Chapter 6

Concluding remarks

The main focus of this work was on developing numerical methods to simulate the acoustic wavefield of the Sun. These calculations are important from the viewpoints of interpreting some results of global and local helioseismology and constructing a clearer picture of acoustic wave propagation and interaction. In terms of helioseismology, there are two significant regimes in the Sun, the deep interior and the near-surface envelope, where the operating physical principles are dramatically different. Just underneath the photosphere lies a seething bed of complexity made so by the competing forces of magnetic fields, plummeting pressure and density, radiation, turbulence, ionization, etc. Things seem to change much more slowly and with less drama in the deep interior, creating this putative natural separation of scales (spatial and temporal). Two different methods, one incorporating spherical geometry to study global phenomena and another to tackle near-surface, approximately Cartesian regions were developed to address these questions.

The ultimate purpose of this study would be construct a full forward acoustically imaged model of the Sun. To do so will presumably require the gradual accumulation of various aspects of solar dynamics and structure. Taking into account all these phenomena at once would defeat the purpose of the work presented here, since the main goal of the effort is to investigate acoustic wave interactions in the Sun. The numerical procedures discussed in chapters 2 and 3 can be used to address a large number of the questions listed herein.

6.1 Forward modeling and helioseismology

There are numerous questions of interest and importance in the context of global resonant modes and their evolution with the solar cycle, their sensitivities to local changes in the background structure of the Sun etc. Merely placing bounds on detectability and quantifying the diagnostic ability of the mechanical modes of the Sun are very instructive tasks. Forward modeling of the near-surface layers of the Sun in the context of seismology is an extremely useful task, firstly because waves spend most of their time in these regions (low sound speed) and secondly, the complexity embedded in these layers are significant contributors to shifts in helioseismic metrics. Various systematics such as the center-to-limb travel-time variation, the strange day to day correlation of noise (Duvall, 2003), foreshortening, the washing machine effect are some problems that can be addressed to some degree with these forward models. Calibration of far-side seismology (Lindsey & Braun, 2000) is a task of relevance to the wider space weather community.

Meridional circulation is thought to play an important role in the solar dynamo and measuring it accurately is linked to understanding the processes of angular momentum exchange. Meridional flow velocities are small ($\sim 20 - 30$ m $\cdot$ s^{-1}) and consequently, they are difficult to measure accurately. By computing the interaction of the acoustic wavefield with various models of meridional flow, the helioseismic signatures obtained thereof can be compared to the solar counterpart to determine which models are most representative. Such a calculation can also give us insight into the signatures associated with a deeper return flow. Controversies associated with the depth of the return flow and the multiple cell meridional flow theory also still remain to be resolved.

The tachocline is a thin layer of intense radial shear across which the solar rotation switches from rigid body to differential. The tachocline is located at roughly 0.70 $R_\odot$ and is considered to be the seat of the solar dynamo. Acoustic signals that penetrate deep enough to sample the tachocline are quite weak when measured at the surface (due to various reasons mentioned in chapter 1), which makes it hard to infer properties of the tachocline accurately. An estimate of the kind of signal to noise required to image this depth and the resolution of the acoustic waves at this depth are important parameters in observational studies of the tachocline.

The impact of diffractive healing on the detectability of perturbations in the solar interior is still an open and unanswered question. Because finite frequency waves possess the curious property of *wavefront healing*, a diffractive effect, some memory of the interactions of waves with perturbations is lost, especially when the wave must propagate large distances (compared to the wavelength) before detection. The size of a perturbation in comparison to the wavelength is quite an important parameter since the wave is likely to heal much more rapidly after it interacts with a small perturbation as opposed to large sized perturbations. Moreover, the ray approximation departs significantly from wave theory as the perturbation becomes sub-wavelength in size. Such studies, especially in the case of global helioseismology, are instructive because we will be able to characterize the inferential ability of waves and obtain estimates on the quantity of data required to probe the deep interior of the Sun.

The interaction of waves with deep convection to see if convective structures have a measurable effect on acoustic wave travel times is an interesting question. Convection in the deep interior is believed to be possess large-scale coherence, lending them the name 'Giant Cells'. These cells have never been convincingly detected; analyses of the helioseismic signatures of the convective flows might lend some insight into the future possibility of giant-cell detection. Initial calculations of travel time shifts of waves with the ASH (Miesch et. al., 2000) convection profiles are somewhat encouraging, although much work needs to be done to characterize the observational effort required to detect interior convection. Because of the large wave-lengths of the propagating acoustic waves at this depth, the resolution with which the convective activity can be imaged is highly limited. Therefore, it would seem that numerical calculations (Miesch et. al., 2000) in conjunction with observational support of the statistical aspects of the interior convection are the only way to proceed, thus highlighting the importance of these measurements.

The realization noise associated with stochastic excitation of acoustic waves interferes with the ability of helioseismology to infer the subsurface solar properties.

Although with current setup, realization noise subtraction is only viable in the numerical case, the possibility of extending it to actual solar data is very tantalizing and no doubt, a scientifically rewarding task. With the constant improvement in the quality of observational data, it seems that the next significant advance would be to model away this realization noise.

6.2 Magnetic field effects

Sunspots are a class of solar phenomena that seem to possess formidable complexity whose structure and dynamics still elude clear comprehension. From the so-called dynamical disconnection of sunspots and their seeming irreverence for neighbouring convective activity (Schüssler & Rempel, 2005) to the strange behemoth that is the penumbra, sunspots are a source of major controversy. Such significant magnetic activity is not related to just the Sun; quite contrarily, some stars exhibit giant spots that grow to occupy a large fraction of the surface area, rendering sunspot seismology relevant to the larger astrophysical community. Ever since the discovery by Thomas, Cram, & Nye (1982) that waves could be used to investigate the structure and dynamics of sunspots, much effort has gone into modeling magnetic effects on waves. Mode conversion and strong near-surface dispersive mechanisms pose non-trivial analytical and modeling hurdles that have yet to be crossed successfully. Truly, a menagerie of magnetically coupled waves (magnetosonic, slow and fast) are presumably unleashed, especially in near-surface regions where the magnetic and hydrodynamic effects are quite comparable. Because analytical techniques are not general in their applicability, the development of numerical methods (Cameron, Gizon, & Daifallah, 2007; Hanasoge, 2007) to study this problem is much required. Questions that relate to the extent of mode conversion and the somewhat controversial theories of mode absorption (e.g., Braun, Duvall, & Labonte, 1987; Bogdan et al., 1993; Braun, 1995; Parchevsky & Kosovichev, 2006), the presence of flows underneath sunspots, the accuracy of the inversion results etc. are very interesting and remain open.