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TIME-DISTANCE HELIOSEISMOLOGY AND THE SOLAR ORBITER MISSION

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ABSTRACT

The latest theoretical and observational results in time-distance helioseismology are presented. We mention some of the scientific questions to be addressed by the Solar Orbiter mission by means of time-distance helioseismology. We finally list basic instrumental requirements.

Key words: helioseismology: time-distance; instruments: Solar Orbiter.

1. TIME-DISTANCE HELIOSEISMOLOGY

With the advent of helioseismology from space, our knowledge of the solar interior has made considerable progress. The Michelson Doppler Imager (Scherrer et al., 1995) onboard the ESA/NASA satellite SOHO has provided helioseismic data of extreme precision. Thanks to global helioseismology, large-scale differential rotation has been mapped in most of the convection zone, and small temporal variations in the zonal flows beneath the Sun's surface have been detected as the present activity cycle unfolds. There have been unexpected and still controversial discoveries, such as a buried jet-like flow and a surprisingly slow rotation rate at high latitudes.

To complement techniques of global seismology, which have no resolution in longitude and are unable to distinguish the northern from the southern hemisphere, recent techniques of local helioseismology are being developed. The aim of time-distance helioseismology (Duvall et al., 1993, 1997) is to produce 3D tomographic maps of the subphotospheric temperature inhomogeneities, magnetic field and flows. This technique gives information about travel-times for wavepackets moving between any two points on the solar surface. Travel-times are determined from the cross-correlation function of the oscillation signal (Figure 1). Some of the main results concern flows and wave-speed perturbations below sunspots (Duvall et al., 1996; Kosovichev et al., 2000), large-scale subsurface poleward flows (Giles et al., 1997; Giles, 2000) and supergranular flows (Duvall & Gizon, 2000). We list below a few of the more recent theoretical and observational advances.

The forward problem of time-distance helioseismology is to compute the sensitivity of travel-time perturbations to local perturbations in a reference solar model, i.e. sensitivity kernels. Recently Jensen et al. (2000) and Birch & Kosovichev (2000) computed wave-based kernels in the single source approximation, where waves at one point are assumed to have been generated by a causal source at the other point. Gizon & Birch (2001) argue in these proceedings that travel-time sensitivity kernels must include two essential ingredients: (i) a physical description of the wavefield generated by distributed random sources and (ii) the details of the travel-time measurement procedure. An example of a kernel computed along these lines is shown in Figure 2. The inverse problem, i.e. using travel-times to learn about how the Sun differs from a model, is a separate issue. Techniques for the 3D inversion of time-distance data have been developed by Kosovichev (1996) and Jensen et al. (1998). There have also been advances on the observational side which would simplify the inversions. In a commonly used scheme the travel-time is measured between a central point and a set of surrounding annuli. These measurements are mostly sensitive to a region close to the central point. Duvall has implemented a different averaging scheme which would enhance the sensitivity at a target location in the solar interior, by considering all rays which intersect at that location (deep-focusing).

Zhao et al. (2001) employed a ray-based regularized least-squares inversion of p-mode travel-times to infer mass flows around a sunspot below the solar surface. Powerful converging and downward directed flows are detected below the sunspot at a depth of 1.5 to 5 Mm, which may provide observational evidence for downdrafts and vortex flows suggested for a cluster model of sunspots (Parker, 1979). Strong outflows which extend more than 30 Mm are found

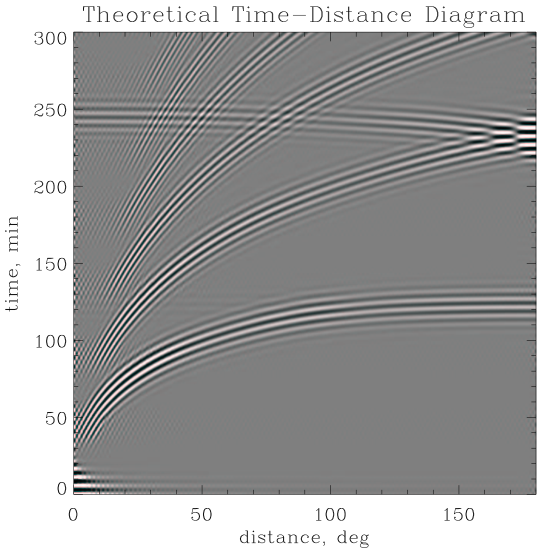

Figure 1. The theoretical cross-correlation function for p modes as a function of delay time and distance between any two points on the solar surface (Kosovichev et al., 2000). The first ridge corresponds to waves propagating in between the two points without additional reflection from the solar surface. The next ridge corresponds to waves which arrive after one reflection from the surface, and the ridges at greater time delays result from waves arriving after multiple reflections. The backward branch associated with the second ridge corresponds to waves reflected on the far side of the Sun.

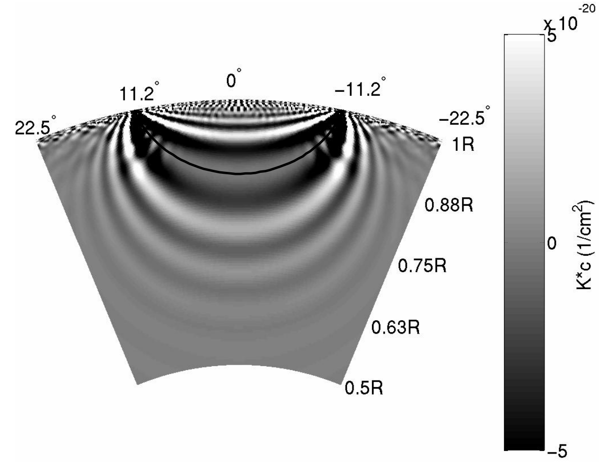

Figure 2. Example of a kernel for the sensitivity of mean travel-time to sound-speed perturbations. The computation uses 4000 coupled normal modes with a realistic Gaussian power spectrum centered at 3.2 *mHz. Acoustic waves are excited by random sources distributed near the surface. The black line connecting the two surface points is the geometrical ray path. Computed by A.C. Birch. See Gizon & Birch (2001) for details.*

below the downward and converging flows. The sunspot is a relatively shallow phenomenon with a depth of 5-6 Mm. A strong mass flow across the sunspot is found at a depth of 9–12 Mm, which may provide further evidence in support of the cluster model as opposed to the monolithic sunspot model. In a complementary study, Gizon et al. (2000) used f modes to probe sunspot flows in the first 2 Mm beneath the surface. The two horizontal components of the flow around several sunspots were obtained by inverting the travel-time data using a regularized iterative LSQR algorithm. 2D wave-based sensitivity kernels were used in the inversion. The sunspots are surrounded by moat flows, with outward velocities peaking at the outer edge of the penumbra. Moat flows have a fairly well defined boundary, despite azimuthal variations. There is a counter flow at the moat boundary, suggesting the existence of a downflow around the moat. In the penumbra, the subsurface outflow is much smaller than the surface Evershed flow observed in Dopplergrams. The Evershed effect may therefore be a very shallow phenomenon, as suggested by observations (Rimmele, 1995) and current theories (Schlichenmaier et al., 1998).

Gizon et al. (2001) used an extensive set of MDI full disk Dopplergrams covering the dynamics runs for 1996, 1998 and 1999 (two months each year). Travel-time data for the f mode were averaged together to form Carrington flow maps. The procedure implies an effective temporal average of 7.5 days at a given Carrington longitude. The longitudinal averages of the zonal and meridional components of velocity vary from year to year. The so-called torsional oscillation was measured and a very good agreement was found with earlier results (Schou, 1999). Poleward meridional motion was not a monotonic function of latitude during periods of high activity. In 1998 (1999) meridional circulation reached a local maximum at latitude 20° (16°). This is consistent with the time-distance observations of Giles (2000). Figure 3 shows an example of a vector flow map for 1999. A 50 m/s large-scale converging flow can be seen around active regions. These new observations may be consistent with claims by Howard (1996) that plages drift toward the average latitude of activity. The flows around active regions contribute to the above mentioned details in the meridional circulation, and produce a longitudinal modulation in the torsional oscillation.

Besides the subsurface motion of the solar plasma, Gizon et al. (2001) also estimate the motion of the supergranulation pattern. It was derived from the temporal evolution of the divergence maps (Figure 4) using a correlation tracking method. Supergranulation rotation is found to be about 25 nHz higher, at the equator, than the rotation of the solar plasma. The torsional oscillation is present with the same phase and amplitude as the torsional oscillation of the material flow. A puzzling result is that only a very weak poleward meridional circulation of the supergranulation pattern is observed. Another original result that can be extracted from f-mode flow maps concerns the influence of the Coriolis force on the supergranulation flow (Duvall & Gizon, 2000).

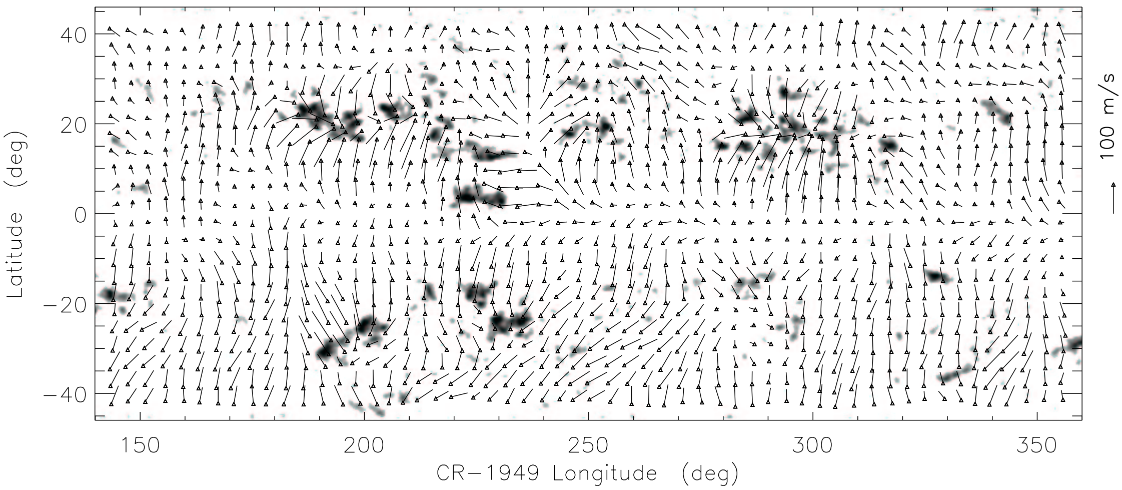

Figure 3. Near-surface horizontal flow map obtained for part of Carrington rotation 1949 after subtraction of a smooth rotation background (Gizon et al., 2001). Arrows are plotted every $3.84°$. *Mean travel-times shorter than average (dark shade) are associated with magnetic activity. One can easily see the poleward meridional flow, as well as large-scale flows converging towards active regions. The data are averaged over 7.5 days at each given Carrington longitude.*

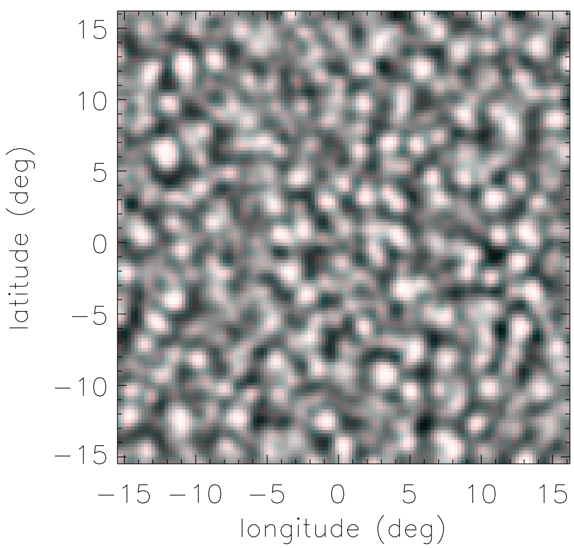

Figure 4. Map of the horizontal divergence of the flow field in the 2 *Mm beneath the surface (Duvall & Gizon, 2000). The data are averaged over* 8.5 *hours. White shades indicate outflow. Supergranulation is clearly visible.*

2. SCIENTIFIC OBJECTIVES

Investigation of the internal structure and dynamics of the polar regions of the Sun is extremely important for understanding the mechanisms of the solar cycle. There are strong empirical indications that the magnetic properties of the polar regions at solar minimum determine the strength of the forthcoming solar maximum. The first indication of this kind was established by Ohl & Ohl (1979) and Simon (1979). They found that the value of the geomagnetic aa index at its minimum was related to the sunspot number during the ensuing maximum. At solar minima this geomagnetic index mostly depends on the solar wind from the polar regions. This means that a new sunspot cycle is started in the polar regions. Schatten (1998) used this idea to make a correct prediction of the current solar cycle from direct measurements of the polar magnetic field. He called this the solar dynamo amplitude index method. However, how the solar dynamo actually operates is not understood. Studying the internal properties of the polar regions will help to solve the puzzle of the solar cycle as well as understand how the solar dynamo works and how other stars generate magnetic fields.

The polar regions are very dynamical. There is evidence that the differential rotation near the poles may vary on a short scale (Ye & Livingston, 1998). Birch & Kosovichev (1998b) have found evidence for significant variation of the subsurface high-latitude rotation with the solar cycle. Therefore, mapping the internal flows near the poles will increase our understanding of the mechanism of the differential rotation and its role in the global circulation of the Sun. Various dynamic phenomena in the polar regions of the solar atmosphere and corona also show close connection to the solar cycle, e.g. the "rush" of Hα filaments to the poles near the periods of magnetic polarity reversals and sudden increases of coronal temperature during these periods (Altrock, 1998). However, there is no basic understanding of how these variations are related to each other and to the internal dynamo processes. Therefore, studying the polar regions of the Sun is fundamental to one of the main questions of solar physics and astrophysics: how and why does the Sun vary?

The Solar Orbiter offers a unique opportunity to learn about the polar regions of the Sun, which remain largely unexplored. The main objective will be to map the flows near the poles using time-distance

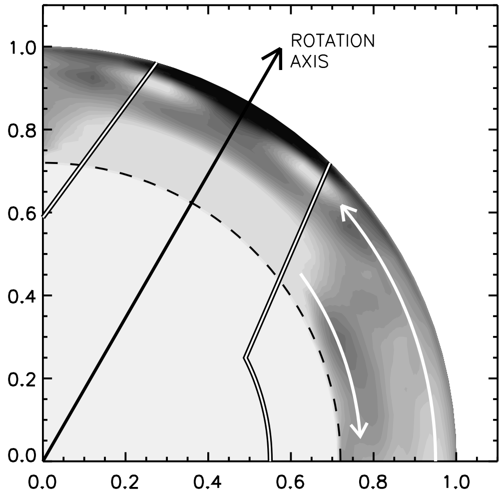

Figure 5. A sketch of flows in the solar convection zone. The black/white shades indicate the difference between the local angular velocity (Schou et al., 1998) and a smooth depth-independent background. White is faster than average and black slower than average. Uncertainties are large in the polar regions beyond the double line. Note the slow near-surface rotation at high latitudes (Birch & Kosovichev, 1998a) and the jet stream at latitude 75°. *Meridional circulation, indicated by the white arrows, is only known in the first half of the convection zone (Giles, 2000) and is not known at high latitudes.*

helioseismology (see Figure 5). The advection of magnetic flux by polar flows is indeed an important aspect of modern dynamo theories (e.g. Charbonneau & Dikpati, 2000). It will be possible to infer the rotation rate in the upper convection zone, and confirm or refute the existence of the high-speed jet at latitude 75°. We will study the convergence at the pole of the meridional flow, and observe how and where the solar plasma dives back into the Sun. Note that ring-diagram observations by Haber et al. (2000) suggest that meridional circulation may reverse sign at high latitudes and develop a two-cell structure. It will be of great interest to monitor the temporal evolution of the flows over the 5 years covered by the mission. Supergranulation, which is not understood yet, will also be studied. For instance, we will measure the size of supergranules at very high latitudes. Figure 4 demonstrates that only a few hours of observations are necessary to make time-distance measurements of supergranulation. A more challenging project would be to probe the tachocline, the shear layer at the base of the convection zone, where the solar dynamo is presumed to be at work. There is some indication in today's data that the depth of the tachocline may be smaller at high latitude.

Another very interesting aspect of the Solar Orbiter mission is the possibility to observe active regions from a co-rotating vantage point. This will help in time-distance studies which focus on the emergence, evolution and decay of active regions (Kosovichev et al., 2000).

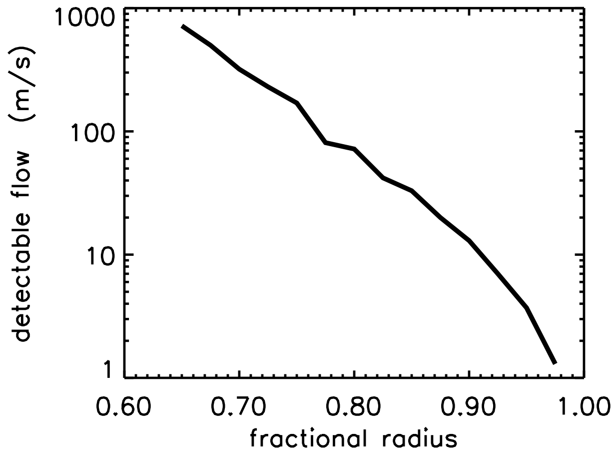

Figure 6. Estimate of the flow perturbation detectable in one rotation as a function of target depth, for a spatial resolution $10° \times 12°$. *This estimate is derived from the rms velocity of deep-focusing travel-time maps (Duvall).*

3. MISSION REQUIREMENTS

The Visible-Light Imager and Magnetometer (Marsch et al., 2000) onboard the Solar Orbiter will provide high-resolution images of the line-of-sight velocity at the solar surface. In order to assess the science that can be extracted from these data by means of local helioseismology, one needs to take into consideration the field of view, the temporal and spatial resolutions, the observation duration, and the overall quality, durability and continuity of the data.

Travel-times are sensitive to inhomogeneities in the vicinity of the geometrical ray path connecting two surface locations. The maximum depth that can be reached is a function of separation distance. Distances greater than 45° are required in order to probe the base of the convection zone. The complete solar disk must therefore appear in the field of view.

A cadence of one image per minute is the norm in helioseismology. Even though traveling waves can be seen at frequencies even higher than 8.33 mHz, there is no obvious need for a better sampling rate. A spatial resolution d on the Sun's surface gives access to spherical harmonic degrees up to $l = \pi R_\odot / d$. No better resolution than 0.9 Mm is required since there is very little mode power beyond $l = 2500$. Waves with the highest degrees do contain information about near-surface convection. However, for most applications of local helioseismology, only waves with degrees up to $l = 1500$ are needed, i.e. $d = 1.5$ Mm. Wavepackets with central harmonic degree $l = 1000$ are commonly used in studies of supergranulation. Lower degrees are essential as we probe deeper into the Sun, but high-l modes remain important in evaluating the surface contribution to the total travel-time perturbations.

The level at which a buried localized perturbation is detectable depends on the depth, size and type of the perturbation, and on the observation duration. Duvall recently made an estimate of the magnitude for which a flow perturbation can be detected in one solar rotation, as a function of depth in the solar interior. He constructed maps of travel-time differences with a resolution of $10^\circ \times 12^\circ$ using rays that intersect at various target depths (deep-focusing technique). The standard deviation of the inferred velocity values gives an estimate of the "noise" level (Figure 6). With a week of continuous observations it should be possible to obtain valuable estimates of the flow field in the upper half of the convection zone. It might however be very challenging to see down to the bottom of the convection zone: more temporal (several orbits) and spatial averaging will be required.

Systematic errors in helioseismic analyses can be introduced by imperfections in the Dopplergrams. Bush et al. (2001) stress the importance of making extensive ground tests in order to understand the behavior of the instrument, and later include calibration details such as focus changes, plate scale, detector misalignment, and point-spread function. The effect of thermal variations on the Visible-Light Imager will need to be addressed very carefully. The available telemetry is a limiting factor. A lot can be learned from the MDI observing program so as to maximize the science that can be done (Bush et al., 2001). Onboard image processing, i.e. binning, will be adapted to the science objectives.

In order to make progress in our understanding of solar activity and variability, helioseismic data will need to be combined with other measurements, especially measurements of the magnetic field (Solanki, 2001). Finally, it is important to keep in mind that local diagnostics of the solar interior, which include time-distance helioseismology, holography and ring diagrams, are still under development today and are likely to be significantly more advanced ten years from now.

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