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Helioseismology at MPS

L. Gizon*, R. Cameron, J. Jackiewicz, M. Roth, H. Schunker, and T. Stahn

Max-Planck-Institut für Sonnensystemforschung, Katlenburg-Lindau, Germany
**Email:* gizon@mps.mpg.de

Abstract. Research in solar and stellar seismology at the Max Planck Institute for Solar System Research (MPS) is supported by the Junior Research Group "Helio- and Asteroseismology" of the Max Planck Society since September 2005. A presentation of the current topics of research is given, with particular emphasis on local helioseismology.

1 Research outline

Millions of modes of vibration, excited by turbulent convection, enable solar physicists to see inside the Sun, just as geophysicists can probe the internal structure of the Earth using records of seismic activity. Over the past twenty years, helioseismology has produced a considerable number of discoveries in solar, stellar, and fundamental physics. The best is still to come, however: three-dimensional helioseismic techniques offer unique prospects for probing complex magnetohydrodynamical processes and uncovering the mechanism of the solar cycle, while the extension of seismic investigations to distant stars will open a new era of observational stellar research.

Methods of helioseismology can be divided into two classes: global and local. The more traditional technique of global helioseismology consists of measuring the frequencies of the modes of oscillation and searching for a seismic solar model whose oscillation frequencies match the observed ones. This reveals the Sun's large-scale structure and rotation as a function of depth and latitude. To complement global helioseismology, new methods of local helioseismology are being developed to make three-dimensional images of the solar interior. The basic idea is to retrieve information at depth from the time it takes for solar waves to travel between any two surface locations.

Global helioseismology has provided by far the most precise tests for the theory of stellar structure and evolution, implying, in particular, a revision of the standard model of particle physics to solve the solar neutrino problem. Today, the most exciting aspect of helioseismology is the search for clues regarding the origin and variability of the Sun's magnetic field, possibly the most important unsolved problem in solar physics. The general belief is that a dynamo process is responsible for the solar magnetic cycle. According to this scenario, magnetic field lines are stretched and twisted by internal shearing motions. Therefore, it is essential to map internal mass motions, structural asphericities, and their temporal variations. Global helioseismology has already provided some fundamental results, revealing regions of rotational shear in the Sun's interior, solar-cycle variations in the rotation rate, and mysterious quasi-periodic changes at the base of the convection zone.

The next advances are expected to come from local helioseismology (Gizon & Birch 2005; Gizon 2006a), which, although still a young science, has already pinpointed a mechanism for the latitudinal transport of the magnetic flux that could determine the period of the solar cycle. Detailed 3D maps of the upper convection zone provide new insights into the structure, evolution and organization of active regions and convective flows. In yet another application, local helioseismology can be used to construct maps of active regions on the far side of the Sun. These few examples illustrate the richness of the science possible with local helioseismology. In all these cases a taste of the possibilities has been provided, but better data and further developments in the technique are required to realize the full potential.

An important technological step for helioseismology will come with the HMI instrument on the Solar Dynamics Observatory of NASA to be launched in 2008. With a high spatial resolution over the entire visible solar hemisphere, HMI is the first instrument specifically designed for local helioseismology. Later, in about one decade, ESA's Solar Orbiter should give access, for the first time, to the subsurface structure and dynamics of the Sun's polar regions. With these new observations, the need for improvements in solar modeling will come. In particular, theoretical studies and numerical simulations will be required to understand wave propagation in strongly magnetized fluids, a necessary condition for the application of local helioseismology to solar active regions. Local helioseismology is very much under development today and promises many more discoveries. Among the most ambitious goals is to directly image the magnetic field in the solar interior.

Asteroseismology, the study of global oscillations on distant stars, is entering a very exciting period of discoveries. Many stars, covering a wide range of masses and evolutionary states, are known to exhibit oscillations. Only in the last few years, however, has it been possible to detect oscillations on Sun-like stars using sophisticated spectrographs on large ground-based telescopes. Stellar oscillations have considerable diagnostic potential and allow stellar mass and age to be determined with unprecedented precision. Such knowledge for a sufficient sample of stars will revolutionize stellar evolution and galactic evolution studies. Asteroseismology has also the potential to constrain internal stellar rotation and locate the borders of convection and ionization zones. Such information would help understand dynamo-generated stellar activity cycles and the solar-stellar connection.

These exciting possibilities for the study of stellar structure, evolution, and activity will be fully realized only once observations become available for a large sample of stars. The precision on the frequencies of the global modes of stellar oscillations, however, is very much limited by available telescope time, which is why dedicated space telescopes are an attractive solution to provide long-term coverage of many types of pulsating stars. High precision photometry from space is expected in 2006 with the launch of COROT of CNES in 2006. The field of asteroseismology will make much progress in the following decades with more ambitious missions like NASA's Kepler and possibly ESA's Eddington. As in the case of helioseismology, there is a strong need to improve our understanding of the oscillations and how they interact with the magnetohydrodynamical processes in stars.

Research in solar and stellar seismology at the Max Planck Institute for Solar System Research (MPS) is supported by the Junior Research Group "Helio- and Asteroseismology" of the Max Planck Society since September 2005. A general presentation of the current topics of research is given below, with particular emphasis on local helioseismology.

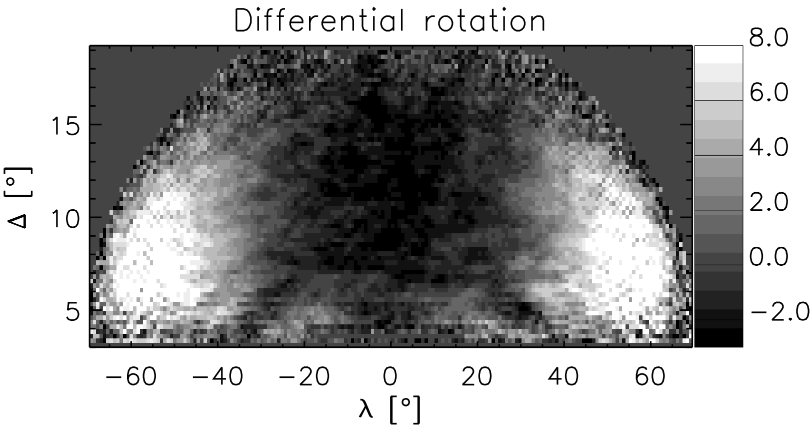

Figure 1. Difference in travel time measured in the west-east direction (travel time for westward propagating acoustic waves minus eastward propagating waves) as a function of horizontal travel distance and latitude. The travel times are measured in a frame that co-rotates with the Sun at the Carrington rotation rate. The latitudinal variation is due to solar differential rotation (faster at the equator than at high latitudes).

2 Measurements of travel times from the MDI Structure Program

Time-distance helioseismology consists of analyzing the travel times of acoustic wave packets that propagate through the solar interior. Flows inside the Sun break the travel-time symmetry between waves propagating in opposite directions. In order to achieve high-precision measurements of flows deep in the solar convection zone, it is important to analyze long, nearly-continuous time series of solar oscillations. We used an extensive set of velocity maps recorded by the Michelson Doppler Imager during the period 1996-2003 (MDI-SOHO Structure Program). A critical step in the data analysis is to extract the seismic travel times from the data. Travel times are determined from the correlation function of the Doppler velocity computed between any two points on the Sun's surface. Two different measurement techniques have been implemented and compared for robustness to solar noise. Figure 1 shows travel-time differences in the west-east direction as a function of horizontal travel distance and latitude. Here the travel-time shifts are caused by solar differential rotation. These measurements suggest that near-surface rotation can be infered with a precision close to 1 m/s using one month of data.

3 Solar-cycle variation of rotation and meridional circulation

The temporal variations of rotation and meridional circulation have a long-term component with a period near eleven years. These small solar-cycle variations of a few m/s are believed to be a manifestation of the evolution of the large-scale magnetic field. We have made helioseismic observations of the solar-cycle variation of flows near the solar surface and at a depth of about 60 Mm, in the latitude range ±45°.

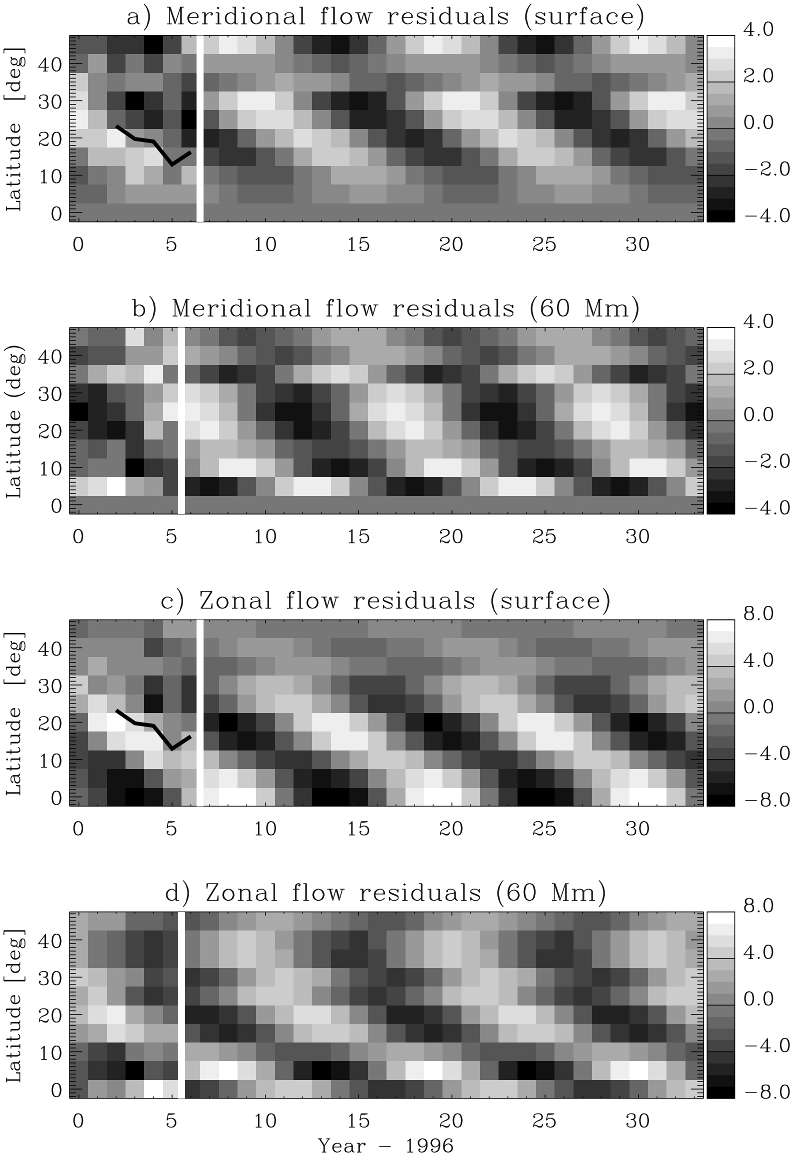

Figure 2. Time-varying components of the meridional (a,b) and zonal (c,d) flows as a function of time. Panels a and c are for the near solar surface, while panels b and d are for a depth of about 60 Mm below the surface. The black lines in panels a and c show the mean latitude of active regions. The eleven-year periodic component of the data is extrapolated into the future beyond the white vertical lines.

Acoustic ray bundles that penetrate deep inside the Sun connect surface locations that are separated by large distances. A depth of 60 Mm corresponds to a travel distance of about 17°. To a first approximation, rotation and meridional circulation at this depth can be estimated

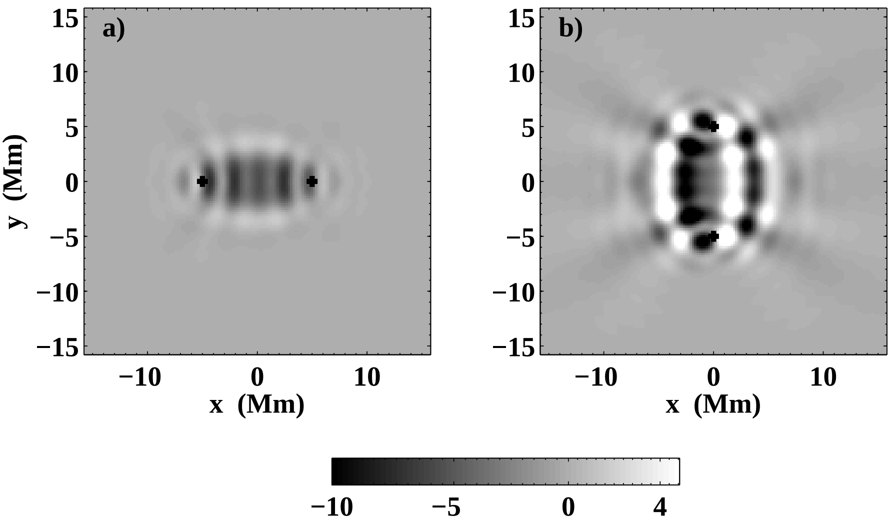

Figure 3. Two-dimensional travel-time sensitivity kernels for flows. This case is for a patch of the Sun 60° towards the west limb on the equator. Each kernel gives the sensitivity of travel-time differences to flows for waves traveling in opposite directions between the two photospheric observation points, which are given by the crosses. (a) Sensitivity kernel for flows traveling in the +x direction. (b) Sensitivity kernel for flows in the +y direction. The units of the kernels are s $(\mathrm{km/s})^{-1}$ Mm^{-2}.

directly from the travel-time differences in the east-west and north-south directions (Sect. 2). For the near-surface layers, we used f-mode time-distance helioseismology to obtain every 12 hour a map of the convection pattern. The near-surface plasma flow is estimated from the advection of the convection pattern according to the method of Gizon et al. (2003).

Figure 2 summarizes the results. The time-varying components of the meridional flow at these two depths have opposite sign, while the time-varying components of the zonal flow are in phase. We investigated a theoretical model based on a flux-transport dynamo combined with a geostrophic flow caused by increased radiative loss in the active region belt. The model and the data are in qualitative agreement, although the amplitude of the solar-cycle variation of the meridional flow at 60 Mm appears to be underestimated by the model. See Gizon & Rempel (2007).

4 High-resolution local helioseismology

We are interested in studying the near-suface flows on the Sun, in particular supergranulation and the flows around active regions, using f-mode time-distance helioseismology. The f modes propagate horizontally in the top 2 Mm of the convection zone. Determining horizontal flows accurately and with a high spatial resolution (less than the f-mode wavelength of $\approx$ 5 Mm) requires two main steps. The first step, called forward modeling, is used to derive an integral relationship between travel-time measurements and internal flows. This relationship is provided by travel-time sensitivity kernels. The second step is to then use the

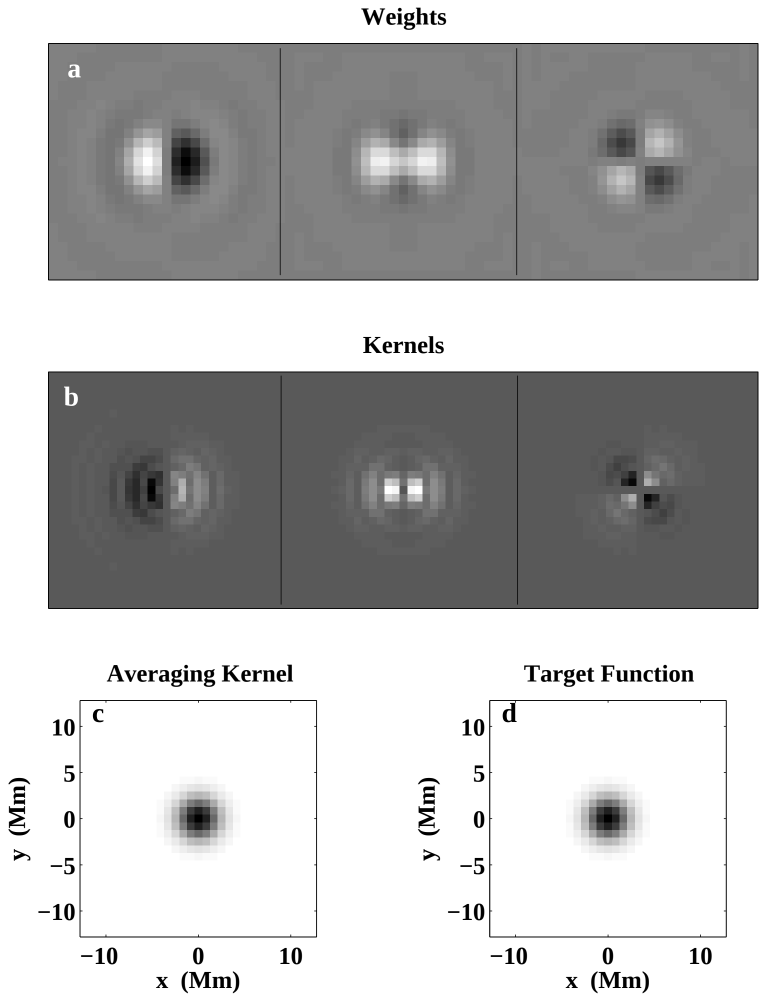

Figure 4. OLA inversion of f-mode travel times. (a) Inversion coefficients (b) Travel-time sensitivity kernels (quadrant averaging scheme). The inversion coefficients are convolved with the kernels to give the averaging kernel of panel (c). The averaging kernel matches the target function (d) well.

sensitivity kernels, along with the travel-time measurements, to infer the underlying flows. This last step is called an inversion.

We have calculated f-mode kernels for flows in the first Born approximation, which is a single-scattering approximation. Figure 3 shows examples of 2D kernels which give the sensitivity of f-mode travel-time differences to localized horizontal flows on the solar surface. The travel times are measured between two individual points on the solar surface. In general, the kernels depend on the position on the solar disk through the line-of-sight vector. We note that it is customary to average travel times (and kernels) over quadrants of arc in the east, west, south and north directions to reduce noise. See Jackiewicz et al. (2006a,b).

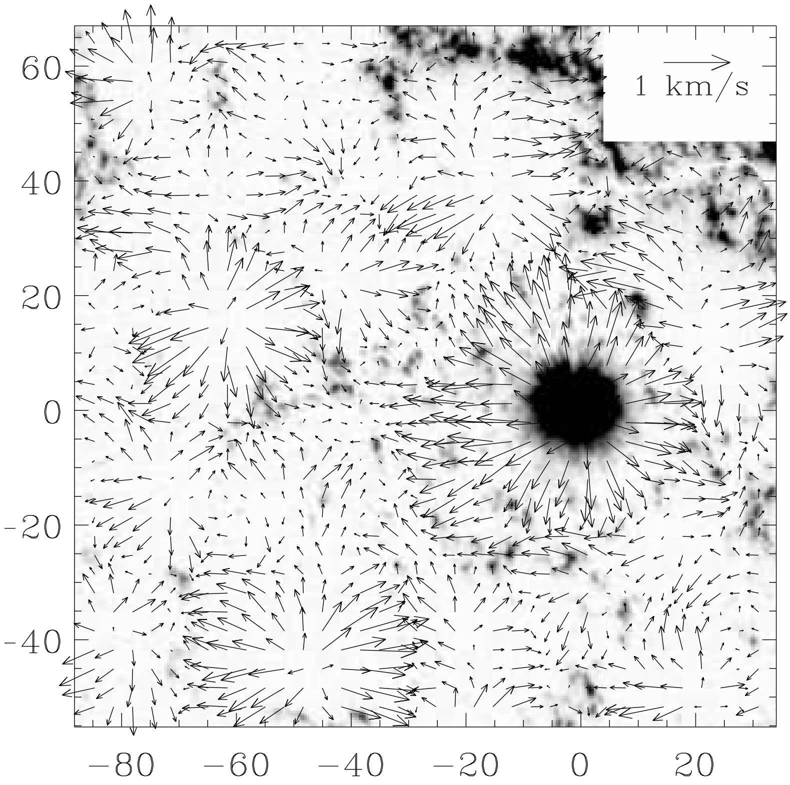

Figure 5. Map of horizontal flows around a sunspot at a depth of 1 Mm below the surface. Flow velocities are obtained by inverting f-mode travel times (quadrant averaging). The outflow around the sunspot, with an amplitude of about 500 m/s, is called the moat. Spatial coordinates are given in units of Mm.

The most important part of the inversion procedure is to determine a set of weights which average the measurements in some way and return the value of the local flow. In our case, the weights are found in a two-dimensional Optimally Localized Averaging (OLA) scheme, whereby one seeks a linear combination of the sensitivity kernels (an averaging kernel) that resemble a Gaussian target function. It is not always desirable to have the averaging kernel and the target function match exactly, since doing this may cause large measurement errors to propagate through the inversion. Therefore, one needs to consider a satisfactory resolution along with a permissible amount of error, which can be chosen by adjusting a trade-off parameter. In Fig. 4 we show results for an inversion. Our choice of trade-off parameter is such that the resolution is quite good, the weights are smooth, and the averaging kernel and target match well. Figure 5 gives an idea of the spatial resolution that can be achieved with only 8 hr of data. Both supergranular flows and the moat flow outside a sunspot are resolved (even though the inversion was not quite optimal in this particular case).

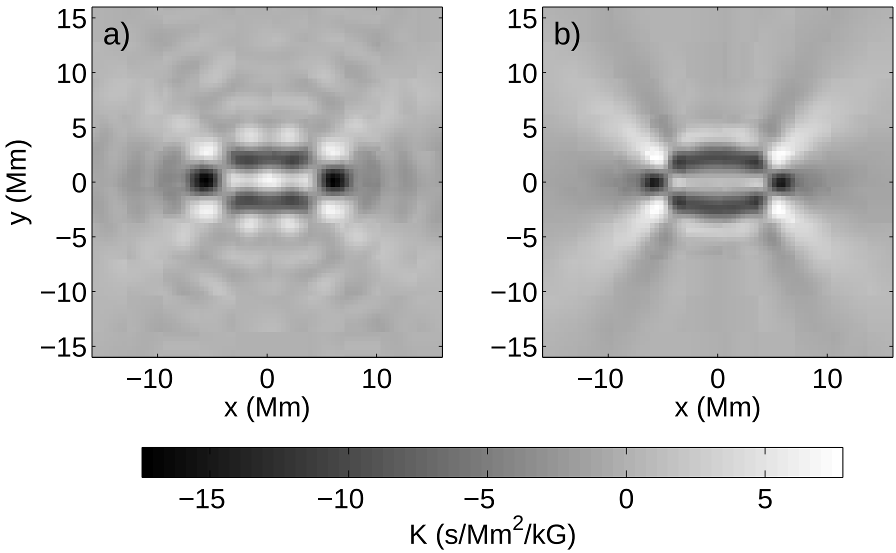

Figure 6. Sensitivity of solar surface-wave travel times to small magnetic features. (a) Observations based on MDI data from the high-resolution field of view. A magnetic feature at position (x, y) causes a shift in the travel time measured between the two observation points (at $x = \pm 4.95$ Mm, $y = 0$). As magnetic features have a finite spatial extent, we applied a simple regularized deconvolution. The grey scale gives the shift in travel time due to a 1 kG magnetic field covering 1 Mm^2. (b) Phenomenological model for a point magnetic scatterer based on single-scattering theory. A scatterer located anywhere along an ellipse (with foci at the observation points) causes travel-time shifts of the same sign, giving rise to Fresnel zones. The hyperbolic features are due to the scattering of waves generated by distant sources.

5 Travel-time shifts caused by small magnetic features

The solar surface magnetic field is dragged by convective motions into concentrations that form the quiet-Sun magnetic network. Because these magnetic features are smaller than the wavelengths of solar oscillations, they are ideal to study the response of finite-wavelength seismic travel times to point-like perturbations.

We used time-distance helioseismology to directly measure the spatial sensitivity of f-mode travel times to a point-like magnetic perturbation. Travel-time maps reveal that the sensitivity is not restricted to the geometrical ray path, is spread on elliptical and hyperbolic curves, and oscillatory (Fig. 6a). We find that these geometrical features are mostly due to finite wavelength effects and to the fact that the sources of excitation of solar oscillations are distributed over the whole solar surface. To reach this conclusion, we developed a simple phenomenological model to explain the travel-time observations. We assumed that scattering from a magnetic feature can be described by a combination of monopole and dipole scattering. Treating solar surface-gravity waves (f modes) as deep water waves, we computed the wave field using a single-scattering approximation, and then adjusted the complex scattering amplitudes to obtain the best match with the observations (Fig. 6b). We find that the dipole and monopole contributions are equally important.

By studying the interaction of seismic waves with localised magnetic features on the Sun, we have provided an observational confirmation of the basic banana-doughnut theory originally developed for finite-wavelength tomography of the Earth, according to which body-wave travel times are sensitive to the wave speed in a broad region surrounding the geometrical ray path. This is the first test outside the laboratory showing the relevance of scattering theory to cross-correlation travel times (laboratory tests exist for ultrasonic waves). As in Earth seismology, we suggest that finite-wavelength modeling will be essential in revealing deep structures in the solar interior. See Duvall et al. (2006).

6 Line profiles of fundamental modes of solar oscillations

We have studied the asymmetry of f-mode line profiles in the power spectrum of solar oscillations, which have received less attention than for acoustic modes (p modes). Line asymmetry is interesting as it contains information about the mechanism of wave excitation.

Using MDI-SOHO data, we find that f-mode line asymmetry is pronounced in the degree range 600-1200 and has opposite signs in velocity and intensity power spectra. One may ask if the mechanism responsible for f-mode line asymmetry can be described in simple physical terms, as is done for p modes. An argument based on wave interference (used to explain p-mode line asymmetry) has little value in the case of f modes, which do not propagate in the vertical direction. Is it at all conceivable that line asymmetry may occur from combinations of exponential wave functions? To investigate this question, we considered the propagation of a surface wave at the interface between two media with different constant densities, forced at a given height by a vertical momentum impulse. We find that, in the limit of a large density discontinuity, line asymmetry can occur when the source is situated above the interface. Although this toy model is not intended to approximate the Sun, it has the merit of demonstrating that line asymmetry can occur even for waves that do not propagate in the vertical direction, such as the f mode. See Gizon (2006b).

7 Modeling wave propagation

7.1 Three-dimensional numerical simulations

The propagation of waves in the near photospheric layers is being studied using numerical simulations, in order to better understand helioseismological observations. The code we have developed follows the linear evolution of perturbations in an inhomogeneous, magnetized atmosphere. We have used a box geometry, a spectral treatment in the horizontal directions, and a finite difference scheme for the vertical direction. The boundary conditions are naturally important. The side boundaries are simple: the box is periodic. For the upper boundary we currently use the condition that the Lagrangian perturbation of the vertical component of the stress tensor vanishes. A practical problem is that the solar atmosphere is superadiabatic beneath the solar photosphere, and so exponentially growing modes are present in the solutions. As we wish to focus on the effects of the convection on the waves, we currently modify the density so that, in the wave simulation, the atmosphere is nowhere unstable. The code is fully three-dimensional. See Cameron & Gizon (2006).

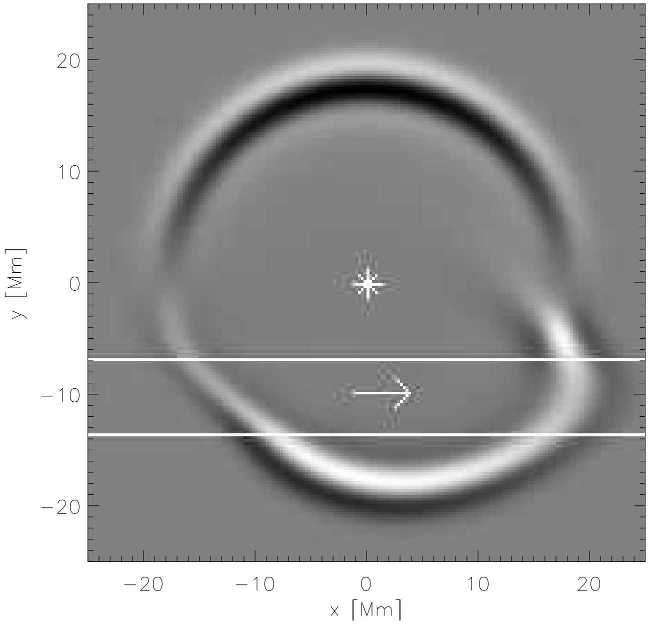

Figure 7. A snapshot from a calculation of an acoustic wave packet propagating across a jet. The background atmosphere has a uniform sound speed of 11 km/s, and is of uniform density and pressure. The two horizontal white lines indicate the presence of a jet flowing from left to right. The jet has a peak amplitude of 10 km/s and has a profile corresponding to one half-cycle of a cosine. The white lines indicate where the velocity has fallen to 5km/s. The source for the wave packet is a displacement in the *y* direction centred on the asterisk.

Many applications are hoped for, in particular to study the interaction of solar waves with sunspots or near-surface convection. The code will certainly be useful to study the effects of strong perturbations. Figure 7 shows the deformation of a wave front as it traverses a 10 km/s jet flow.

7.2 Interaction of acoustic waves with a magnetic cylinder

The interaction of acoustic waves with sunspot magnetic fields is strong in the near surface layers. As a result, the effect of the magnetic field on the travel times is not expected to be small near the surface. Deeper inside the Sun, however, the ratio of the magnetic pressure to the gas pressure becomes small, and it is tempting to treat the effects of the magnetic field on the waves using perturbation theory.

With the aim of studying magnetic effects in time-distance helioseismology, we used the first-order Born approximation to compute the scattering of small amplitude acoustic plane waves by a magnetic cylinder embedded in an otherwise uniform medium. Because this simple problem has a known exact solution for arbitrary magnetic field strengths, we can study the validity of the linearization of the wave field on the square of the magnetic field. We show, by comparison with the exact solution, that travel-time shifts computed in the single-scattering Born approximation are everywhere valid to first order in the ratio of the magnetic to the gas pressures. We conclude that, for typical values of the solar magnetic field, the Born approximation should be good at depths larger than a few hundred km below the photosphere (Gizon et al. 2006). We note that the exact solution can be used to validate the numerical simulation of Section 7.1.

7.3 Acoustics in spherical geometry

Methods of local helioseismolgy are also being tested using numerical simulations of wave propagation in spherical geometry. A setup in spherical geometry is necessary when wavelengths are not small compared to the solar radius. The acoustic wave field is obtained by solving the three-dimensional Euler equations in a general background solar model (no magnetic field). The excitation of the oscillations is modeled by many uncorrelated sources of excitation which are randomly distributed delta functions in a narrow spherical shell close to the solar surface. We are hoping to validate the various methods of helioseismological data analysis with this numerical code. The effect of differential rotation, meridional circulation, sound speed anomalies on the acoustic wave field will be studied. See Hanasoge et al. (2006).

8 Farside imaging

Space weather forecasting is important due to the impact that solar flares have on space weather. Large, complex active regions tend to be the source of strong solar flares which eject charged particles into the solar wind, and directly affect Earth operations. Farside imaging offers up to two weeks notice of active regions rotating to the nearside, providing that the active region is evident at the surface over the full term of its farside tenure. Although there are many short-term predictive tools, the importance of farside imaging is not to be under-estimated.

It is well known that magnetic fields interact with acoustic waves, in particular they absorb their energies and change their travel times in the vicinity of the magnetic field. Phase-sensitive holography is used to calculate the travel time perturbations. Farside imaging is a particular application of phase-sensitive holography (Braun & Lindsey 2001). Given observations of acoustic waves on the front side and for each target point (or focal point) on the far side, two basic computations are done: the ingression and the egression. The egression is a reconstruction of the wave field that has emanated from the focal point at time t based upon the observed Doppler signal in an annular pupil. The ingression is the time reverse of the egression: the wave field in the pupil is propagated forward in time to reconstruct the wave field at the focal point. The correlation between the ingression and the egression gives the phase lag (travel time difference) between waves going into, and waves going out from, the focal point on the Sun's far surface. A time decrease (or negative phase as it is shown on this scale) indicates the presence of a strong surface magnetic field proportional to its strength.

Here we have used GONG+ data to calculate the farside image for November 12, 2003. In Fig. 8, two large active regions are clearly visible as dark patches on the farside: AR 0486 (southern hemisphere) and AR 0488 (northern hemisphere). The optical paths of waves used for farside imaging have single-skip distances in the approximate range 0.8–1.5 rad, with spherical harmonic degree up to 70, which produces a much coarser spatial resolution than

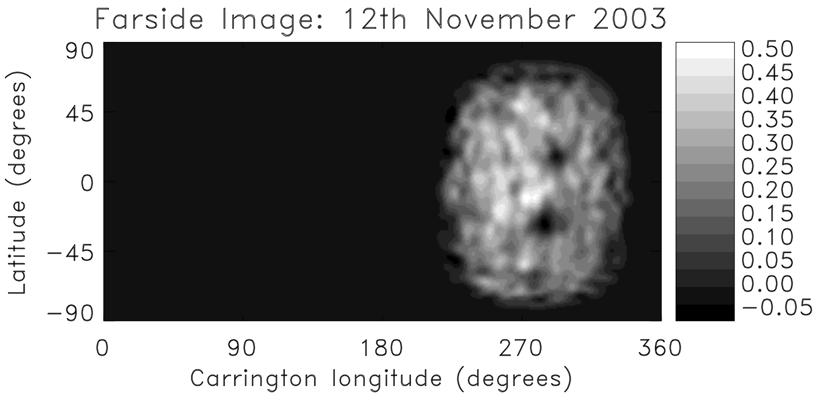

Figure 8. Farside holographic image of the Sun on the 12th November 2003 versus heliographic longitude and latitude. The greyscale gives the phase shift in radians. Two large active regions appear as dark patches on the farside: AR 0486 (southern hemisphere) and AR 0488 (northern hemisphere).

for seismic imaging of the nearside. At a frequency of 3.5 mHz a diffraction limit of about 5° is imposed which is good enough to image significant plage regions. The analysis here uses 2×2 skip holography. Therefore, this farside image is limited to approximately 50° from the antipode of disk centre.

9 Distant stars

9.1 Asteroseismology of K Giants

Radial-velocity measurements of the K Giant α Hydra using the FEROS spectrograph at the 2.2 m MPG/ESA telescope in La Silla, Chile, reveal pulsations periods of 3–4 days (Fig. 9). The main oscillations have periods in good agreement with theoretical expectations. The high-frequency part of the oscillation spectrum, however, is far from being understood. It has been suggested that oscillations in red giants are due to solar-like pulsations excited by turbulent convection. The possibility that all or part of the observed modes could be self-excited Mira-like pulsations is, however, not ruled out. More observational data on K Giants will become available in the next few years to clarify the nature of the oscillations and to provide seismic constraints on the structure of these stars. See Setiawan et al. (2006).

9.2 Analysis of time series of stellar oscillations.

Quantitative asteroseismology requires extremely precise measurements of the frequencies, amplitudes, phases, and lifetimes of the stellar oscillations. The data analysis can be accomplished in the time domain or in Fourier space. In both cases, gaps in the data introduce complications. In the Fourier domain, the signal is convolved by the transformed of the observation window and Fourier amplitudes at different frequencies are correlated. We are

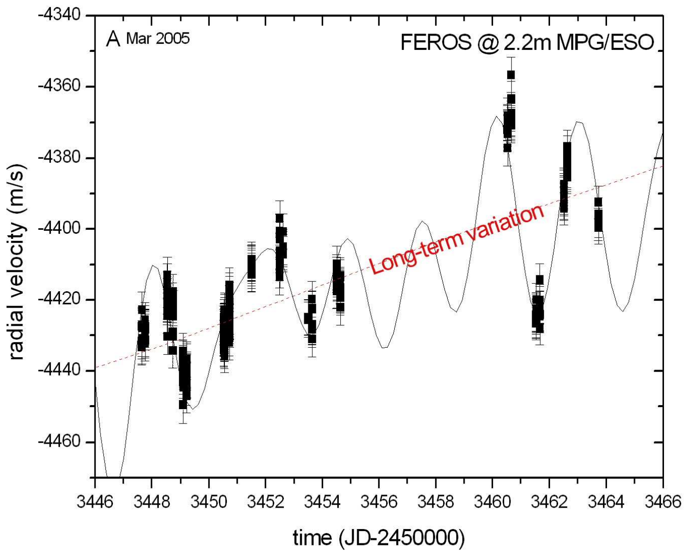

Figure 9. Radial velocity measurements of the K Giant α Hydra recorded during 12 days in March 2005. The solid line gives a fit of 5 superposed sine functions with periods 7.96, 3.6, 2.95, 2.48, and 2.29 days. Besides the periodic behaviour, a long term variation is visible.

developing methods and analysis tools that take into account these correlations. In the case of solar-like oscillations, Monte-Carlo simulations show that our improved fitting method returns less noisy estimates of the line widths and amplitudes of the modes of oscillation. The improvement is less significant for long-lived, deterministic pulsations. Figure 10 shows a fit to a mode triplet in the Fourier domain (only the real part is shown) for a classical pulsator, the pre-white dwarf PG1159-035 (Winget et al. 1991).

10 European network for helio- and asteroseismology

HELAS is a new European network for helio- and asteroseismology, funded by the European Union for the period 2006-2010 (EU Framework Program 6). The MPS is an important component of HELAS (MR is Project Scientist, LG is Chair of the Local Helioseismology Network Activity). The objectives of the Local Helioseismology Network Activity are to (1) coordinate and consolidate European research activities in the field of local helioseismology, exchange knowledge and share experiences; (2) identify areas for which common actions are desirable; (3) promote the exchange of data for tests, comparisons, and analysis; (4) coordinate the process of developing common software tools; (5) facilitate the preparation for the SDO and Solar Orbiter missions. Three workshops are planned and one large conference will be organized in Göttingen in 2007.

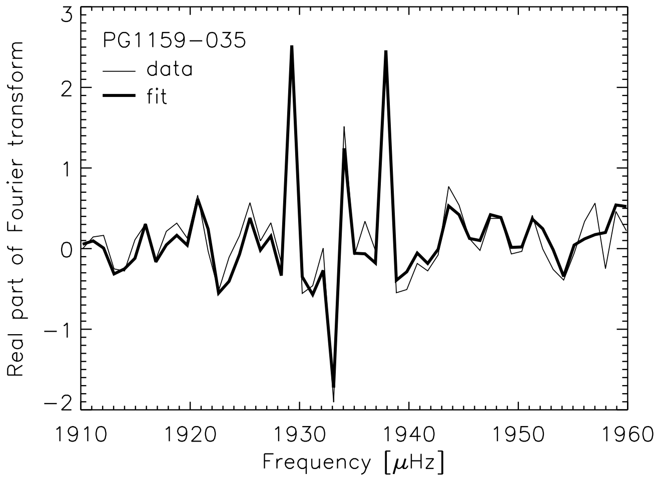

Figure 10. Section of the Fourier spectrum of PG1159-035 around the strongest dipole triplet near 1937 μHz. The thin line is the real part of the Fourier transform of the data, the thick is the fit. Most of the variations away from the peaks is due to the convolution by the window function. Although it is not shown here, the imaginary part is fitted together with the real part.

Acknowledgements. The research presented in this paper is the result of work done in collaboration with others, including J. G. Beck, A. C. Birch, D. C. Braun, T. L. Duvall, S. Hanasoge, C. Lindsey, M. Rempel, and J. Setiawan.

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