Progress in sunspot helioseismology

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Abstract. Local helioseismology is a set of methods that are used to study wave propagation and infer physical conditions in the solar interior. Sunspots are a particularly challenging target for local helioseismology. In this review, I will show that some new methods (magnetoconvection simulations and numerical wave propagation simulations) lead to shallow sunspot models that are apparently inconsistent with traditional inferences from local helioseismology. In addition, I will show that inferences for the depth structure of moat flows are not in general agreement either.

1. Introduction
Local helioseismology is a collection of methods that are used to study the three dimensional structure and dynamics of the solar interior. All of these methods are based on the interpretation of measurements of solar oscillations. Recent reviews of local helioseismology are given by [1–5].

Sunspots are one of the most challenging targets for local helioseismology. Detailed reviews of this topic were given by [1] and [6]. Here, I will focus on very recent work on this topic. The two main questions about sunspots are the nature of their subsurface structure (i.e. the three-dimensional distribution of sound speed, magnetic field, density, etc.) and the associated subsurface flows. I will first discuss the question of structure (§2) and then review recent work on subsurface flows (§3). In section 4, I will discuss some potential avenues for further progress in the helioseismology of sunspots.

2. Sunspot Structure
As summarized by Figure 1, there is not general consensus regarding the subsurface structure of sunspots. As discussed by Crouch et al. [7], models can be categorized as “deep” models in which significant deviations from quiet-Sun structure extend below a few Mm and “shallow” models where the structure beneath the sunspot is very similar to that of the quiet Sun at depths below a few Mm.

Traditional time-distance helioseismology measurements have led to “deep” models that feature a near-surface layer (surface to roughly 3 Mm depth) with reduced wave speed and a deeper region (roughly 3 to to 15 Mm) of increased wave speed (e.g. [11; 12; 16–18] among many others). Ring-diagram inversions have led to models in which the wave speed is significantly different than the quiet Sun sound speed at depths well below a few Mm (e.g. [19; 20]). Comparisons of time-distance and ring-diagram inversions for the same Active Region using the same input data sets have shown that the two types of inversions can give quite different results [5; 6; 18; 21], with the caveat that the horizontal resolution of the two methods is quite different.
Figure 1. Fractional wave-speed perturbations for a variety of models for the structure of sunspot umbrae. For magnetic models, the wave-speed is taken to be the fast-mode speed. For non-magnetic models the sound speed is shown. The solid red curve shows the phenomenological model of Fan et al. [8] which was a sound-speed model designed to explain the Hankel analysis measurements of [9]. The dashed red curve shows the results of a non-linear inversion for a simplified magnetic model [10], also aimed at explaining the measurements of [9]. The solid green curve is the result of a ring diagram inversion, with the amplitude increased by a factor of ten, as the ring diagram inversion does not have the spatial resolution to isolate the umbra. The solid blue curve shows the result of a traditional time-distance inversion, and is qualitatively similar to what has been seen in other time-distance inversions (e.g. [11; 12]). The dashed blue curve is from the semi-empirical model of [13], other aspects of this model are shown in Figure 2. The black solid line shows the structure from the magnetoconvection simulation of [14]. This is Figure 16 from [5].

Figure 2. Models for the sound-speed (left) and density (right) for the quiet Sun (black) and umbra (blue) for empirical sunspot model of Cameron et al. [13]. The red dashed line in the right-hand panel shows the density from the umbral model of Maltby et al. [25]. In both panels the vertical black (red) dashed lines show optical depth of one in the quiet Sun (umbral) model. In this model, the umbral sound speed and density are indistinguishable from their values in the quiet Sun below a depth of about one Mm. Adapted from Figure 1 from [13].
In the “shallow” models, the near-surface wave speed is enhanced relative to its value in the quiet Sun. Models of this type have been inferred from Hankel analysis [8] and [10], from direct simulation of magnetoconvection in a sunspot-like feature [14], and from magnetic wave propagation simulations [13].

At this point, it is not clear what the sources of the disagreement are. Gizon et al. [5] suggested some possible issues, including among many others: 1) linear forward models (and inversions) may not be capable of capturing the large effect of sunspots on solar oscillations (in some models the perturbations to the wave speed are more than 100% of the quiet Sun sound speed) and 2) traditional forward models do not explicitly include magnetic fields (the effect of the magnetic field is included in a phenomenological sense in a “wave-speed” perturbation).

In addition, it may not be sufficient to describe sunspots simply in terms of a local change in the sound speed, but rather it may be important to include an explicit model for the Wilson depression (this will be discussed in §2.2). In the following subsections, I will review recent work that may be helpful in resolving the apparent incompatibility of the “deep” and “shallow” models.

2.1. radiative transfer effects
Rajaguru et al. [22] presented observations of wave propagation in a sunspot made using different parts (corresponding to different formation heights) of a magnetically sensitive line (Fe I 6173 Å) and a magnetically insensitive line (Fe I 7090 Å). The line cores (wings) are thought to be formed at a height of about 270 km (20 km) above the continuum optical depth of unity ([22] and references therein). They showed that the sunspot supported upward propagating waves at frequencies below the acoustic cutoff frequency (this has been seen before, e.g., [23]). In addition, they showed that the observed travel-time shifts depend on the formation height at which the Doppler velocities are measured. For the case of ingoing waves, the choice of observation height can cause an effect of about 10 s in magnitude, while for outgoing waves the choice of observation height leads to an effect of 40 s (see Fig. 3). Especially for the case of outgoing waves, this can be a large fraction of the total signal (typically about a minute). In addition, they observed differences of up to about 15 s (at 3.5 mHz) between travel times measured in the magnetically sensitive and insensitive lines. This difference between the observations made in magnetically sensitive and insensitive lines is potentially extremely important as current methods of local helioseismology make no attempt at a formal accounting for the radiative transfer that connects plasma motions with the observed Dopplergrams.

2.2. progress in forward modeling
Forward modeling is the process of predicting the local helioseismic observations (e.g., time-distance travel-time shifts) that would be expected to result from a particular model of the solar interior (e.g., a model for the subsurface structure of a sunspot). In the past year there has been progress in not only computing forward models for sunspots, but of finding sunspot models that can largely explain the observed travel-time shifts (and the measured wave absorption as well).

Cameron et al. [13] presented a method for constructing a model sunspot based on standard models for umbrae, penumbrae, and quiet Sun together with a simple self-similar model for the magnetic field. In this model, the fast-mode speed is greatly enhanced due to the magnetic field near the surface and the sunspot looks much like the quiet Sun below a depth of 1 Mm (see Figs. 1 and 2).

Cameron et al. [13] used a series of wave propagation simulations to show that this sunspot model was able to explain, within the observational errors, observations of wave propagation (both phase shifts and amplitude changes) through a sunspot made using MDI data [24]. This work shows one example of a “shallow” sunspot model that appears to be consistent with helioseismic observations. It is important to note that this work does not use observations of solar
Figure 3. Changes in the outgoing travel times as functions of the inclination $\gamma$ of the magnetic field. The change in the travel times is defined as $\delta \tau_{\delta,0}^+ = \tau_{\delta}^+ - \tau_0^+$ where $\tau_{\delta}^+$ is the outgoing travel time measured near the wings of the line (formation height of about 20 km above the photosphere) and $\delta \tau_0$ is the outgoing travel-time shift measured in the core of the line (formation height of about 270 km above the photosphere) at the travel distance of $\Delta = 16.95$ Mm. The open square symbols show travel-time shifts for a magnetically sensitive line (Fe I 6173 Å) and the filled square symbols are for a magnetically insensitive line (Fe I 7090 Å). This is a modified version of Figure 3a from [22].

Figure 4. Phase shifts for wave propagating through the empirical sunspot model of Cameron et al. [13]. The panels show phase-shifts measured from MDI data (filled circles with error bars) and from the numerical wave propagation simulation (solid lines) for the f (left panel), $p_1$ (middle panel), and $p_2$ (right panel) modes. The simulation also reproduces the observed changes in the amplitudes of the waves that propagate through the sunspot. Adapted from Figure 9 from [13].

oscillations inside the penumbra or umbra of the sunspot, but rather is based on measurements of the travel-time shifts and amplitude changes in waves that have traveled through the sunspot. As a result, the potentially complicated radiative transfer in sunspots is not a factor in the observations (though may certainly play a role in the wave propagation).

Lindsey et al. [26] also showed an example of a “shallow” sunspot model. This work was
Figure 5. Comparison of measured and theoretical travel-time shifts for nearly vertically propagating waves incident on a sunspot umbra from below. The observations are shown as filled circles with error bars; the error bars represent the scatter in a sample of two sunspots observed for a few days with the MDI instrument. The heavy curves show the results of finite wavelength forward calculations for the umbral models LRRMC-25 (solid) and GHSE-07 (dashed). The thin curves show the results of ray theory calculations for the same umbral models. The LRRMS-25 model is based on a magnetoconvection simulation carried out using the method of [14]. The GHSE-07 is a modification of LRRMS-25 that was designed to provide a better fit to the observations. This is based on Fig. 11 from [26] and is reproduced by permission of the AAS.

Based on a simple one-dimensional vertical wave propagation calculation aimed at understanding observations of almost vertically propagating waves interacting with sunspot umbrae. In the approximations that 1) the acoustic waves are propagating vertically, 2) the horizontal variations in the sunspot structure are not important, and 3) the magnetic field is vertical, the wave propagation calculation reduces to a simple one-dimensional non-magnetic problem. Lindsey et al. constructed a model umbra “GHSE-07” that produces travel-time shifts that mostly fit the observations. This model does not require an enhancement in the sound speed to explain the travel-time deficit. Rather, the travel times are reduced by the reduction in the path length due to the lower temperature of the umbra. This reduction in path length more than compensates for the reduced sound speed.

Braun et al. [27] compared travel-time shifts measured from MDI observations of sunspots with travel-time shifts measured from a magnetoconvection simulation. Figure 6 shows a comparison of mean (i.e. average of ingoing and outgoing) travel-time shifts averaged over the penumbrae for two different sunspots (one seen in the high-resolution MDI data and one in the MDI full-disk data) with mean travel-time shifts measured from the vertical velocity at fixed optical depth $\tau = 0.1$ from a magnetoconvection sunspot simulation [14]. The simulation reproduces the general trends seen in the observed travel-time shifts for the phase-speed filters centered at 14.9 km/s, 17.5 km/s, and 25.8 km/s. The simulation is not as close to the observations for the case of the smallest phase-speed filter; this is also the filter for which the largest difference between the two observed sunspots is seen.

Parchevsky et al. [28] showed numerical simulations of wave propagation through a model sunspot. The aim of the simulations was to understand the observed variation of travel-time shifts with the angle between the magnetic field vector and the line of sight [29–31]. The results suggested that the magnetic field does indeed introduce a dependence of the travel-time shifts on the line-of-sight direction. Rajaguru et al. [32] observed vertically propagating waves in a
sunspot penumbra and proposed that phase shifts resulting from these waves combined with radiative transfer effects can also cause apparent line-of-sight variations of travel-time shifts. Further work is needed to disentangle the radiative transfer issues from the wave propagation.

2.3. measurement issues
In principle, the details of a procedure for measuring travel-time shifts (i.e., data-analysis filters, definition of travel-time shift) can be accounted for in the forward modeling process (e.g. [33]). In practice, the situation in sunspots may be more complicated than can be easily accounted for using traditional ray-approximation forward models (e.g. [34]) or models based on perturbation theory around quiet Sun models (e.g. [35]). As a result, there are “systematic effects” (by which I mean effects that are not accounted for in a forward model) in the local helioseismology of sunspots. In this subsection I will describe a few investigations of potential systematic effects that have appeared in the literature very recently.

Travel-time shifts measured using time-distance helioseismology and helioseismic holography, in general, depend on the frequencies and phase speeds of the waves that contribute to the measurement (e.g. [36] among many others). As a result, data analysis filters (i.e. phase-speed...
or ridge filters) can have substantial effects on the measurements (e.g. [3; 6; 37]). In modeling these effects, the detailed shape of the power spectrum of the waves can play an important role (e.g. [6]). Zhao et al. [12] used intensity observations from the SOT instrument on the Hinode spacecraft [38] to test the impact of phase-speed filters on time-distance measurements. They found that the phase-speed filters caused up to a 40% change in observed travel-time shifts, with the largest changes occurring at the shortest travel distances. This result demonstrates the importance of accounting for the phase-speed filters in the forward modeling process. In addition, Zhao et al. carried out inversions for the subsurface structure of a sunspot and found a result that was qualitatively similar to that of [11] and the results shown in Figure 1, both of which were obtained from MDI Doppler velocity measurements.

Braun et al. [39] showed that the spectral content of helioseismic holography cross-correlations measured in sunspot umbrae and in the quiet Sun are very different; the cross-correlations in the umbra have less power at high frequency than those in the quiet Sun. This effect causes changes in the positions of the phase peaks in the cross covariance that can be confused with travel-time shifts depending on the details of the fitting procedure that is applied.

3. Subsurface flows associated with sunspots
The traditional approach to ring-diagram analysis has been to carry out one-dimensional (depth only) inversions while assuming that the subsurface flows and structure are horizontally homogeneous across the measurement patch. Featherstone et al. [15] show a generalization of this procedure to the case of three-dimensional inversions for subsurface flows. This inversion approach is different than that usually employed in time-distance helioseismology as it does not assume horizontal translation invariance of the noise covariance matrix. As a result, the inversion cannot be done using a MCD-type [40] decomposition into horizontal Fourier modes. The inversion is therefore expensive and iterative methods are employed to obtain approximate solutions.

Figure 7 shows one example inversion result from [15]. The horizontal resolution of the inversion decreases with depth (short wavelength modes have shallow lower turning points). Notice that the moat flow can be seen clearly at the depths of 0.2 and 4 Mm. It is less visible at 7 Mm and cannot be clearly seen at 11 Mm. There is no hint of a return (inward) moat flow. This result is apparently inconsistent with the shallow inflows seen using time-distance helioseismology [e.g. 41]. It is possible, however, that the subsurface structure of the moat flow varies strongly from one sunspot to another, or over the life cycle of sunspots. A direct comparison using the same observational data for the same sunspot at the same time period is needed.

Braun et al. [39] showed flows obtained from an inversion of travel-time differences measured using helioseismic holography of HMI data (see Fig. 2 from that paper). The near surface (0-3 Mm) moat flow was similar to that seen in Figure 7. A comparison between the moat flow inferred from time-distance, ring-diagrams, and helioseismic holography in the style of Figure 1 has not been done.

4. Discussion
There is not general agreement on the subsurface structure of sunspots. Some methods lead to “deep” sunspot models which feature substantial wave-speed variations (relative to the quiet Sun sound speed at the same depth) at depths below a few Mm. Other methods lead to “shallow” sunspot models in which the wave speed is essentially the same as the quiet Sun sound speed at depths below a few Mm. The sources of this disagreement are not known.

In the past year, however, there has been progress in many aspects of the local helioseismology of sunspots. It is now feasible to carry out simulations of wave propagation through model sunspots and make direct comparisons between these simulations and measurements [13]. Using
Figure 7. Three-dimensional ring diagram inversions for flows around a sunspot. From top left to bottom right, the panels show slices through the inferred flow field at depths 0.2, 4, 7, & 11 Mm. In all of the panels, the arrows show the horizontal flows and the color scale shows an MDI line-of-sight magnetogram. Notice that the spatial resolution is best near the surface and decreases with increasing depth. There is a clear moat flow surrounding the sunspot (dark green feature in the magnetogram at Longitude 132° and Latitude -8°) seen near the surface. The moat flow can be seen in the inversion at 7 Mm depth but is not obvious at 11 Mm depth. The supergranulation signal also decays with depth and is not clearly visible at or below 7 Mm. Adapted from [15].

this approach, it will be possible to determine if any particular sunspot model is compatible with observations. This is a crucial test of any proposed sunspot model. In addition, direct numerical simulations of magnetoconvection that include sunspot-like magnetic structures will provide synthetic data for testing methods of local helioseismology [14].

A direct comparison of the subsurface nature of moat flows inferred from time-distance methods, ring-diagrams, and helioseismic holography has not been done. This comparison is important and should be carried out.

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