Chapter 9

Summary and Perspective

This thesis has presented a variety of applications of time-distance helioseismology measurements and inversions, and many new results have been obtained by this technique. In the following, I summarize all the major results presented in the previous chapters as the first part of this chapter, and discuss perspective of future works in the second part.

9.1 Summary

It has been proved that time-distance helioseismology is a useful technique to study solar interior sound-speed structures and dynamics on both small and large scales. Two inversion techniques, one based on the LSQR algorithm and one based on Multi-Channel Deconvolution, have been developed; comparisons between these two inversion techniques give reasonable agreement.

Time-distance measurement and inversion have been applied to study local structures: sunspots and supergranules. For sunspots, it was found that the sound-speed is slower relative to the quiet Sun immediately below the solar surface, but faster than the quiet Sun below the depth of approximately 5 Mm. Converging and downward flows were revealed beneath sunspots, which may play important roles in keeping sunspots stable for more than a few days even a few weeks, and also may be observational evidence for the sunspot cluster model (Parker, 1979). However, below the regions of converging and downward flows, divergent and upward flows were seen.

For supergranules, the vertical velocity cannot be reliably derived due to the strong cross-talk effects between the weak vertical velocity and the strong divergence (convergence) at the center (boundary) of supergranules. However, the horizontal velocities near the surface and at some depth display a convective cell structure. The correlation coefficients between the divergences at the surface and at a few different depths suggest that the depth of supergranules is approximately 14 Mm, close to the expectation of many researchers.

A sunspot with fast self-rotation was studied by use of time-distance helioseismology, in order to detect the interior structure of this unusual sunspot, and try to connect the subsurface flow fields with the coronal activities. By comparing the subsurface sound-speed structures with the photospheric magnetic field, a structural twist was found beneath the sunspot, which may explain the twists of vector magnetic field observed in the photosphere. A vortex, which is in the same direction as seen by white light movies, was found beneath the surface, but an opposite vortex was found in some deeper layers at depths of about 12 Mm. Such flow fields could significantly twist the magnetic flux and store a huge amount of magnetic energy and helicity for solar eruptions in the chromosphere and corona. A statistical study of 88 active regions in both hemispheres showed that the sign of subsurface kinetic helicity has a slight hemispheric preference, even weaker than the hemispheric preference found by the statistics of magnetic helicity. It also showed that the sign of kinetic helicity is opposite to that of the magnetic helicity in the same solar hemisphere.

Large-scale properties, such as zonal flows, meridional flows and vorticity distribution, were also derived from our studies of one Carrington rotation each year from 1996 to 2002, covering from the solar minimum to maximum. Synoptic flow maps were constructed from the surface to a depth of 12 Mm for all the selected Carrington rotations. Faster zonal flows, residing on the equatorial side of the activity zones and also known as torsional oscillation, were found from our study and had similar magnitudes as obtained by previous researchers. The residual meridional flows, after the meridional flows of the minimum year were subtracted from the flows of all the following years, display a converging flow toward the activity zones in both hemispheres, which implies downward flows in the activity zones. These properties migrate together with the activity zones toward the solar equator with the evolution of the solar cycle toward its maximum. The global vorticity distribution is largely a linear function of latitude, and mainly results from solar differential rotation but with some variations.

Once we had synoptic flow maps, we overlapped the synoptic flow map with the magnetic synoptic map to study the relationship between the magnetic field strength and the rotational speed of magnetic features on the solar surface. After masking the major active regions, we found that the residual rotational speed of weak magnetic features, pores and network structures, is nearly linearly proportional to its magnetic field strength. This linear relationship varies with the evolution of the solar cycle, and the slope is largest during solar maximum years. In addition, it was found that the plasma of following polarity has a faster speed than the plasma of leading polarity with the same magnetic field strength.

9.2 Perspective

Time-distance helioseismology has already revealed many new results in the solar interior sound-speed variations and dynamics. Some efforts are still ongoing and should be done in the future to improve the accuracy and reliability of time-distance helioseismology results.

9.2.1 Artificial Data from Numerical Simulation

Some artificial models have been made and used in Chapters 3, 4 and 5 of this thesis, however, these artificial data were simply created to test the reliability of inversion codes, but might not represent the reality inside the Sun.

More realistic artificial data are necessary to test time-distance helioseismology, including both measurements and inversions. Such data should be simulated by employing the compressible hydrodynamical equations, or perhaps even magnetohydrodynamical equations, including perhaps radiative transfer equations. The final dataset should have long enough time series, large enough surface areas with spatial resolution better than or comparable to the real observation, and more importantly, acoustic waves should be present through the plasma. Granulation, and maybe supergranulation, should be expectedly obtained in such numerical simulations. Then, time-distance measurements and inversions are applied upon such numerical data, in an attempt to reveal the structures and flow fields initially set inside this numerical model. Such a numerical experiment could fully test the reliability of time-distance helioseismology, and estimate the systematic and random errors involved in this technique. Such an effort is ongoing.

9.2.2 Wave Approximation

All results that have been presented in this thesis are based on the ray-approximation. As already discussed in Chapter 2, the wave approximations, including Fresnel-zone approximation and Born approximation, have proved that for the sound-speed perturbation, the major results derived from ray-approximation are valid (with no phase-velocity filtering applied to both kernels), although the depth and magnitude of features are slightly at odds (Couvidat et al., 2004). The wave-approximation inversion kernels for flow fields, with the phase-velocity filtering being applied as well, are currently under development, and soon a comparison between velocities obtained by different inversion kernels will be available.

However, since the solar regions in our study are often sunspots or active regions, where strong magnetic fields are present, it is considerably difficult to derive the proper inversion kernels with different scales of magnetic field taken into account, and also it is difficult to disentangle the effects of magnetoacoustic waves from the normal acoustic waves, as also pointed out in Chapter 2. Therefore, considerable efforts should be put on modeling the magnetic-acoustic interaction for better interpreting time-distance results in solar active regions.

9.2.3 Deep-focus Time-distance Helioseismology

Conceivably, more measurements are often necessary to derive results with better accuracy. Deep-focus time-distance helioseismology is designed to complement surface-focus time-distance helioseismology, the sole technique used through this thesis; deep-focus can bring us more information of deeper structures. Deep-focus time-distance helioseismology is introduced in Appendix B of this thesis.

Some attempts (see Appendix B) have also been made to incorporate the deep-focus and surface-focus time-distance measurements, then inversions were performed based on both measurements. Although the major results obtained from such inversions, e.g., faster sound-speed, converging and downward plasma flows beneath sunspots, are similar, the detailed sound-speed structures, the flow magnitudes and directions are somewhat different with the inversion results from surface-focus alone.

The differences may be caused by a few aspects: the measurements from the deep-focus time-distance are significantly noisier than the measurements from surface-focus, which may introduce many unpredictable uncertainties to the inversion results; the accuracy of inversion kernels derived from the ray-approximation for the deep-focus time-distance is unknown, and may partially introduce some errors to the inversion results; without knowledge of the noise level (or error covariance) of both surface- and deep-focus time-distance measurements, it is hard to determine the proper regularization parameters and infer the best possible results. Therefore, it is very important to design better schemes for the deep-focus time-distance measurements, which can optimally cover the regions of interest and depths to complement the surface-focus time-distance. It is equally important to derive the deep-focus wave-approximation inversion kernels.

9.2.4 Connections between Subsurface Flows and Coronal Activity

This may be a very interesting topic for the future study, and potentially a new field. It is well known that the shearing flows at the footpoints of solar flares play a very important role in triggering solar flares, and it is also known that, part of, or even most part of the magnetic energy released by solar flares is built up under the solar photosphere. Thus, it is interesting to study the connections between subsurface flow fields and coronal activity.

Three-dimensional subsurface velocity derived from time-distance inversions enables us to compute the subsurface kinetic helicity, and to look for shearing or vortical flows under active regions. Abnormal kinetic helicity and shearing flows may be pointers to potential solar eruptions a few minutes or hours later. Therefore, such a study can not only help us to understand the helicity and energy build-up procedure below the solar surface to power solar eruptions, but also can identify the indicators to forecast the solar eruptions well ahead the occurrence of solar flares.

Some preliminary studies have been performed, trying to establish such connections by analyzing the "Thanksgiving events" of 2000. A series of five X-class solar flares occurred on November 23 and 24, 2000 in NOAA AR9236. Preliminary time-distance analyses have shown that for the first three cases of X-class flares, approximately 4 hours before the onset of each flare, vortical flows were found around the footpoints of the solar flares, and abnormal converging flows were found flowing toward the footpoints. If these features are able to be confirmed in other solar flares, these features may serve as indicators of potential solar eruptions. The major difficulty is that the temporal resolution of time-distance is rather low, and spatial resolution from time-distance results is also low compared to the size of solar flare footpoints.

I believe this is a very interesting and novel topic, and is definitely worth substantial research effort in the future.