RECENT RESULTS AND THEORETICAL ADVANCES IN LOCAL HELIOSEISMOLOGY

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ABSTRACT

Local helioseismology is being used to study a variety of solar phenomena, including active regions, supergranulation, meridional circulation, torsional oscillations, solar rotation, and giant cell convection.

Key words: local helioseismology; sun

1. INTRODUCTION

Local helioseismology, loosely defined as any problem that cannot be attacked with first-order global-mode techniques, is rapidly growing. Some of its problems would seem very global in nature, as *e.g.* the axisymmetric meridional circulation, which through an accident of symmetry is not readily studied with global modes. Subsurface meridional circulation has recently been detected in the outer 4% of the radius with the time-distance technique (Giles et al. 1997), and its existence subsequently confirmed with ring diagrams (Schou & Bogart 1998, González Hernández et al. 1998). Local helioseismology has been slow to develop, as it was just not obvious how to proceed to solve the problems. A variety of techniques has been tried, as compiled in Table 1.

2. RING DIAGRAMS

It was Gough & Toomre (1983) who first showed how a $k-\omega$ spectrum (k is the horizontal wavenumber and ω the temporal frequency) computed over a local region would be affected by convection in this neighborhood. Their idea of measuring frequency shifts of the ridges of power was first tested observationally by Hill et al. (1983), and with further development became what is now known as ring diagram analysis (Hill 1988, Patrón et al. 1997). The important ideas here are that the frequencies of the ridges of power in a $k-\omega$ spectrum are determined (at least partly) by the advection and thermal properties in the local environment. A similar idea was pursued in the study of sunspots (Thomas et al. 1982).

3. FOURIER-HANKEL DECOMPOSITION

An important idea was introduced to local helioseismology by Braun et al. (1987), the idea that it was not necessary to observe inside the target feature (sunspot), but that an annular region outside the spot could be studied to gain knowledge of the spot. In this case, the problem is reduced to an analogy with a scattering problem in quantum mechanics. Using the Fourier-Hankel decomposition, the ingoing and outgoing waves from the scattering center are separated, and then compared at similar values of k, ω, and the azimuthal order m.

In the original work (Braun et al. 1987), it was shown that the amplitudes of the outgoing waves were smaller than the ingoing waves, suggesting that the sunspot absorbed waves. Later work showed that sunspots shifted the phase of outgoing waves with respect to the ingoing waves (Braun et al. 1992), consistent with a higher wave speed below the spots compared to the quiet sun. In further analogy to more traditional scattering problems, off-diagonal elements of the S-matrix have been estimated (Braun 1995), corresponding to mode mixing from one p-mode ridge to the adjacent ones at constant ω. Bogdan & Braun (1995) suggest that mode conversion of p-modes to magneto-atmospheric waves may be the physical mechanism responsible for the observational results. Bogdan et al. (1998) do an interesting comparison between this method and the time-distance method in the neighborhood of sunspots.

4. TIME-DISTANCE HELIOSEISMOLOGY

Duvall et al. (1993) first demonstrated that the travel time for waves to traverse subsurface ray paths could be measured. An example of some near-surface rays is shown in Figure 1. The shape of the ray paths can mostly be understood from the increase of sound speed with depth, which causes a wave to refract away from the vertical until it is reflected at the depth at which the horizontal phase speed equals the local sound speed. The key to the travel time measurement was the realization that the cross correlation of the signals at the two endpoints should contain a signature of the travel time. Because we do not have an infinite bandwidth and the travel time depends on frequency (Jefferies et al. 1994, D'Silva 1998), the

Table 1. Different techniques used for local helioseismology, along with some references. Not all of the techniques are currently active.

Technique	References
time-distance	Duvall et al. (1993), Duvall et al. (1997), Kosovichev & Duvall (1997)
ring diagrams	Hill (1988), Patrón et al. (1997), Schou & Bogart (1998)
acoustic imaging	Chang et al. (1997), Chen et al. (1998), Chou et al. (1998)
helioseismic holography	Lindsey & Braun (1990), Lindsey & Braun (1997), Lindsey & Braun (1998)
Fourier-Hankel decomposition	Braun et al. (1987), Braun (1995), Bogdan et al. (1998)
Hilbert transforms	Gough et al. (1991), Gough et al. (1992), Julien et al. (1995)
back-side imaging	Lindsey & Braun (1990), Peri & Libbrecht (1991)
sunquakes	Brown et al. (1992), Kosovichev & Zharkova (1998), Goode et al. (1998)

signature is not a delta function, but looks like a Gabor wavelet. In Figure 2 is shown an example of the cross correlation function versus the great-circle distance between the two points (Δ) and the time.

If there is a subsurface inhomogeneity along the ray path, *e.g.* a hotter region than normal, to first order the ray path stays the same, but the travel time is reduced. There would be a corresponding shift in the cross correlation function. If there is a flow with a component in the direction of the ray path, the travel time measured in the direction of the flow is reduced, while the measurement of waves travelling in the opposite direction yields an increased travel time. So flows can be distinguished from temperature inhomogeneities by taking the difference and average of travel times measured in the two directions connecting two points.

A magnetic field also affects the wave speed (Kosovichev & Duvall 1997), with both an isotropic component and a component that is different for travel in the direction of the field and perpendicular to the field. This anisotropic wave speed, which has not been detected yet, may be the only way to unambiguously ascertain that there are magnetic fields in the solar interior. As shown by Zweibel & Gough (1995), an acoustic perturbation can be constructed that would show the same signature as a magnetic field when looking at global mode frequencies.

The measurement of this anisotropic wave speed with time-distance helioseismology is much more difficult than the measurements of flows or temperature effects, as we are no longer computing the cross correlation at the end points of a single ray, but must look at rays that intersect at some subsurface point. However, if one considers just two rays that intersect at a subsurface target point, it is possible to make an acoustic perturbation that would mimic a magnetic field located at the subsurface point. One might argue that with complete coverage of the surface this could not be done, but it is not obvious. Possibly a better way to approach this problem would be to try to create an example of a subsurface field that would give a unique signature at the surface that could not be easily mimicked by an acoustic perturbation.

Once one measures travel times between many different locations on the solar surface, it is possible using the ray theory to construct 3-D tomographic maps of flows and wave speed perturbations in the interior (Kosovichev 1996, Kosovichev & Duvall 1997, Duvall et al. 1997). With such a technique, it is possible to study convective flow of supergranular scale and also active region formation and evolution.

One hypothesis is that supergranules would be a cellular convective motion that would show a countercell, that is, at some depth the flow would be opposite to the horizontal flow at the surface. One way to check this hypothesis is to take the horizontal velocity at the surface determined by the tomographic inversion and cross correlate it with the horizontal velocity at depth. This was done for the inversions presented in Duvall et al. (1997) with the results shown in Figure 3. In this figure, we see that the correlation falls off away from the surface, until it falls to zero at a depth of 5 Mm. At lower depths it becomes negative, the hypothesized indicator of a counter cell. At 8 Mm depth, the correlation returns to near-zero values. This would suggest that the depth of the supergranular layer is 8 Mm.

In addition to the exciting meridional flow detection (Giles et al. 1997, Giles & Duvall 1998), it has also been possible to study the torsional oscillations first detected at the surface by Howard & LaBonte (1980), and first seen helioseismically using global-mode analysis of the f mode by Kosovichev & Schou (1997). Using the time-distance method, Giles et al. (1998) have detected the torsional oscillations. An advantage of using this method is that it is possible to measure the flow in the north and south separately, while the global modes are only sensitive to the mean of north and south. They found small differences between north and south, although the flow is predominately symmetric about the equator. That

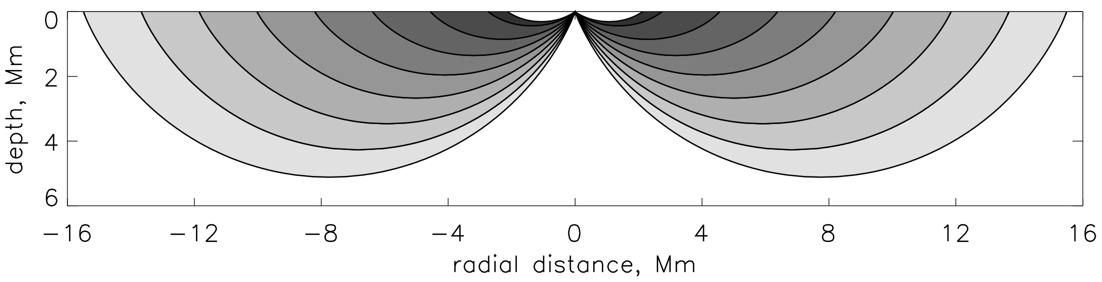

Figure 1. Some shallow rays below the solar surface

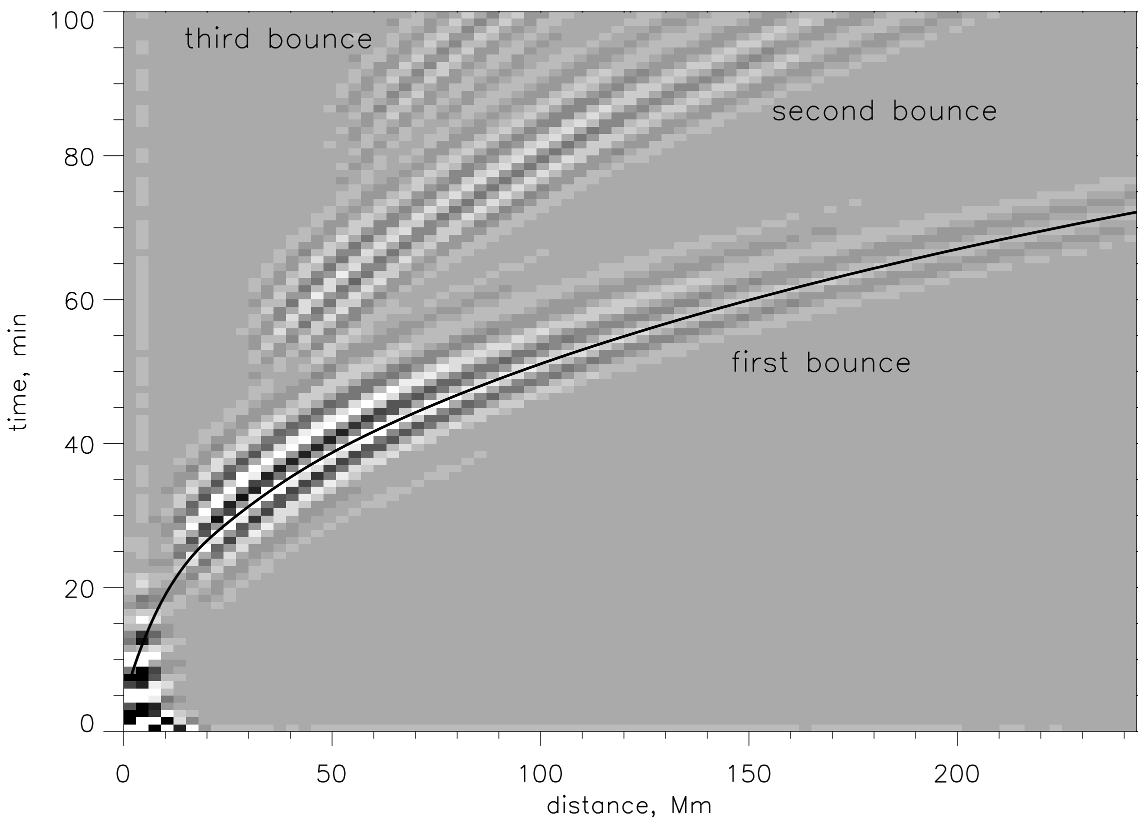

Figure 2. The average cross correlation function for different point separations and different time lags. Also shown is a theoretically calculated curve of travel time.

a ±25m/s meridional flow has been detected with local helioseismology is remarkable, while that a ±5m/s zonal flow has been detected was completely unexpected (by this author). Giles et al. (1998) have extended the earlier meridional flow measurements to a depth of 10% of the solar radius. It appears that near $r/R = 0.93$ that the poleward flow reverses direction.

Although the global mode measurements of solar rotation with depth and latitude are very good (Schou et al. 1998), it is useful to have an independent measure. It is also useful to have a check on the validity of the time-distance technique, which is not as mature as the global mode technique. The time-distance technique can also reveal differences between the north and south which the global mode method cannot.

D'Silva (1996) calculated travel times in the presence of rotation. Duvall et al. (1998) detected solar rotation from time-distance analysis, although the time interval analyzed was too short to make significant conclusions. Giles & Duvall (1998) find rotation near the surface to be within 1% of the surface rotation obtained by Ulrich et al. (1988). They also find that the southern hemisphere is rotating faster, with the

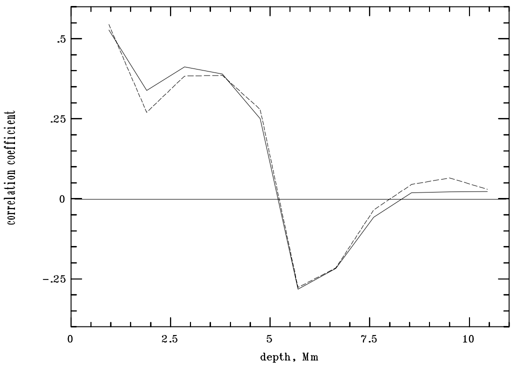

Figure 3. Correlation coefficient versus depth of the second layer. The horizontal velocities (separately for the two components) at the surface are correlated with the same component at depth. The two curves correspond to the east-west and north-south velocity components.

difference maximum at the latitude 60 deg of $\approx 1\%$. Giles et al. (1998) present the first time-distance rotation inversions. The inversions cover the outer 10% of the radius. They also find the southern hemisphere rotating faster with twice as much data as the earlier study.

5. ACOUSTIC IMAGING

This is possibly the newest technique of local helioseismology (Chang et al. (1997)). The basic idea is to reconstruct the acoustic signal at a subsurface point from the signal measured at the surface. This is done through an analogy with a phased-array imaging system. The signal at a point on the surface is considered a source of waves that propagates according to a time-distance relation (Figure 2). For travel between surface points, a measured time-distance curve can be used, while for subsurface points a calculated one is necessary.

By using a "lens" which is an annulus at the surface, it has been possible to simulate the signal at a surface point and then to compare it with the measured value (Chou et al. 1998). A correlation of 0.68 between the simulated and measured signal was found. This confirms that the basic idea is sound.

It is possible to reconstruct the signal at a subsurface target point from the waves going into the point, that is, from earlier data. Likewise, it is possible to use the outgoing waves by essentially propagating them backwards in time. These two signals are useful in the case of an absorber (or emitter), as the ingoing waves have not interacted with the target point, while the outgoing ones have. The well-known absorption near sunspots has been confirmed (Chang et al. 1997, Chou et al. 1998).

Chen et al. (1998) have compared the phase of the ingoing and outgoing signals, which is sensitive to the wave speed in the neighborhood of the target point. Faster propagation below sunspots was found, superficially consistent with the results of Fourier-Hankel decomposition (Braun et al. 1992) and time-distance helioseismology (Duvall et al. 1996).

It would seem possible to get information about flows by reconstructing the signal at a subsurface target point from ingoing waves over only a part of the annulus, say the eastern part, and comparing this to the reconstruction from outgoing waves going to the western part of the annulus. The phase difference between these two signals, when compared to the counter-propagating phase difference, should carry information about flows.

6. HELIOSEISMIC HOLOGRAPHY

An independent effort to reconstruct the acoustic signals below the surface has been developed (Lindsey & Braun 1990, Lindsey & Braun 1997, Lindsey & Braun 1998), and called helioseismic holography. The connection to optical holography has been difficult for some to grasp, and possibly acoustic imaging would be a better name to describe the technique. Lindsey & Braun (1997) approach the problem from two perspectives, a space-time and a spectral one. In the space-time perspective, subsurface signals are generated by propagating signals from the surface, in a similar way to the acoustic imaging described above, possibly with a different weighting function. In the spectral perspective, the coefficients of an eigenfunction expansion of the waves is measured at the surface. To evaluate the acoustic signal at depth, the radial part of the eigenfunction is evaluated at a different radius.

Absorption below sunspots has also been seen with this technique (Lindsey & Braun 1998), and in addition a more diffuse absorption possibly spatially coincident with the plage surrounding the spot, has been labeled the acoustic moat. The method has been extended to be sensitive to flows. Lindsey et al. (1996) see outflows around active regions, in apparent contradiction to the time-distance results of Duvall et al. (1996) and Kosovichev (1996).

7. SUNQUAKES

Although time-distance helioseismology is somewhat similar to terrestrial seismology, a better analogy would be isolated sources, similar to earthquakes. That solar flares might provide such impulsive sources was realized very early in the subject (Wolff 1972). The first attempts to detect the helioseismic response to a flare were probably unsuccessful (Haber et al. 1988, Haber et al. 1988, Braun & Duvall 1990). The recent detection of the signal from a flare by Kosovichev & Zharkova 1998 has opened up the possibilities of studying both flares and the solar interior.

Another possible isolated source is the near-surface convection (Brown et al. 1992). Goode et al. (1998) believe they have detected isolated convective sources, enabling the study of small near-surface features.

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