Chapter 1

Introduction

THE DATA “MUST BE GREATLY AMPLIFIED AND STRENGTHENED.”

—Beno Gutenberg, Physics of the Earth’s Interior, 1959

Seismology is an observational science, based on data called seismograms. By reading seismograms, seismologists have obtained the most high-resolution pictures of the Earth interior and earthquakes. Availability of better data has always been the fundamental stimulator or driver of progresses in seismology. For example, in the early 1900’s, seismograms (mostly travel times) from regional to global scales led to the discoveries of the Earth’s primary structures, the Mohorovičić discontinuity, the liquid outer core, and the solid inner core. In 1960, newly-invented long-period seismometers by Hugo Benioff recorded the Great Chilean earthquake and provided the first definitive observation of the Earth’s free oscillations.

From the 1960’s, a series of progresses in computing theoretical seismograms made interpretation of detailed waveform shapes (wiggles) possible. After that, rapidly growing high-quality seismic waveforms have revealed complex structures of different scales (e.g. D’’, ULVZ, ICB, transition zone, sharp super-plume), and kinematic ruptures of large earthquakes. Seismologists today are still working toward more effective and efficient use of seismic waveforms. In the meanwhile, just like many other science disciplines, seismology evolves into many high-specialized sub-disciplines. Even within the observational seismology, it becomes difficult to study different kinds of problems to fully appreciate the wide spectrum of seismic data.

Fortunately, the free atmosphere and great research resources in Caltech seismolab allow students like me to get involved in many different aspects of observational seismology, from local to global scales, from earthquake waveforms to ambient noise, from seismic structure to earthquake rupture. Through this process, I become more and more enthusiastic about seismic waveforms. I realize that every waveform is unique, and contains incredible amounts of information about the Earth. In this thesis, out of many interesting projects I have been involved in, I summarize seven different projects in which I have been the leading contributor. These seven studies are largely independent, but can be classified roughly by two groups: Part I, ambient noise correlations; and Part II, earthquake waveforms.

The idea of retrieving the Green's functions between stations by correlating ambient noise has been widely applied to studying Earth structure, earthquake locations, and monitoring velocity changes. Part I of this thesis includes four studies on ambient seismic noise.

(1) I relocate earthquake centroid by calibrating surface-wave path effects with noise cross-correlation functions. Test with the 2008 Chino Hills earthquake shows significant improvement in the centroid location and potential application for quick estimate of rupture directivity.

(2) While only fundamental mode surface waves emerge in most previous studies, I retrieve the Moho-reflected shear wave (SmS) and its multiples from noise cross-correlations at regional scales. I also demonstrate how an uneven distribution of noise sources can mask weaker body-wave phases.

(3) Ambient noise cross-correlations are now being used to detect temporal variations of seismic velocity, which are typically on the order of 0.1%. At this small level, temporal variations in the properties of noise sources can cause apparent velocity changes. I demonstrate that temporal variability of noise frequency content can

cause spurious velocity changes when noise correlations are used to monitor velocity changes.

(4) I apply the noise cross- and auto-correlation methods to the Amery Ice Shelf. I find that the noise field on the ice shelf is dominated by energy trapped in a low velocity waveguide caused by the water layer below the ice. Within this interpretation, I obtain independent estimates of the water-column thickness and the structure of the firn layer.

Part II of this thesis presents three studies on earthquake waveforms.

(1) The 2011 Mw 9.1 Tohoku-Oki earthquake had unusually large slip concentrated in a relatively small region. Detailed analysis of earthquakes in the Tohoku-Oki region reveals steeper earthquake dip angles than the previously imaged plate interface. I explain this discrepancy as evidence for a complex plate interface.

(2) The physical mechanism of deep earthquakes remains enigmatic. I develop and apply a full-waveform sub-event method to the two largest deep earthquakes, the recent Great 2013 Sea of Okhotsk earthquake (M8.3) and the Great 1994 Bolivia earthquake (M8.3). Both earthquakes display complex rupture histories, and significantly different rupture speeds, possibly related to the slab thermal states.

(3) I observe and model teleseismic waveforms from earthquakes in the Kuril subduction zone with strong broadening caused by the subducted slab. I obtain a ~5% velocity perturbation in the slab, significantly higher than most tomographic models.