The Need for Physics-based Inversions of Sunspot Structure and Flows



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# The Need for Physics-based Inversions of Sunspot Structure and Flows

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**Abstract.** Current controversy exists in the interpretation and modeling of helioseismic signals in and around magnetic regions like sunspots. Unresolved issues include the dependence of the sign of both the inferred flows and wave speed on the type of filtering used, and the discrepancy between the relatively deep two-layer wave-speed models derived from standard time-distance methods and shallow, positive wave-speed models derived using forward models which include effects of mode conversion To make full use of the year-round, almost limb-to-limb, coverage provided by the *Solar Dynamics Observatory*, an efficient and reliable inversion method incorporating possible magnetic effects and the currently unexplained sensitivity to methodology is critical.

## 1. Introduction

A cool layer inferred below sunspots in many helioseismic (time-distance) inversions is largely derived from positive (slower) travel-time perturbations, relative to the quiet Sun, observed at small values of the mode phase speed [1] [2]. Controversy exists whether these positive travel-time perturbations may arise due the effects of filters applied to the observations [3] [4] [5]. Travel-time perturbations within sunspots show strong variations, including changes of sign, with frequency at fixed phase speed [3] [6]. This behavior has also been qualitatively (and in some cases remarkably quantitatively) reproduced with artificial data – derived from hydrostatic models [7], magnetostatic models [8], and MHD models [9] – in which no slower layer is present. In contrast to measurements made using phase-speed filters, travel-time perturbations derived using ridge filters are exclusively negative (implying faster wave speeds) in sunspots [4]. A number of forward models, including some with magnetic fields, provide evidence for shallow, positive wave speed perturbations below sunspots [10]. Thus, considerable uncertainty remains in the inference of the wave-speed structure below sunspots. However, an efficient, robust inverse method which includes the effects of magnetic fields has not yet been developed.

## 2. Travel-time measurements in spots

The measurement of travel-times in sunspots is subject to a fair amount of uncertainty and can be systematically sensitive to details of the measurement procedure. The effects of a reduced wave amplitude (or reduced excitation) in magnetic regions on the measurement of travel times have been recently explored [11] [12] [13] [14]. Additional complications arise due to differences, between sunspots and quiet-Sun, of the temporal-frequency content of the cross-covariance functions. Figure 1 shows some cross-covariance functions and their power spectra for both a real sunspot and the realistic sunspot simulation of Rempel and collaborators [16] [9]. The power spectra of the cross-covariance functions show that, in both the real and artificial data, there is a shift in power towards lower temporal frequencies in the sunspot umbrae as compared to the quiet Sun. In the temporal domain, this can be seen as an increase in the spacing between the peaks (or valleys) of the umbral-averaged cross-covariance functions, relative to those of the quiet-Sun cross-covariance functions. The result is that the difference between the phase travel-time shifts (spot minus quiet-Sun travel times), determined through wavelet fitting, will vary according to which peak (or valley) is used to fit the phase travel time.

As one might expect, tests have indicated that the sensitivity of the travel-time measurements to methodology decreases considerably with cross-covariance functions computed after narrow temporal-frequency bandpass filters are applied to the data. This type of filtering is useful for studying the frequency variation of travel-time perturbations in both real and artificial data [3] [9].

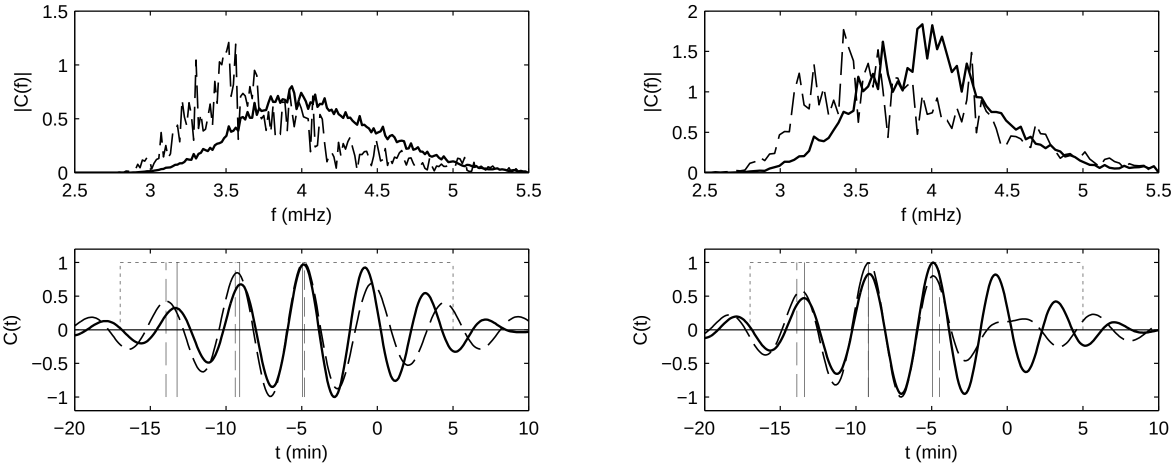


**Figure 1.** Cross-covariance functions and their power spectra determined for a region containing a sunspot observed with MDI [15] (left panels) and for the artificial sunspot modeled in a realistic magnetoconvection simulation [16] [9] (right panels). The bottom panels show the cross-covariance functions, averaged over the sunspot umbra (dashed curves) and a region of quiet Sun (solid curve) determined by helioseismic holography and corresponding to outgoing waves with the application of a standard phase-speed filter (filter "2" of [2]). The zero point of the (horizontal) time axis is arbitrary, and the amplitude of the umbral cross-covariance functions has been multiplied by a constant to facilitate comparison with the quiet Sun. The vertical lines indicate phase travel-times determined from wavelet fitting tuned to individual peaks in the cross covariances. The dotted lines illustrate the window used in the fitting. The top panels show the power spectra of the cross-covariance functions, with the line-types having the same meaning as the lower panel. It is evident, in both the real and simulated sunspot, that the power in sunspot umbrae is shifted to lower frequencies, which results in a larger spacing between peaks observed in the umbral-averaged cross-covariance functions.

## 3. Ridge-filtered Inversions for Flows

As for the sign of the near-surface wave-speed perturbation, the inferred direction of subsurface flows below sunspots also appears to be highly dependent on the analysis methodology. In particular, shallow inflows are inferred with phase-speed filters [17] [5] while outflows at the same depths are seen in inversions with ridge filters [4].

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We carried out an inversion for subsurface flows from ridge-filtered travel-time measurements made using 7.8 hours of Doppler velocity measurements from the Helioseismic and Magnetic Imager (HMI) onboard the *Solar Dynamics Observatory.* A region containing several sunspots (AR 11057), observed by HMI starting 2010 March 28 was selected for analysis. This inversion is based on travel times measured for the modes $n$ = 0,1,2, & 3. In addition to the ridge filters we also used filters that isolated 0.5 mHz wide bands in frequency. The kernels for the inversion were computed in the Born approximation. Figure 2 shows an example inversion result for flows in a layer extending from the surface to 3 Mm below the surface. Notice that there are outflows from the sunspots. In addition, the outflows associated with the supergranulation pattern can be clearly seen. The shallow sunspot outflows obtained with this ridge-filtered inversion differ substantially from flow inversions (which show shallow inflows) performed on the same set of HMI data after applying phase-speed filters [18]. On the other hand, this result is consistent with outflows surrounding sunspots seen in inversions of other sunspots using MDI observations as well as photospheric motions of magnetic features [4].

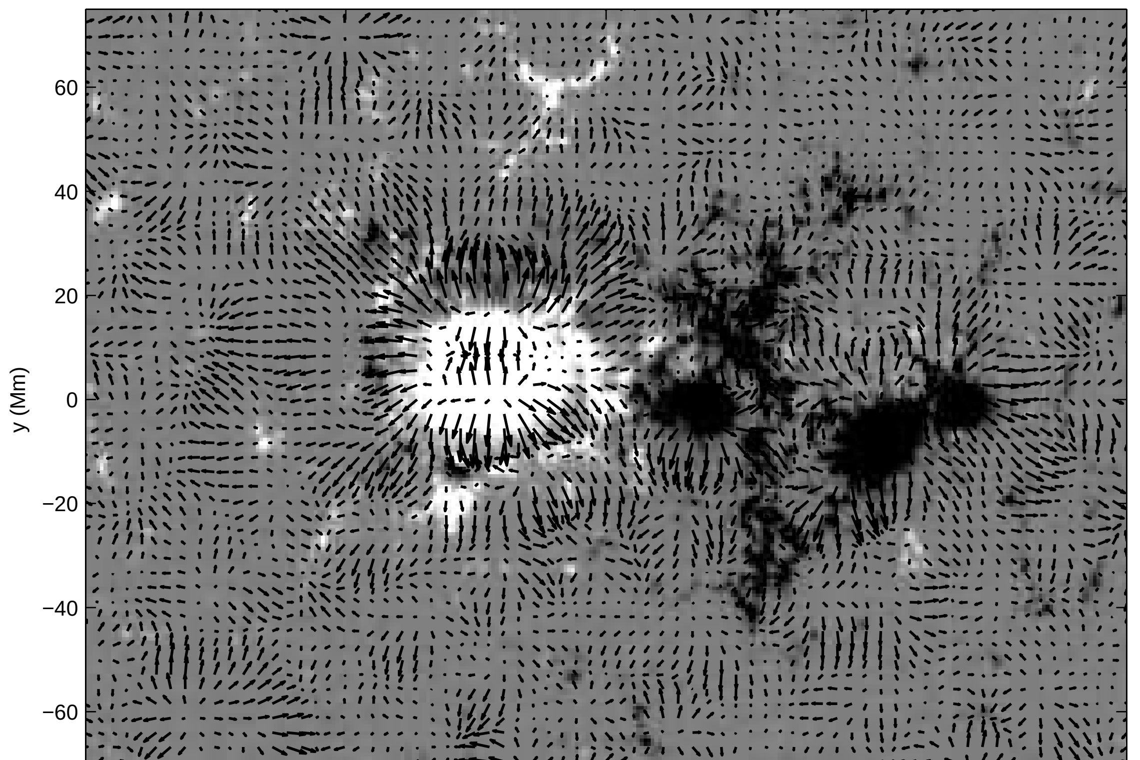


**Figure 2.** Results of an inversion for horizontal flows from helioseismic holography applied to SDO/HMI Dopplergrams for the active region AR 11057. The largest vectors represent velocities of a few hundred m/s. The background is the line-of-sight magnetic field saturated at ± 300 Gauss.

## 4. Magnetic Effects

Although anomalous sensitivities of measurements and inversions to the details of the methodology may be behind some of the discrepancies in the structural models of sunspots and active regions [10], the role of the magnetic field must also be considered. For example, it is possible that, under conditions likely for sunspots, travel-time perturbations may not be related to simple wave-speeds (either the sound speed or an isotropic fast-mode speed). This is illustrated by forward models [19] [20] which include the effects of mode conversion, and which are based on measurements of both travel-time perturbations (or equivalently, phase-shifts) and absorption [21]. Although no inversion method has yet been developed which includes magnetic effects, a promising start is the computation of translationally invariant inversion kernels which include the effects of magnetic fields [22].

## 5. Conclusions

The effort to understand and resolve these and other issues in sunspot seismology relies heavily on numerical computations of wave propagation through model sunspots, including realistic MHD models [16] as well as magneto-hydro-static (MHS) models (such as translationally invariant models [22]). MHS models are relatively efficient to construct, making them particularly useful to understand the physics of the interaction between waves and magnetic structures. They may also play a critical role as a background (reference) model for inversion methods. Realistic MHD models help to predict what conditions may actually be relevant for real sunspots, as well as provide the necessary validation of helioseismic methods in magnetic regions.

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