Current Issues in Helioseismology

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Abstract. Helioseismology is a powerful tool for studying the solar interior. Some of the important current issues in helioseismology are: the detection of g-modes, the development of models for the dynamics and structure of the solar interior, and the observation and modeling of wave propagation in active regions. I will highlight some important aspects of these problems and discuss prospects for future work in helioseismology.

1. Introduction
There are many open questions regarding physical conditions in the solar interior, including for example: what is the subsurface nature of active regions and sunspots? what are the structure and dynamics of the solar interior? Answering these, and related questions, will provide constraints on theories of active regions, stellar dynamos, and also provide tests for models of stellar structure. Helioseismology, the use of solar oscillations as probes of interior conditions, is a powerful tool for working towards answers to these, and many other, questions.

In this paper I will provide a very brief introduction to methods of helioseismology (§2), review some of the current issues (§3), and discuss prospects for the future of the field (§4).

2. Introduction to Helioseismology
The quiet Sun supports oscillations of three general classes: acoustic modes modified by gravity (p-modes), surface-gravity modes (f-modes), and internal gravity modes (g-modes). For a recent detailed discussion of solar oscillations see e.g. [1] (for stellar oscillations in general see e.g. [2]). Of these classes of modes, p- and f-modes are routinely observed. The detection of g-modes is a current topic of intense interest, e.g. [3, 4, 5].

Helioseismology has traditionally been divided into two subfields: global helioseismology, in which the resonant frequencies of global oscillation modes are used to infer longitudinal averages of structure and flows in the solar interior, and local helioseismology, in which measurements of local wave propagation properties are used to constrain three-dimensional models of solar structure and dynamics.

2.1. Observations for Helioseismology
Observations for helioseismology typically consist of time-series of Dopplergrams (maps of line-of-sight velocity) or maps of intensity at the solar surface (an exception is Sun-as-a-star measurements which do not have any spatial resolution, e.g. [6]). Currently, much of the commonly used helioseismic data are from the MDI/SOHO [7], GONG [8], GOLF/SOHO [9],
VIRGO/SOHO [6], and BISON, e.g. [10], experiments. For a discussion of future prospects for instruments for helioseismology see [11].

The length of the time series which are employed range from two hours for some time-distance work (e.g. [12]) to decades for the detection of oscillation modes with small amplitudes (e.g. [13, 5]). The spatial extent of the maps can range from a small fraction of the solar disk to full-disk maps depending the oscillation modes of interest and the science targets. Typically, local helioseismic analysis is carried out on observations that have been tracked to remove the main effects of rotation.

2.2. Global Helioseismology

Global helioseismology is based on the measurement and interpretation of the frequencies of the normal modes of the Sun. For a recent, and vastly more detailed, review see [1]. The typical data analysis procedure in global helioseismology begins with time-series of full-disk, or nearly full-disk, measurements of the intensity or Doppler velocity.

The first step of the data analysis is typically to project each map onto spherical harmonics $Y_{\ell,m}(\theta, \psi)$ where $\ell$ is the angular degree, $m$ the azimuthal order, $\theta$ the co-latitude, and $\psi$ the longitude. This results in a time series $\phi_{\ell,m}(t)$ for each $(\ell, m)$. Typical global helioseismology studies use $\ell$ up to 300, though some studies have used $\ell$ up to 900 or higher (e.g. [14]). The next step consists of fitting, in the temporal Fourier domain, these time-series to obtain estimates for the resonant frequencies of the Sun, $\omega_{nm}$, which depend on a radial order $n$ as well as the angular degree and azimuthal order (for examples see [15, 16, 17, 18, 19, 20] and references therein).

The frequencies $\omega_{nm}$ can be used to infer models of the structure and flows in the solar interior. This is typically achieved through linear inversion (for a recent review see [1]). Typical targets for these inversions are estimates of spherically symmetric solar structure (e.g. recently [21, 22]), azimuthal and north-south averages of rotation (e.g. recently [23, 24, 25]), and the longitudinal average of solar structure (e.g. [26]).

2.3. Local Helioseismology

Local helioseismology is based on the measurement of local wave propagation properties. In this section I will give a short introduction to the mostly commonly employed methods: time-distance helioseismology (§2.3.1), helioseismic holography (§2.3.2), and ring diagrams (§2.3.3). For a comprehensive and recent review of local helioseismology see [27]. As described in §2.1, local helioseismic analysis typically begins with time series of Dopplergrams or intensity images.

2.3.1. Time-Distance Helioseismology

Time-distance helioseismology [28] is a method for measuring the time required for waves to propagate between pairs of points on the solar surface. Typically, time-distance analysis begins by filtering the data to isolate the particular oscillation modes of interest. For a data cube (i.e. time series of images), $\phi(\mathbf{r}, t)$, where $\mathbf{r}$ is the two-dimensional position vector on the solar surface and $t$ is time, filtering consists of multiplying the three-dimensional Fourier transform of $\phi$ by a filter function,

$$\phi_T(k, \omega) = F(k, \omega) \phi(k, \omega),$$

where $\phi_T$ is the filtered data cube in the Fourier domain, $\mathbf{k}$ is the horizontal wavevector, $\omega$ is the temporal frequency, and $F$ is the filter function. The role of the filter is to select the particular modes of interest, in some cases this also results in substantial improvement in the signal-to-noise ratio [29].

The next step in a typical analysis is to compute the cross-covariance of the filtered data

$$C(\mathbf{r}_1, \mathbf{r}_2, t) = \int \phi_T(\mathbf{r}_1, t') \phi_T(\mathbf{r}_2, t' + t) dt'.$$
where \( C(r_1, r_2, t) \) is the cross covariance as a function of time lag, \( t \), between points \( r_1 \) and \( r_2 \) on the solar surface. Depending on the goals of any particular study, the cross-covariances can be averaged in a number of geometries. The final step in the data analysis process is to extract wave travel times from the cross-covariances. A number of techniques have been employed to do this. For recent discussions of the relative merits of some of these methods see [12] and [30].

Time-distance travel times have been interpreted in the ray approximation (e.g. [31, 32]), the Fresnel-zone approximation (e.g. [33, 34]), the Rytov approximation ([35] in the context of time-distance helioseismology), and the Born approximation (e.g. [36, 37]). For a recent review see [27].

### 2.3.2. Helioseismic Holography

Helioseismic holography [38, 39] is based on the idea that the wavefield in the solar interior can be estimated using observations at the surface (this idea was also proposed independently by Chang et al. [40]). In practice, Holography is based on the computation of the “egression” and “ingression” [39]. These quantities are both estimates of the wavefield in the solar interior at a target, or “focus”, point. The “egression” is nominally an estimate made using only waves diverging from the target point and “ingression” from waves converging towards the target. The egression, \( H^+ \), and ingression, \( H^- \), are computed as

\[
H^{\pm}(r, z, \omega) = \iint G^{\pm}(r' - r, z, \omega) \phi(r', \omega) \, dr',
\]

(3)

where \( z \) is the depth of the target point. The functions \( G^{\pm} \) are theoretical Green’s functions, \( G \), multiplied by a pupil function, \( P \),

\[
G^{\pm}(r, \omega) = P(r) G^{\pm}(r, \omega).
\]

(4)

The two methods for computing Green’s function are the “eikonal” method [39] and the “wave-mechanical” method [41]. Case studies [41] have shown that holography results are not sensitive to the choice between these two methods for estimating Green’s functions. Pupil functions are chosen based on the particular targets of any particular study and typically selected by ray tracing.

With the ingression and egression in hand, the six quantities that constitute the full suite of holography measurements are the ingression and egression power, the ingression and egression and local control correlations, and the ingression-egression correlation. The egression (ingression) power is an estimate of the wave power seen diverging from (converging towards) the target point. These quantities have been used in studies of the acoustic waves excited by flares (e.g. [42, 43]) and wave excitation in and around active regions (e.g. [44]). The local control correlations are closely related to time-distance cross-covariances and have been used in many of the same applications (recently [45, 46, 47]). The ingression-egression correlations are also very similar to the time-distance cross-covariance and have been used in the studies of subsurface structure (e.g. [48]), flows (e.g. [49, 46]), and far-side active regions [50].

### 2.3.3. Ring Diagrams

Ring diagrams [51] are local power spectra (in \( k-\omega \) space). Measurement of the positions of the ridges in these power spectra provides estimates of the local resonant frequencies, which in turn contain information regarding subsurface conditions, e.g. flows or changes in sound speed. For a detailed review of ring diagrams methods see [27].

Ring diagram measurements begin with a choice of apodization function \( A(r) \) which defines the region over which the local power spectrum is computed. Ring diagrams are typically computed on regions spanning 15° on a side. The ring diagram, \( P(k, \omega) \), is the power spectrum of the apodized wavefield

\[
P(k, \omega) = |\text{FFT3D}[A(r)\phi(r, t)]|^2,
\]

(5)
where FFT3D denotes the three dimensional (two space dimensions plus time) Fast Fourier Transform.

The next step in ring diagram analysis is to fit the local power spectrum, $P$. One technique is to fit on cylinders of constant $k = \|k\|$ [52]. Fitting methods which simultaneously employ a range in $k$ are described by [53] and [54]. In all cases, the result of the fitting is a set of parameters which can be used to infer subsurface conditions.

The details of which parameters are measured from the ring spectra, and the inverse methods, depend somewhat on the physical quantities of interest. As examples: Patron et al. [55], Basu et al. [54], and Haber et al. [56, 57] describe inversions for flows. Basu et al. [58] developed inversions for sound-speed and the first adiabatic exponent, including a phenomenological surface term.

3. Review of Current Issues

In this section I review some current issues in helioseismology. I will first cover global helioseismology (§3.1) and then local helioseismology (§3.2).

3.1. Current Issues in Global Helioseismology

Some of the current issues in global helioseismology are related to: (1) detection of new oscillation modes (§3.1.1), (2) observations over long time series to characterize solar-cycle variations (§3.1.2), and (3) improvements in solar models and modeling capabilities (§3.1.3). I emphasize that the intent of this section is not to present a comprehensive review of the current state of Helioseismology, but only to present some of the current issues.

3.1.1. Detection of New Oscillation Modes

The detection of new oscillation modes is important as each new mode provides a constraint on models of solar structure, magnetic field, and rotation in the solar interior (e.g. recently [59, 60, 61, 62]). There are two main directions of current research: the use of long time series to detect small amplitude p-modes and development of novel data analysis techniques to detect g-modes.

The detection of small-amplitude $p$-modes depends on the use of long time series (e.g. [63]). One important approach is the use of “Hare and Hounds” type exercises [17] to test the data analysis techniques involved in such searches for small-amplitude modes. Chaplin et al. [17] showed that estimates of the rotational splittings for very low degree modes ($\ell = 1, 2, 3$) are somewhat dependent on choices made during different data analysis procedures. This discovery highlights the importance of this type of blind study. Similarly, comparison of mode frequencies obtained from different data sets is an important test of systematic errors (e.g. [58]).

The search for g-modes has been ongoing for decades (see section 3 of [64] for a recent review). Recently, García et al. [5] presented evidence for a series of $\ell = 1$ g-modes (with $n$ ranging from -26 to -1): a series of peaks, equally spaced in period, in GOLF/SOHO data (Fig. 1). In addition, this study suggested that these peaks are split due to rotation and correspond to modes with finite lifetimes. Mathur et al. [60] discussed the importance of these modes for constraining solar models and also suggests observational evidence that the observed g-modes are excited at the base of the convection zone. Further observational work will determine the stability of these first detections.

3.1.2. Solar Cycle Variations

Soares et al. [65] measured the variations of high degree ($100 < \ell < 900$) modes with the solar cycle. This work confirmed that even for high degree modes, the solar cycle variations in the frequencies scaled by mode inertia are functions of frequency alone (rather than both frequency and angular degree). This result shows that the solar cycle frequency shifts are dominated by surface effects. The frequency dependence of the solar-cycle frequency shifts has not been substantially understood and is a promising area for
future work. This frequency dependence also provides a potential opportunity to relate global helioseismic measurements to local measurements (§3.2.1).

Global helioseismology can also be used to study which changes in solar structure and magnetic field are correlated with the observed frequency shifts. Recently, for example, Chaplin et al. [66] studied the variation of normal-mode frequencies using 30 years of data from BiSON. This study found that normal-mode frequencies have a significant response to the weak surface magnetic field (not simply the magnetic field of sunspots).

3.1.3. Models and Modeling Capability Recently, non-helioseismic estimates of the abundances of the most common heavy elements in the photosphere have been updated (in these new estimates, the abundances of the heavy elements are substantially reduced [67, 68, 69]). These new abundances substantially disagree with the abundances that had previously been in agreement with the solar models that in turn are in good agreement with observed normal-mode frequencies (for a review of earlier models see [1]). The numerous attempts to produce solar models which have photospheric abundances in agreement with the recent observations and also normal-mode frequencies in agreement with helioseismic measurements have not been entirely successful (e.g. [22] and references therein). The resolution of this apparent contradiction will represent substantial progress in global helioseismology (or perhaps progress in methods of estimating abundances from photospheric absorption lines, or both).

Another major topic in solar modeling is the inclusion of dynamical effects and magnetic fields in models of solar/stellar evolution (e.g. the DynaMICS Project [64]). One issue for this work is that the internal magnetic field of the Sun is not known, though helioseismology has provided some limits (e.g. [70]). Further work on helioseismic detection of subsurface magnetic fields is needed. Another important ingredient in dynamic solar models (and in flux transport dynamo models as well) is the meridional flow (e.g. [64, 71, 72]). The meridional flow has been measured down to the middle of the convection zone ([73]). However, the meridional flow at the base of the convection zone has not been directly detected, only inferred from mass conservation. Another ingredient is differential rotation, which has been well constrained in much of the solar interior (e.g. [23]). In may be that dynamic solar evolution models are needed to help understand the abundance issue described in the previous paragraph.
3.2. Current Issues in Local Helioseismology

There has been a tremendous amount of progress in local helioseismology in recent years, far more than can be adequately in a short review paper. For a summary of the field as of 2005 see Gizon & Birch [27]. Here I will cover only some current issues related to local helioseismic observations of active regions (§3.2.1) and related theory and modeling efforts (§3.2.2).

3.2.1. Observations of Sunspots and Active Regions

Jackiewicz et al. [74] carried out time-distance measurements and inversions to study subsurface flows. For the one sunspot studied, this study showed a moat flow (see e.g. [75] for a detailed review of flows related to sunspots) that is substantially deeper (and of opposite sign in the near-surface layers) than has traditionally been obtained using time-distance helioseismology (e.g. [76]). Further work is needed to determine the source of this apparent discrepancy.

Braun & Birch [45] studied, using helioseismic holography, the frequency dependence, at fixed horizontal phase-speed, of time-distance travel times in active regions (frequency dependence of travel-times had been reported, though not emphasized, in earlier work [77, 48, 41]). A similar frequency dependence was observed using time-distance by Couvidat et al. [78]. Braun & Birch [46] extended earlier observations by carrying out a more detailed survey of travel-time shifts around active regions and showed that some types of helioseismic holography measurements are quite sensitive to choices regarding the analysis filters. These studies highlight the need for additional modeling efforts (see §3.2.2) to understand the numerous detailed local helioseismic observations of active regions.

The effects of active regions can also be seen in mode frequencies measured by ring diagram analysis. Rabello-Soares et al. [79] used ring diagrams to study the statistical dependence of these frequency shifts on various properties of active regions. This work showed that fractional frequency shifts approximately scale linearly with the Magnetic Activity Index (MAI) of the active regions. In addition, Rabello-Soares et al. [79] showed that these frequency shifts are roughly compatible with the frequency shifts associated with the solar cycle; providing evidence for earlier suggestions (e.g. [48]) that solar-cycle frequency shifts are largely due to the number of active regions on the Sun. Again, modeling efforts will likely be crucial in understanding the physical mechanisms behind these measurements.

A final issue related to the application of local helioseismology to active regions is the possibility of using helioseismic measurements to predict events of significance to space weather (e.g. active region emergence, flaring, or coronal mass ejections). A case study by Komm et al. [80] explored the relationship between the surface magnetic flux of active regions and the enstrophy of subsurface flows as estimated by ring diagram measurements. This work showed that, on average, higher enstrophy is measured in active regions with large total magnetic fluxes. In addition, there are suggestions that the emergence of active regions may be preceded by a change in subsurface flow vorticity. The statistical significance of this result is not known.

3.2.2. Theory and Modeling

Currently, observations of sunspots and active regions (§3.2.1) are far ahead of modeling efforts; there is no existing model of wave propagation through sunspots (or active regions) that has been demonstrated to be consistent with all, or even many, existing observations. Two promising approaches to predicting the helioseismic signatures that would be expected for models of sunspots and active regions are (1) direct numerical simulations, (2) the ray approximation and semi-analytical normal-mode theory.

Numerical simulations of wave propagation promise to efficiently determine if particular models of the sub-surface structure of sunspots are compatible with observations (see e.g. [81, 82] for more detailed discussions). Cameron et al. [82] showed simulations of the propagation of f-modes through three-dimensional (azimuthally-symmetric) model sunspots (Fig. 2). For model sunspots with photospheric magnetic fields that are consistent with observations, the simulated
wave fields compare very favorably with observations of f-mode propagation. The extension of these simulations to p-modes will substantially increase our understanding of helioseismic observations of sunspots.

Numerical simulations have also been used to study the effects of the suppression of wave-sources (as a result of the suppression of convection by the magnetic field) in sunspots [83, 84]. Parchevsky & Kosovichev [83] showed that a complete absence of wave sources in a circular region of the size of a typical sunspot leads to a reduction of acoustic power by up to roughly 40% inside the “sunspot” region (this is about half of the observed reduction). An extension of these simulations to include a (magnetic) model sunspot will be a substantial aid in understanding helioseismic measurements of wave absorption in sunspots (e.g. [85]). Hanasoge et al. [84] showed that the suppression of wave sources inside a sunspot sized region leads to travel-time shifts (relative to quiet Sun) of up to about 15 s, a substantial fraction of observed travel-time shifts. Correction for this type of effect may be important in obtaining accurate estimates of the subsurface structure of sunspots.

Birch et al. [47] showed an analysis of wave propagation, computed using the code of Hanasoge et al. [84], in simple toy models consisting of subsurface sound-speed enhancements. This study showed that shallow (depth scale of 1 Mm) sound-speed perturbations essentially reproduce the observed frequency variation of travel times around sunspots [45, 46]. In addition, in these simple toy models, enhancements in sound-speed were seen, for some choices of data analysis filters, to lead to positive travel-time shifts (in direct contradiction with the ray approximation).

Another current approach to understanding wave propagation in sunspots is the ray approximation (e.g. [31, 32, 86, 87] in the context of sunspot seismology). Recently, Cally & Goossens [88] studied the process of mode conversion from up-going fast modes to up-going Alfvén modes and found that this conversion can in some cases be significant and play a role in explaining observations of wave absorption in sunspots (e.g. [85]). Moradi & Cally [89] applied the ray approximation to estimate the time-distance travel-time shifts that would be expected for
a model sunspot. This work shows that it is now feasible to use ray theory in model sunspots to produce travel-time shifts than can meaningfully compared with observations. Another approach to modeling wave propagation (and helioseismic observations) in sunspots is the semi-analytical normal-mode based approach introduced by Crouch & Cally [90]. This approach has proven able to reproduce many aspects of the Hankel Analysis measured [91, 85] of sunspots [90, 92]. It has, to date, not been applied to model time-distance or helioseismic holography measurements of sunspots.

4. Opportunities

In this section I would like to summarize some of the big opportunities for substantial advances in global and local helioseismology:

The apparent disagreement between non-helioseismic measurements of photospheric heavy element abundances and helioseismic normal-mode frequencies is an exciting opportunity. The resolution of this “crisis” will put solar modeling efforts on an even stronger footing.

Another approach to constraining solar models is the measurement of additional mode frequencies. In particular, additional work on the detection and characterization of solar g-modes promises to provide g-mode frequencies and rotational splittings. These measurements will provide strong constraints on models of structure and rotation in the deep interior.

In local helioseismology, one of the most promising areas for future advances is the use of direct numerical simulations of wave propagation. These simulations promise to help elucidate the basic physics of the interactions of waves with active regions. Simulations can also be used to provide artificial (simulated) data. These artificial data sets can then be subjected to data analysis procedures in order to test the performance (e.g. biases and signal-to-noise ratios) of those procedures. Continuing observational efforts combined with such modeling efforts promise to provide robust pictures of the subsurface nature of active regions.

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