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Probing Surface Flows and Magnetic Activity with Time-Distance Helioseismology

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Abstract. We estimate near-surface flows using the techniques of f-mode time-distance helioseismology together with MDI/SOHO data. (1) Synoptic maps of horizontal flows are obtained for 1996, 1998 and 1999. Rotation, torsional oscillations and meridional circulation are measured. We detect weak large-scale flows converging toward active regions. Travel times are found to be shorter at locations of high magnetic activity. In addition, we measure the motion of the supergranulation pattern. (2) Realistic travel-time sensitivity kernels are used in an iterative deconvolution to infer horizontal flows at a high spatial resolution. The radial outflow outside a sunspot penumbra, called the moat, is measured.

1. Synoptic Maps

Duvall & Gizon (2000) have recently described how time-distance helioseismology with f modes can be used as a tool to probe horizontal flows in the 2 Mm beneath the photosphere. Here, we repeat the same analysis for an extended set of MDI full-disk Dopplergrams covering the Dynamics runs of 1996, 1998 and 1999 (2-3 months each year). A region of size $90^\circ \times 90^\circ$ is tracked for 24 hr at the Carrington rotation rate. This operation is repeated periodically to decrease the Carrington longitude at image center by 12° at each step. For each 8-hr data cube, travel-time differences between surface waves propagating in opposite directions are measured (East-West, South-North). In addition, we measure the mean (isotropic) travel time and the divergence signal (In-out). The average travel distance used in this study is 8 Mm. Travel-time maps are then interpolated onto a latitude-longitude grid (0.24° resolution) and averaged together to form synoptic images. This procedure implies an effective temporal average of 7.5 days at a given Carrington longitude. We translate travel-time differences into velocities using the earlier calibration of Duvall & Gizon (2000).

The longitudinal averages of the zonal and meridional components of velocity are found to vary from year to year. We detect the so-called torsional

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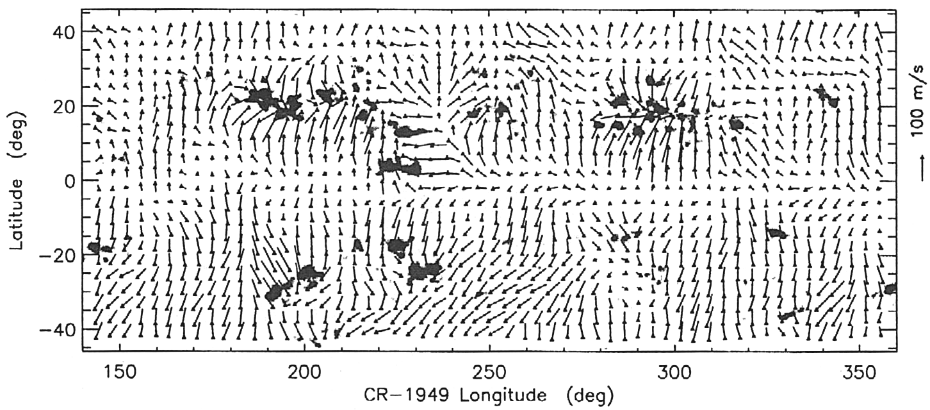

Figure 1. Horizontal flow map obtained for part of rotation 1949 (in 1999) after substraction of a smooth rotation background. Arrows are plotted every 3.84°. Mean travel times shorter than average (dark shade, up to 3% relative change) are associated with magnetic activity.

oscillation and find very good agreement with earlier results (Schou 1999). We observe that poleward meridional motion is not a monotonic function of latitude during periods of high activity. In 1998 (resp. 1999) meridional circulation reaches a local maximum at latitude 20° (resp. 16°). Other studies reveal a similar behaviour (Giles 1999; Meunier 1999).

Figure 1 shows an example of a vector flow map. We detect a large-scale converging flow (~ 50 m/s) around active regions. These new observations may be consistent with claims by Howard (1996) that plages drift toward the average latitude of activity; but do not seem to agree with observations by Ambroz (1993). These flows around active regions contribute to the aforementioned details in the mean meridional circulation. More work needs to be done to interpret mean travel-time anomalies, which are related to magnetic perturbations and enhanced frequency-dependent damping.

Besides the subsurface motion of the solar plasma, we can also estimate the motion of the supergranulation pattern. It is derived from the temporal evolution of the divergence maps, using a correlation tracking method (dt=8hr, FWHM=3.8°). Supergranulation rotation is found to be about 25 nHz higher (equator) than the rotation of the solar plasma; although the torsional oscillation is present with the same phase and amplitude (see also Beck & Schou 2000). A more puzzling result is that we find no clear evidence for poleward meridional circulation of the supergranulation pattern.

2. High-Resolution Tomography

We also studied a series of Dopplergrams obtained on 6 Dec 1998 in the MDI high-resolution field of view. In order to resolve flows on a scale comparable or even smaller than the horizontal wavelength (5 Mm for a 3 mHz f mode), one must have a wave-based interpretation of travel-time anomalies. Gizon, Duvall

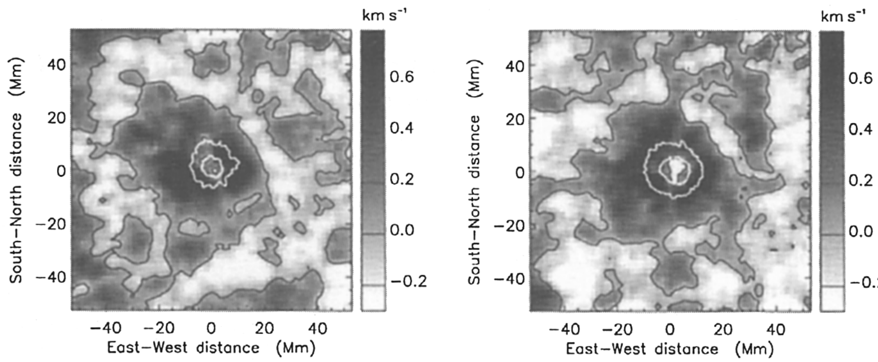

Figure 2. Radial component of the flow measured from the center of two different sunspots, obtained by inversion of f-mode travel times (8 hr of MDI HiRes data). Maps have a spatial resolution of 1.64 Mm. Thin lines indicate contours of zero radial velocity.

& Larsen (2000) have recently computed 2-D travel-time sensitivity kernels for horizontal flows which take into account finite-frequency effects, wave attenuation, and random sources of wave excitation. The two horizontal components of the flow can then be obtained by inverting the data using a regularized iterative LSQR algorithm (Gizon et al. 2000).

We have calculated sub-surface horizontal flow maps around two sunspots. Figure 2 displays the inferred radial flows measured from the center of the sunspots. Both sunspots are found to be surrounded by moat flows, with values peaking at the outer edge of the penumbra ($\sim$ 600 m/s). Moat flows have a fairly well defined boundary, despite azimuthal variations. They seem to be surrounded by a counter flow, suggesting a downflow at the moat boundary. In the penumbra, the sub-surface outflow is found to be much smaller than the Evershed flow observed in Dopplergrams. The Evershed effect may therefore be a very shallow phenomenon, as suggested by current theories (see e.g. Schlichenmaier, Jahn, & Schmidt 1998).

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