# Preface to the Second Edition

Scattering due to randomly distributed small-scale heterogeneities in the earth significantly changes seismic waveforms of local earthquakes especially for short periods. Scattering excites long lasting coda waves after the direct arrival and broadens the apparent duration of oscillation with increasing travel distance much longer than the source duration time. Models of propagation through deterministic structures such as those with horizontally uniform velocity layers cannot explain those observed phenomena. Our goal in writing this book is to put a focus on the phenomena of seismic wave scattering by distributed heterogeneities in the earth, especially in the lithosphere, where stochastic treatment is essential to describe both heterogeneous media and wave propagation through them. Stochastic approaches and deterministic approaches are complementary for the construction of a unified image of the earth's structure.

Keiiti Aki was a distinguished pioneer who extensively developed various stochastic methods for short-period seismology. His strong encouragement and continuous support for us were essential in motivating us to write the first edition of this book. Before Kei passed away in 2005, he kindly cited our book when he argued for the importance of the study on seismic wave scattering caused by small-scale heterogeneity in his letter to V. I. Keilis-Borok, "... 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. ... "(Aki 2009).

The first edition of this book was fortunately accepted in the geophysical community as a textbook, especially for graduate students. Furthermore it has been often cited in the physics community since this book introduced various aspects of wave scattering in real heterogeneous media. During the decade following the publication of the first edition, there were developments in stochastic methods and analyses focusing on seismogram envelopes. Radiative transfer theory has been used not only for the study of coda envelopes but also for the analysis of whole seismogram envelopes. These studies made it possible to resolve the spatial variation of scattering strength. There have been developments in the statistical description of wave propagation in random media that reliably predict the delay of peak amplitude from the onset and the broadening of seismogram envelopes with increasing travel distance. Those methods have also been extended from scalar waves to vector waves. Investigators from throughout the world participated and collaborated in these developments as members of the IASPEI task group on "Scattering and Heterogeneity," of which the summary was published in Sato and Fehler (2008).

In 2008, we started to write the second edition of this book. We expanded from the first edition by introducing recent developments in theory and analysis, updated illustrations and references, and wrote more precise steps in mathematical equations. The radiative transfer theory chapter and the Markov approximation chapter have been enlarged. We added two newly created chapters; one is a bridge between wave propagation in random media and the radiative transfer theory and the other one is on the Green's function retrieval from the cross-correlation function of ambient noise.

We would like to express our sincere gratitude to the following colleagues and ex-graduate students for their collaboration and fruitful discussions: M. Korn, R.S. Wu, M. Ohtake, A. Jin, T. Nishimura, H. Nakahara, K. Yoshimoto, M. Yamamoto, O. Nishizawa, S. Kinoshita, T. Yamashita, K. Yomogida, S. Matsumoto, J. Kawahara, M. Hoshiba, K. Obara, K. Nishigami, N. Uchida, T.W. Chung, T. Saito, U. Wegler, L. Margerin, M. Campillo, G. Poupinet, R. Snieder, L.J. Hunag, M. Nishino, Y. Fukushima, K. Shiomi, T. Takahashi, K. Lee, W.S. Lee, M. Kubanza, K. Sawazaki, E. Carcole, J. Tripathi, N. Takagi, K. Emoto, H. Zhang, Y. Asano, H. Kumagai, T. Furumura, T. Matsuzawa, T. Ueno, S. Padhy, S. Takemura, T. Takemoto and H. Asano. Special thanks to National Research Institute for Earth Science and Disaster Prevention, Japan for kind permission for us to use digital seismograms of their networks.

*Haruo Sato*
*Michael C. Fehler*
*Takuto Maeda*

# Preface to the First Edition

The structure of the earth has been extensively studied using seismic waves generated by natural earthquakes and manmade sources. In classical seismology, the earth is considered to consist of a sequence of horizontal layers having differing elastic properties, which are determined from travel-time readings of body waves and the dispersion of surface waves. More recently, three-dimensional inhomogeneity having scale larger than the predominant seismic wavelength has been characterized using travel-time data with velocity tomography. Forward and inverse waveform modeling methods for deterministic models have been developed that can model complicated structures allowing many features of complex waveforms to be successfully explained. Classical seismic methods are described in books like *Quantitative Seismology: Theory and Methods* by Aki and Richards (1980), *Seismic Waves and Sources* by Ben-Menahem and Singh (1981), *Theory and Application of Microearthquake Networks* by Lee and Stewart (1981), *Seismic Wave Propagation in Stratified Media* by Kennett (1985), and *Modern Global Seismology* by Lay and Wallace (1995). High-frequency ($>1$ Hz) seismograms of local earthquakes, however, often contain continuous wave trains following the direct S-wave that cannot be explained by the deterministic structures developed from tomographic or other methods. Array observations have shown that these wave trains, known as "coda waves," are incoherent waves scattered by randomly distributed heterogeneities having random sizes and contrasts of physical properties. The characteristic scale of the heterogeneity that has the most influence on a given wave is not always much longer than but is usually the same order of the wavelength of the seismic wave. Strong random fluctuations in seismic velocity and density having short wavelengths superposed on a step-like structure are found in well-logs of boreholes drilled even in old crystalline rocks located in stable tectonic environments. These observations suggest a description of the earth as a random medium with a broad spectrum of spatial velocity fluctuations and the resulting importance of seismic wave scattering.

In the 1970s, geophysicists began to investigate the relationship between seismogram envelopes and the spectral structure of the random heterogeneity in the earth. Initial models were based on a phenomenological description of the scattering process. Later, in parallel with additional observational work, there have been theoretical studies using perturbation methods, the parabolic approximation, the phase screen method, and another phenomenological method known as the radiative transfer theory. These developments have gradually established a description of the scattering process of seismic waves in the inhomogeneous earth and have allowed a characterization of the statistical properties of the inhomogeneity.

This book focuses on developments over the last two decades in the areas of seismic wave propagation and scattering through the randomly heterogeneous structure of the earth with emphasis on the lithosphere. The characterization of the earth as a random medium is complementary to the classical stratified media characterization. We have tried to combine information from many sources to present a coherent introduction to the theory of scattering in acoustic and elastic materials that has been developed for the analysis of seismic data on various scales. Throughout the book, we include discussions of observational studies made using the various theoretical methods, so the reader can see the practical use of the methods for characterizing the earth. The audience includes both undergraduate and graduate students in the fields of physics, geophysics, planetary sciences, civil engineering, and earth resources. In addition, scientists and engineers who are interested in the structure of the earth and wave propagation characteristics are included.

Many people have helped us. Keiiti Aki's encouragement and pioneering work in this field were major factors in getting this project started. Yoichi Ando kindly invited us to contribute to this book series. We benefited from careful reviewing of the manuscript by Keiiti Aki and Ru-Shan Wu. We thank Masakazu Ohtake, Ryosuke Sato, Alexei Nikolaev, Tania Rautian, Vitaly Khalturin, and Eystein Husebye for continuous encouragement. Many of our colleagues, friends, and graduate students have collaborated with us in the development of stochastic studies of seismic wave scattering, helping us to learn more than we knew: Shigeo Kinoshita, Frank Scherbaum, Leigh House, Peter Roberts, Rafael Benites, Steve Hildebrand, W. Scott Phillips, Hans Hartse, Kazushige Obara, Mitsuyuki Hoshiba, Anshu Jin, Bernard Chouet, Alexander Gusev, Yuri Kopnichev, Osamu Nishizawa, Satoshi Matsumoto, Kiyoshi Yomogida, Teruo Yamashita, Yasuto Kuwahara, Kinichiro Kusunose, Yanis Baskoutas, Kazuo Yoshimoto, Hisashi Nakahara, Ken Sakurai, Kazutoshi Watanabe, Katsuhiko Shiomi, Lee Steck, Lian-Jie Huang, Takeshi Nishimura, Fred Moreno, and Tong Fei. Michael Fehler gratefully acknowledges James Albright and C. Wes Myers for encouraging his work on this book. Ruth Bigio assisted in drafting some of the figures. We thank Maria Taylor of Springer-Verlag/AIP Press for her encouragement throughout this project and Anthony Battle of Springer-Verlag for his cooperation.

*Haruo Sato*
*Michael C. Fehler*

http://www.springer.com/978-3-642-23028-8

Seismic Wave Propagation and Scattering in the
Heterogeneous Earth : Second Edition
Sato, H.; Fehler, M.C.; Maeda, T.
2012, XVI, 496 p., Hardcover
ISBN: 978-3-642-23028-8