Progress Report of the Task Group on Scattering and Heterogeneity

Haruo SATO
Tohoku University, Sendai, Japan

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We have started to edit a book as a state-of-the-art summary of researches on seismic wave scattering and heterogeneity of the Earth since the 2005 IASPEI general assembly in Santiago, Chile. We put a special focus on small-scale heterogeneities that cause seismic wave scattering in short periods. This is the most important objective of our task group for the last four years. We completed the editorial process in early summer of 2008. Now the book entitled "Earth Heterogeneity and Scattering Effects on Seismic Waves" is published by Academic Press as the 50-th volume of the Advances in Geophysics. This book is dedicated to a pioneer of short period seismology, the late Keiiti Aki.

We show the preface and the table of contents of the book as the progress report of our task group in the following:

"Earth Heterogeneity and Scattering Effects on Seismic Waves"
Volume 50 of Advances in Geophysics

Series Editor: Renata Dmowska
Guest Editors: Haruo Sato and Michael C. Fehler

Preface

Seismic waves generated by earthquakes have been interpreted to provide us information about the Earth's structure across a variety of scales. As a scientific activity of the Commission on Seismological Observation and Interpretation of the IASPEI, focusing on the seismic wave scattering in the Earth from heterogeneities having various types and scales, we organized a task group on "Scattering and Heterogeneity of the Earth". As the first product of this task group, Wu and Maupin (2007) edited a book entitled "Advances in Wave Propagation in Heterogeneous Earth" as the 48 volume of "Advances in Geophysics" (Series Editor, R. Dmowska). That volume mainly contains introductions to and basic review of modeling methods for elastic waves in laterally heterogeneous structures that are most commonly used in contemporary seismology.

For short-period seismic waves (e.g. those having periods less than 1 second), scattering due to randomly distributed small-scale heterogeneities in the Earth significantly changes the envelope of seismograms with increasing travel distance and excites coda waves. Models of propagation through deterministic structures such as those with horizontally uniform velocity layers used in traditional seismology cannot explain these phenomena. In addition to the invention of the velocity tomography, the study of coda waves in the heterogeneous lithosphere started by Aki (1969) marked a new era in short-period seismology. The former reveals the existence of three-dimensional deterministic heterogeneity from onset readings; the latter reveals the existence of small-scale random heterogeneity. The two approaches are complementary for the construction of a unified image of the real Earth; however, here we mainly focus on the latter subject, seismic wave scattering by random small-scale heterogeneity in the Earth.

This volume is edited as the second product of the task group. Topics covered are recent developments in wave theory and observation including: weak localization of seismic waves, synthesis of short-period seismic wave envelopes, laboratory investigations of ultrasonic wave propagation in rock samples, coda wave analysis for mapping medium heterogeneity and for monitoring temporal variation of physical properties in the crust, radiation of short-period seismic waves from an earthquake fault, and borehole measurements of Earth properties on a range of scales. Various types of forward modelling and inversion schemes are introduced.

As a compelling description of the value of the study of the field of seismic wave scattering in the heterogeneous Earth, we refer to words of late professor Keiiti Aki in a letter he wrote to Dr. V. I. Kelis-Borok in 2003 from his lecture note (Aki, 2003), "…To a geodynamicist, the earth's property is smoothly varying within bodies bounded by large-scale interfaces. Most seismologists also belong to this "smooth earth club", because once you start with an initial model of smooth earth your data usually do not require the addition of small-scale heterogeneity to your initial model. As summarized well in a recent book by Sato and Fehler (1998), the acceptance of coda waves in the data set is needed for the acceptance of small-scale seismic heterogeneity of the lithosphere. There are an increasing number of seismologists who accept it, forming the " rough earth club". I believe that you are also a member of the rough earth club, judging from the emphasis on the hierarchical heterogeneity of the lithosphere..."

The book starts with theoretical approaches for modeling wave propagation and scattering in randomly inhomogeneous media. *Chapter 1* (Margerin) reviews recent theoretical developments on the weak localization of coda waves: the amplitude of coherent back-scattered waves in the vicinity of the source is larger than what predicted from the classical radiative transfer theory. For cases where the wavelength is shorter than the scale of medium inhomogeneity, the WKBJ approximation is used in *Chapter 2* (Zheng and Wu) to arrive at a new stochastic theory for the coherence function of log amplitude and phase for waves passing through random media with a depth dependent background velocity structure. As a statistical extension of the phase screen method for the parabolic wave equation, the Markov approximation is known to be an effective method to predict wave envelopes in random media for high-frequency waves. *Chapter 3* (Sato and Korn) reviews an extension of that approximation for scalar waves to vector waves. The newly developed theory reliably predicts envelope broadening and the excitation of the orthogonal component of motion (the transverse component for P-waves) with increasing travel distance. The validity of the approach is tested by comparison with sets of wave traces generated by finite differences. *Chapter 4* (Kaslilar et al.) discusses the travel time statistics of acoustic waves in random media based on geometrical optics. They develop a method to estimate the statistical parameters characterizing the random media from travel-time fluctuations of reflected and refracted waves. *Chapter 5* (Müller et al.) presents a theory for attenuation and dispersion of compressional seismic waves in inhomogeneous, fluid-saturated porous media in the framework of wave propagation in continuous random media. The statistical smoothing method treats both intrinsic attenuation due to wave-induced flow and scattering attenuation as the redistribution of wave energy in space and time in a unified manner.

The following two chapters treat practical modeling of seismic wave propagation through the heterogeneous Earth. *Chapter 6* (Shearer and Earle) focuses on the envelopes of teleseismic P waves traveling through the heterogeneous mantle. Envelopes calculated by using a statistical synthesis based on the Born scattering amplitudes for random elastic media are fitted to the observed stacked P wave envelopes. *Chapter 7* (Furumura and Kennett) presents a scattering slab model for the Pacific plate and the Philippine Sea plate beneath Japan that explains the observed efficient wave-guide for high frequency seismic waves in this region. The heterogeneous component of their slab model consists of an anisotropic random velocity fluctuation with a longer correlation distance in the plate down-dip direction and a much shorter correlation distance across the plate thickness. Precise numerical simulations well explain the frequency selective wave propagation effect.

The following two chapters treat laboratory experiment and scaling issues in borehole surveys. *Chapter 8* (Nishizawa and Fukushima) presents laboratory experiments of ultrasonic wave propagation through heterogeneous rock samples by using a laser Doppler vibrometer. Variations in travel times, fluctuations of amplitude, phase, and particle-motion, as well as envelope formation are examined with respect to the statistical properties of random heterogeneities of rock in the range of millimeters. *Chapter 9* (Cheng) reviews the latest technologies in down-hole seismic measurements: acoustic logging, cross well seismic and vertical seismic profiling. They cover a frequency range from about 10 kHz down to about 10 Hz, and can investigate heterogeneity in the Earth from a scale of 10's of centimeters to 100's of meters. This chapter contains a discussion of the scale over which the various methods can resolve heterogeneity.

The following chapters treat various types of observations and analyses of coda waves. *Chapter 10* (Yoshimoto and Jin) presents the general characteristics of coda waves of local earthquakes and theoretical models based on the radiative transfer theory. This chapter discusses the non-uniform distribution of coda energy in tectonically active regions. The measurement of coda attenuation is focused especially as a useful tool for monitoring the temporal change in physical parameters in the curst. *Chapter 11* (Nishigami and Matsumoto) presents the inversion of coda wave envelopes of local earthquakes for the spatial distribution of scattering strength in the crust. The idea is based of the assumption that the lapse-time dependent residual of individual coda envelope from a smooth master curve reflects the spatial variation of scattering strength. Applying this method to data retrieved in the San Andreas Fault system, they show a good correlation between sub-parallel active faults and relatively stronger scattering zones in the crust. This chapter also has a discussion about slant stacking of seismic array waveform data for the energy evaluation under the assumption of a single scattering model. *Chapter 12* (Phillips et al.) develops a calibration technique to estimate the source spectra from the spectra of Lg and Sn coda waves of local earthquakes. Applying these techniques to records registered at stations across central and eastern Asia, they determine the regional variation of coda attenuation and apparent stress of earthquakes. *Chapter 13* (Del Pezzo) reviews scattering studies in various volcanic regimes. In some cases, the frequency dependence of coda attenuation in volcanoes is found to be less than that measured in non-volcanic areas. According to the multiple lapse time window analysis of the data, scattering loss dominates over intrinsic loss with increasing frequency because of strong heterogeneity in volcanoes. Different from the above envelope analyses, *Chapter 14* (Poupinet et al.) focuses on the phase information of coda waves and presents a cross-correlation (-spectrum) moving window technique of coda waves of local earthquake doublets for monitoring the temporal change in the velocity structure of the crust. This technique is tested by earthquake doublet seismograms registered by a digital seismic network with a high time precision. This chapter also presents a technique that creates 'virtual doublets' from the correlation of long seismic noise sequences.

The last two chapters treat earthquake strong motions and source models. *Chapter 15* (Nakahara) presents a seismogram envelope inversion for short-period seismic energy radiation from an earthquake fault. The basic idea is to use the envelope Green function derived from the multiple isotropic scattering model for short period S-waves to invert for the spatial variation in radiation from a fault. This chapter compiles the characteristics of short-period seismic energy radiation from moderate to large earthquakes. *Chapter 16* (Lavallee) presents an earthquake source model based on the assumption that the slip distribution obeys a Lévy law. This model predicts that the sum of these amplitudes observed at a given distance from the sources will also be distributed according to a Lévy law.

The text is written for graduate students, scientists and engineers of geophysics, physics, acoustics, civil engineering, environmental sciences, geology and planetary sciences. A glossary of special terms relevant to the study of scattering of waves in random media is placed at the end of this book. For further understanding, there are monographs that treat medium heterogeneity and wave scattering as follows: Chandrasekhar (1960) is a classic text for radiative transfer theory in scattering media. Ishimaru (1978) and Rytov et al. (1987) offer advanced mathematical tools for the study of wave propagation in random media and a link between wave theory and the radiative transfer theory. Shapiro and Hubral (1999) puts special focus on wave propagation through stratified random media focusing on 1-D problems. Goff and Holliger (2002) summarizes observations of crustal heterogeneity. Sato and Fehler (1998) reviews seismological observation facts and mathematical models of scattering phenomena especially focusing on short period seismic waves and small-scale heterogeneity.

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