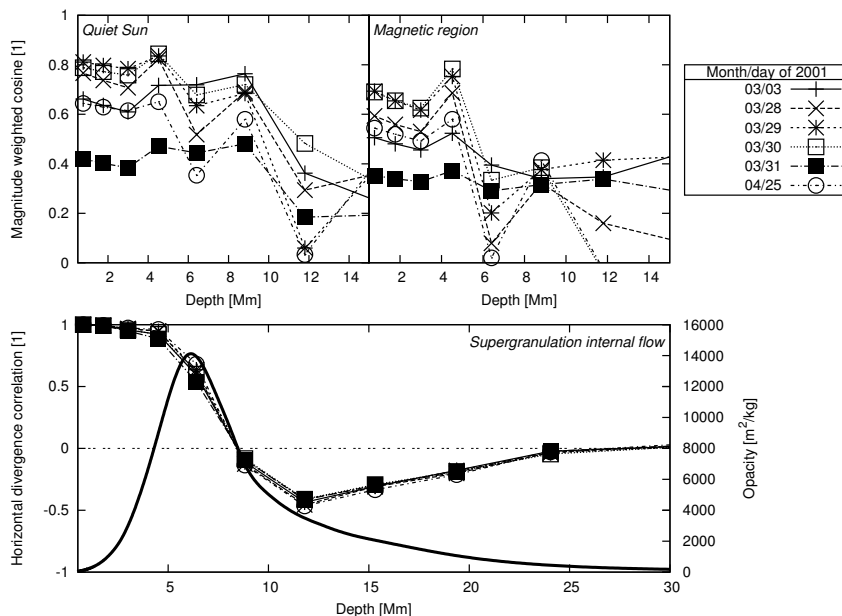


Figure 2. Top frame shows the dependence on depth in the solar convection zone of the similarity in the velocity fields provided by time-distance helioseismology and the flows calculated by LCT (top frames). Bottom frame shows the correlation of the internal supergranulation velocity field between the surface and given layers with the opacity trend overplotted (bottom frame).

### 3 Results

**Large-scale horizontal flows.** The results of the comparison are displayed in Figure 1. We basically see a large similarity of the velocity fields measured by both methods in higher levels of the solar convection zone. Our analysis shows that the large-scale flow does not vary much with depth down to 10 Mm (see Figure 2) in the quiet-Sun regions. In the magnetized regions it is more difficult; the dominant structures in the Dopplergrams are the structures connected to the magnetic field rather than to the supergranulation. In our results, we see that in magnetized regions the detected flows are coherent to depths of 5 Mm. This corresponds to the depth where sunspots stop existing as the regions of suppressed heat transport (e.g. Zhao et al. 2001).

**Vertical structure of supergranulation.** The results obtained can be interpreted as a fulfillment of the basic assumption of our method that supergranular structures may indeed be treated as objects carried by the large-scale velocity field. To confirm this interpretation, the structure of the supergranules themselves must be analyzed. We therefore modified our analysis and subtracted the large-scale velocity field from helioseismic flow maps, so that only the internal velocities in the supergranules remained. From these maps we calculated the horizontal divergence as a representation of down-/up-flows and correlated it between layers.

The divergence signal is very similar in the quiet Sun region in depths 0.77–6.4 Mm (see Figure 2). Down to  $\sim 7$  Mm the correlation is positive, implying coherence in the structure of supergranules. Deeper down the correlation turns negative, which suggests evidence of the return flow in the supergranules. Similar results were achieved by Zhao & Kosovichev (2003).

In Figure 2 the trend of the opacity in the sub-surface layers of the convection zone from reference model S (Christensen-Dalsgaard *et al.* 1996) is overplotted. We see that the opacity starts to increase at  $\sim 25$  Mm depth. It reaches its maximum at 6 Mm, and closer to the surface, it drops again. At 25 Mm, the trend of the correlation between the layers in the solar interior and the near-surface layers turns from zero to negative values. The convection connected to the supergranulation seems to start here. The cell-like structure can be detected at 12 Mm, where the anti-correlation with surface layers is high enough. At the depth of maximum opacity, the inflow-outflow structure forms a surface-like pattern, which stays highly coherent up to the surface layers.

#### 4 Conclusions

Using comparisons of large-scale horizontal flows obtained by local correlation tracking and by local helioseismology, we find that the resulting flow maps represent well the horizontal dynamical behavior of flows to depths of 10 Mm below the solar surface. The supergranulation is coherent within layers that show correlated large-scale horizontal flows. This interpretation of supergranules is closer to that of real convective cells. The supergranulation exists as a highly coherent structure down to  $\sim 7$  Mm. The possible return flow may exist down to  $\sim 12$  Mm. Deeper down, the supergranulation loses its coherence, and below 25 Mm it does not exist anymore. The depth of the loss of correlation in large-scale horizontal flows coincides with the layer where supergranules as a strong pattern should be formed.

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