SEISMIC AMBIENT NOISE

EDITED BY

Nori Nakata, Lucia Gualtieri
and Andreas Fichtner

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The seismic ambient field allows us to study interactions between the atmosphere, the oceans, and the solid Earth. The theoretical understanding of seismic ambient noise has improved substantially over recent decades, and the number of its applications has increased dramatically. With chapters written by eminent scientists from the field, this book covers a range of topics including ambient noise observations, generation models of their physical origins, numerical modeling, and processing methods. The later chapters focus on applications in imaging and monitoring the internal structure of the Earth, including interferometry for time-dependent imaging and tomography. This volume thus provides a comprehensive overview of this cutting-edge discipline for graduate students studying geophysics and for scientists working in seismology and other imaging sciences.

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Foreword

This volume presents a series of contributions that provide an overview of the latest developments in the recent and rapidly developing field of noise-based seismology. While earthquake records have already revealed most of the features of the deep Earth, seismic sensors are now sensitive enough to resolve the permanent vibrations of the ground that continue between earthquake shakings. Often referred to as “noise,” these weak permanent vibrations are the physical signals that are produced by seismic waves, although their sources are often poorly understood, and they change their nature and location with the frequency band considered. This natural noise is particularly strong in the microseism band (0.04–0.2 Hz), which is also of interest for imaging purposes at the lithospheric and global scales. The relationships between meteorological activity, oceanic swell and microseisms were noted in the earliest days of the study of seismograms. The issue of using noise to study Earth structure has attracted the attention of seismologists for a long time, with notable contributions such as those of Aki in 1957, Claerbout in 1968, and Nogoshi and Igarashi in 1971.[1]

Back in 1980, in his presidential address to the Seismological Society of America, Aki[2] proposed to use the microseisms generated under the oceans:

> We know now it is possible to simultaneously determine the locations and origin times of local earthquakes and the structure of the earth in which the earthquakes are taking place, if we have a sufficient number of stations. In principle, this method of simultaneously determining the source and structure parameters can be extended to the microseisms, because the source of microseisms can probably be described by a finite number of parameters.

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[1] Aki, K. (1957), Space and time spectra of stationary stochastic waves with special reference to microtremors, *Bull. Earthq. Res. Inst.*, **35**, 415–456.
Claerbout, J. (1968), Synthesis of a layered medium from its acoustic transmission response: *Geophysics*, **33**, 264–269.
Nogoshi, M. and Igarashi, T. (1971), On the amplitude characteristics of microtremor (part 2). (*in Japanese with English abstract*). *J. Seismol. Soc. Japan*, **24**, 26–40.

[2] The full text is available from: Aki, K. (1980) Presidential Address: Possibilities of seismology in the 1980’s, *Bull. Seismol. Soc. Am.*, **70**(5), 1969–1976.

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Interestingly, he also indicated:

> The advantage of microseisms is that they exist 24 hours a day, all year around. A signal processing method may be developed to extract the body wave part of microseisms, in order to use them for deep structure studies.

These sentences look particularly pertinent today, although so far they have not been followed by many direct applications of the principles that they state. Indeed the sources of noise have proved to be multiple, and they result from complex processes and are difficult to reduce from the seismological measurements to a small number of parameters.

The potential to exploit the continuous noise records has recently become a critical issue. This comes with the advent of large networks that can provide huge amounts of continuous digital data that can be easily accessible from public databases and are now ready for massive processing with our improved computing capabilities. To take advantage of the wealth of noise records, an approach slightly different from the one foreseen by Aki can be proposed. This consists of seeking information on the medium in the propagation properties of the waves themselves, with limited reference to their sources. This was done 15 years ago with the use of long-term averages of the correlations between the noise records of distant stations, to retrieve the propagation properties between the two stations.[3] Correlations of coda waves and ambient seismic vibrations are effectively and widely used now to reconstruct impulse responses between two distant passive receivers, as if a source was placed at one of them. We have to acknowledge Aki for his 1957 study where he initially proposed a way to study the local structure with noise records, without knowing the source of the noise. This was an important conceptual advance. Assuming a single surface wave mode, Aki used a specific local array geometry to remove the effect of directivity of the noise by azimuthal averaging. The modern version relies on the spatio-temporal variability of the noise source, or on scattering, to produce the required averaging. In practice, the central part of the processing of noise records is the estimation of a time-average cross-correlation that can be identified as the impulse seismic response of the Earth between two sensors. Note that under restrictive conditions on the nature of the noise, firm theoretical ground exists to support this approach without inter-station distance limitations or hypotheses as to the structure of the medium. Although these conditions on the noise properties are rarely fully satisfied, the magic of waves is operating in the form of time reversibility and spatial reciprocity that leads to partial reconstruction of the impulse responses between two points from the correlations of

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[3] A short report of the emergence of noise correlations is given in Courtland, R. (2008), Harnessing the hum, *Nature*, **453**, 146–148.

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passive records. Noise correlations can be understood as a realization of an experiment of time-reversal self-focusing.[4] This simple physical interpretation explains the robustness of the method and the positive role of scattering on the quality of the retrieval of the impulse responses that are observed when dealing with the data. Importantly for imaging applications, the precision of the measurements of travel times deduced from noise records can be quantified, and it has been shown to be sufficient in practice for most tomographic applications.

On these grounds, passive imaging has grown rapidly, first with surface-wave tomography, as surface waves are the most easily retrieved components of the seismic field. With a large array of N three-component station arrays, a set of $N \cdot (N-1)/2$ inter-station paths can be built for each nine cross-component correlation to be computed for positive and negative time. This means that large sets of local measurements can be produced that allow in practice not only to repeat what can be done with earthquake data, but also to reach unprecedented resolution. This approach has been applied worldwide at scales ranging from shallow layers for engineering purposes to lithospheric imaging. The reconstruction of body waves is more problematic with sources distributed at the surface. High-frequency body-wave retrieval appears to be possible through the significant scattering that occurs at high frequencies. Long-period body waves are weakly sensitive to scattering, and specific analyses have to be done before apparent travel times can be used in correlations for inferring Earth structures. This is a typical example where detailed knowledge of the structure of the wavefield is required.

The characteristics of the noise are well studied nowadays. The ambient noise wavefield is investigated from the available large sensor arrays, with specific processing and beamforming techniques. With the same class of techniques, it is possible to locate the sources of noise and to validate the physical models of generation based on oceanographic data. Together with refined models of microseism sources constructed from seismological analysis and from independent meteorological and oceanographic observations, the initial strategy of Aki in the 1980s to invert for sources and structures can be reconsidered with up-to-date inversion procedures.

An exciting opportunity offered by using the ambient noise is to repeat the measurements at different dates, and to move forward to time-dependent imaging of the Earth. It has been shown that very small changes in the elastic properties of rock at depth can be observed through measures of the temporal changes of seismic velocities evaluated with the scattered parts of the retrieved impulse responses.

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[4] A heuristic presentation of the correlation methods in a general framework of wave physics can be found in Derode, A., Larose, E., Campillo, M., and Fink, M. (2003), How to estimate the Green's function of a heterogeneous medium between two passive sensors? Application to acoustic waves, *Appl. Phys. Lett.*, **83**(15), 3054–3056.

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This is a perspective for various applications, including the monitoring of underground industrial activities, or the detection of the small precursory changes before instabilities related to natural hazards, such as volcanic eruptions, landslides, and earthquakes. For the study of deep processes, the difficulty is that the Earth's crust is also changing through various external forces (e.g., rainfall, snow load, tidal and thermal effects), and that these effects have to be removed from the actual temporal observations to isolate the changes related to internal processes of natural or industrial origins. At the same time, this shows that seismology can contribute to a vast domain of environmental sciences, including hydrology, man-induced hazards, and monitoring of climate-related processes.

Ambient noise seismology is a promising field that is in rapid evolution, and that has turned out to be one of the main components of geophysical imaging. In this time of development of observations with new sensors (e.g., large nodal arrays, optical fibers, rotation sensors), the possibilities are numerous, and wide avenues are open for new applications of passive seismology. The perspectives merged in this volume will help the reader to understand the present-day challenges. As solutions are proposed, new questions appear, more and more scientists are involved, and novel data analyses lead to discoveries; there can be no doubt that the years to come will be fascinating. Ambient noise still holds a lot of the mysteries of the Earth to reveal.

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We would like to acknowledge colleagues and friends who helped us with this project during the past one and a half years. First and foremost, we thank all the authors who contributed a chapter to this book. We know very well that a book chapter is sometimes (and we think incorrectly) not considered a top-level scientific contribution, which makes it even harder to reserve time to write. We nevertheless hope that the prospect of reaching many students and colleagues will be sufficiently rewarding. Without the authors' deep knowledge, a book on such a diverse and rapidly growing topic like seismic ambient noise would have been impossible.

Critical readings of each chapter were undertaken by (in alphabetical order) Michael Afanasiev, Florent Brenguier, Evan Delaney, Laura Ermert, Koichi Hayashi, Dirk-Phillip van Herwaarden, Naiara Korta, Lion Krischer, Kiwamu Nishida, Anne Obermann, Patrick Paitz, Anya Reading, Michael Ritzwoller, Korbinian Sager, Christoph Sens-Schönfelder, Leonard Seydoux, Yixiao Sheng, Roel Snieder, and Victor Tsai. We appreciate their valuable comments, advice, criticism, and understanding of the concept of the educational aspects.

We are particularly grateful to Cambridge University Press. Susan Francis supported us in establishing the concept of this book and kept encouraging us to complete it. Zoë Pruce and Sarah Lambert always promptly and patiently replied to countless emails, making it as easy as possible for us to finalize this book. We are grateful for the opportunity to edit and write this book, and for the pleasure and little bit of struggle during this task.

Nori, Lucia & Andreas

Introduction

ANDREAS FICHTNER, LUCIA GUALTIERI,
AND NORI NAKATA

In the late 1860s and early 1870s, the Italian priest Timoteo Bertelli (1826–1905) mounted a pendulum on the wall of the college where he taught natural sciences. With the help of a lens, he observed the phenomenon that he had traced in historic records back to the year 1643: small, spontaneous movements that did not have any obvious explanation. Following improvements of his instrument and thousands of experiments, he was able to exclude passing vehicles, wind, and temperature variations as possible sources (Davison, 1927). In 1872 he concluded that some of his microseismic observations coincided with distant earthquakes but also with barometric depressions (Bertelli, 1872). Furthermore, they seemed to be stronger in winter than in summer. He had made some of the first reliable observations of the ambient seismic field, providing a first indication of its possible sources.

I.1 The Ambient Seismic Field

The surface of the solid Earth is subject to continuously acting forces caused by the whole bandwidth of human activities, and by a wide range of natural phenomena. The ambient field generated by these forces constitutes the seismic background radiation of the Earth, historically referred to as *microseisms*. Observations in the early days of instrumental seismology already suggested a close relation between microseisms and meteorological conditions (e.g., Klotz, 1910; Burbank, 1912; Banerji, 1925), long before the first physical theories for microseism generation were proposed (e.g., Miche, 1944; Longuet-Higgins, 1950; Hasselmann, 1963).

The ambient field is omnipresent, and its amplitude varies with position, time, and frequency. The quasi-random nature of the ambient field, a small snapshot of which is shown in Figure I.1, disables the detection of distinct arrivals, well-known from the analysis of earthquakes, explosions, or other sources of short duration that

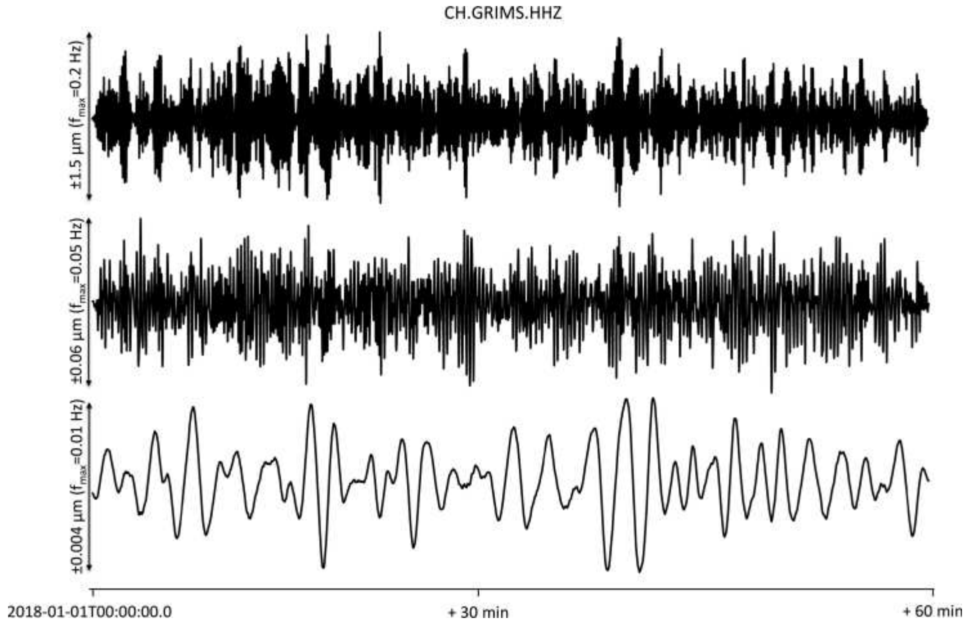

Figure I.1. One hour of ambient seismic field recording on the vertical component of station GRIMS, located at 1746 m altitude inside a tunnel system in the Swiss Alps. Shown are three traces, low-pass filtered at 0.2 Hz (top), 0.05 Hz (middle), and 0.01 Hz (bottom). Note the different vertical scales.

have traditionally been the subject of seismological investigations. The absence of an easily identifiable, deterministic signal has led to the common classification of the ambient field as *seismic ambient noise*. Despite being quasi-random, the ambient field obeys the laws of physics, which imprint a coherent structure into the apparent disorder. Most fundamentally, ambient noise is a seismic wavefield travelling between two points $\mathbf{x}_A$ and $\mathbf{x}_B$ at an apparent velocity v controlled by the elastic properties of the Earth's interior — just as any other wavefield. A wave packet $u(\mathbf{x}, t)$ passing by position $\mathbf{x}_A$ will reach position $\mathbf{x}_B$ after some time $\Delta t = |\mathbf{x}_A - \mathbf{x}_B|/v$. Therefore, we expect the wavefield recordings $u(\mathbf{x}_A, t)$ and $u(\mathbf{x}_B, t - \Delta t)$ to be statistically similar, or correlated.

Though being conceptually simple, this line of arguments suggests that the hidden coherence of the ambient field might be extracted through the computation of correlations between pairs of stations. Indeed, when averaging over long enough times, the interstation correlation

$$C(\mathbf{x}_A, \mathbf{x}_B, t) = \int u(\mathbf{x}_A, \tau)\, u(\mathbf{x}_B, t + \tau)\, d\tau \,, \tag{i}$$

approximates the wavefield that would be recorded at receiver position $\mathbf{x}_B$ if a source had acted at receiver position $\mathbf{x}_A$. Equation (i) effectively turns stations A

and B into a large interferometer that emphasizes those parts of the ambient field that travel coherently between them, while suppressing incoherent components. The interferogram $C(\mathbf{x}_A, \mathbf{x}_B, t)$ has two outstanding properties: It can be repeatedly computed at any time because noise is always present, and the virtual source A can be positioned anywhere, independent of any real wavefield sources.

Expressions that relate correlations of noise to a deterministic wave travelling between two points in space have been known for decades (e.g., Aki, 1957; Claerbout, 1968). As illustrated in Figure I.2, knowledge that coherent signals may be extracted largely precedes the recent boom of ambient noise seismology and of ambient noise tomography in particular (e.g., Sabra et al., 2005; Shapiro et al., 2005). This suggests that the apparent simplicity of equation (i) might be deceiving. Indeed, it hides the presence of instrumental noise and of transient signals, for

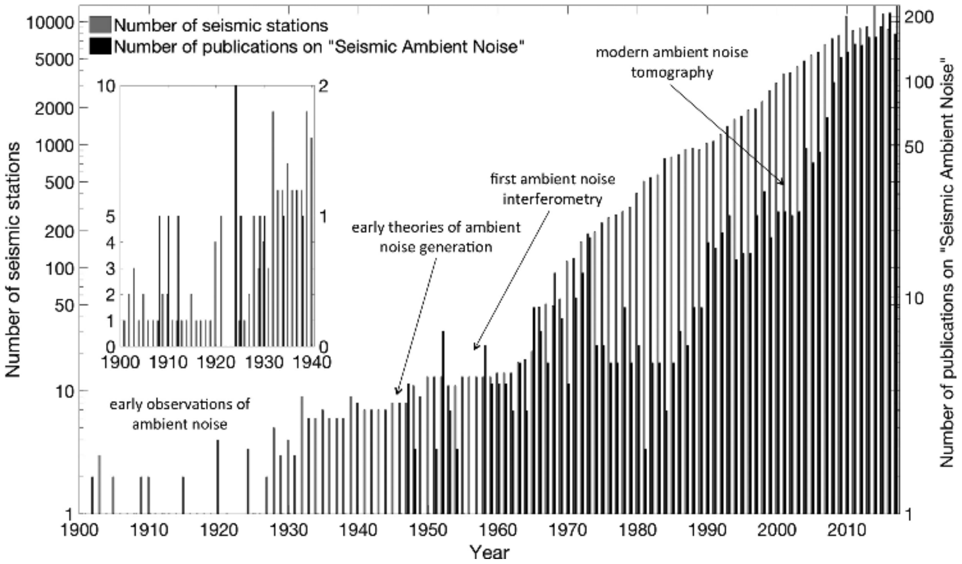

Figure I.2. Histograms showing the number of seismic stations in the *IRIS* data archive (www.iris.edu) and the number of publications in the *Web of Science* since the beginning of the 20th century, containing the words “seismic ambient noise” or “microseisms.” Early observations mostly related ambient noise recordings to meteorological phenomena (e.g., Klotz, 1910; Burbank, 1912; Banerji, 1925). Pioneering theories for ambient noise generation and interferometry appeared in the 1950s and 1960s (e.g., Miche, 1944; Longuet-Higgins, 1950; Aki, 1957; Hasselmann, 1963; Claerbout, 1968; Haubrich and McCamy, 1969). The number of publications experienced a rapid growth after the first applications of seismic interferometry to image the Earth structure (e.g., Sabra et al., 2005; Shapiro et al., 2005). The present book is intended to respond to the needs of an increasing number of scientists who are approaching the field of ambient noise seismology.

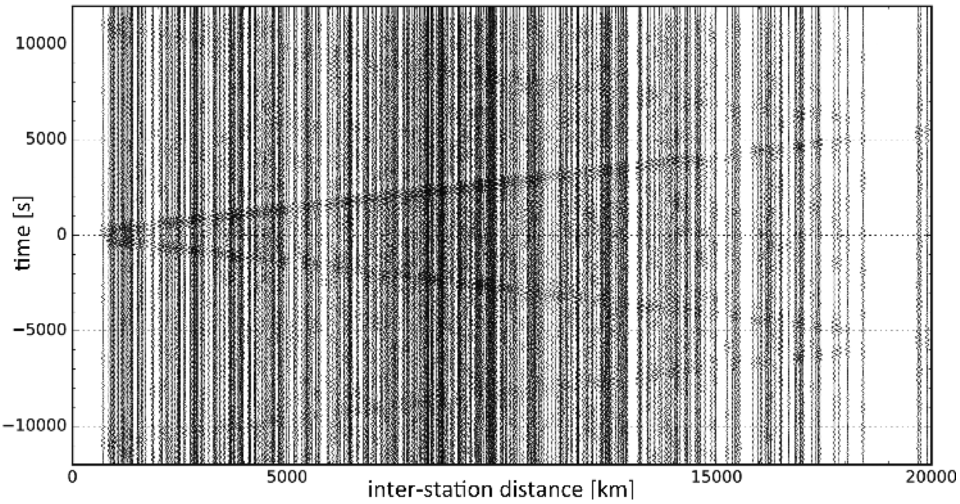

Figure I.3. Ambient noise correlations of 420 globally distributed station pairs, averaged over 1 year, from 1 January 2014 to 1 January 2015. The frequency range is 3–5 mHz. Coherent arrivals, corresponding to vertical-component Rayleigh waves, are clearly visible. (Figure prepared by Laura Ermert and Alexey Gokhberg.)

instance from earthquakes, that may, by far, overwhelm the low-amplitude ambient signal. As a consequence, the emergence of noise interferometry as a widely used technique had to await improvements of seismic instruments (with lower instrumental noise compared to ambient noise), the deployment of seismic arrays that enable the detection of weak coherent signals, and the development of processing techniques to suppress large-amplitude transients.

Today, the seismic ambient field is known to be coherent over length scales exceeding the circumference of the Earth (e.g., Nawa et al., 1998; Nishida et al., 2009), as illustrated in Figure I.3. It is used constructively in applications ranging from volcano and reservoir monitoring to global seismic tomography. Though the usefulness of the ambient field is meanwhile undisputed, its classification as noise stubbornly persists – probably as a deliberate antagonism between the past when most seismologists tried to suppress the ambient field, and the modern era where noise has indeed become signal. In choosing the title of this book, we could not resist following this trend.

I.2 The Scope of This Book

Writing a book about a topic that is as dynamic as ambient noise seismology is not a trivial task. On the one hand, we are convinced that such a book is needed,

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not only for our academic colleagues, but also for many young students working in this field. On the other hand, we are well aware of the fact that the very latest developments may not be included, and that the half-life of some of the book's content may be rather short.

Despite being a comparatively young branch of geophysics, ambient noise seismology is already too diverse to be covered with sufficient competence by a single author. This led us to compile a sequence of chapters written by well-known experts in their fields. While this strategy promotes depth and completeness, it also comes with the risk of slight divergences in opinion, notation, and presentation style. We hope that the benefits of this diversity overcompensate for its disadvantages.

First and foremost, this book is written for students and professionals with no or little experience in ambient noise seismology. Its character is largely educational. Therefore, the chapters are more or less self-contained, starting at the level of mathematics and physics of a beginning PhD student with some background in natural sciences.

We tried to cover a wide range of topics, including the observation and processing of ambient noise signals, the physical origin and numerical modeling of ambient noise, the theoretical foundations of noise and coda-wave interferometry, as well as applications from local to global scales. With limited space available, we had to make decisions concerning topics and the level of detail. We very much hope that colleagues whose topics we were unable to cover will understand this decision.

I.3 Outline

This book is roughly organized to proceed from the phenomenology and observations of the ambient noise field and its sources, to theory and methods for random wavefield interferometry, and finally to applications at various scales.

Chapter 1 by McNamara and Boaz (2018) describes the spectral properties of the ambient field, from the high frequencies that result from human activity, to low frequencies caused largely by ocean waves. The chapter introduces the power-spectral density as one of the most useful tools to characterize the noise level experienced by a seismic network. Knowing the noise power-spectral density is crucial for applications like earthquake monitoring and detection where small but interesting events may easily drown within the noise.

The wave type and propagation direction of the ambient field are the topics of Chapter 2 by Gal and Reading (2018), who introduce beamforming and polarization analysis. A special focus is on single-component plane-wave beamforming and on data-adaptive beamforming. These techniques are widely used to infer, for instance, the location and strength of ambient field sources in space and time.

The effect of seismic array geometry on the frequency-dependent resolution of a beamforming technique is discussed in detail.

Beamforming and polarization analysis hint at the actual physics of ambient noise generation, covered in Chapter 3 by Ardhuin et al. (2018). At frequencies below 1 Hz, where anthropogenic noise excitation is weak, ocean waves are the dominant source. Though seismic waves have wavelengths much longer than ocean waves, for a given frequency, two mechanisms are shown to provide efficient coupling to the solid Earth: the direct interference of ocean waves with shallow ocean bottom topography, and the interference of pairs of ocean waves that exert small pressure variations also at greater depths.

The extraction of coherent, deterministic signals from quasi-random noise recordings is the subject of Chapter 4 by Fichtner and Tsai (2018). Assuming wavefield equipartitioning or homogeneously distributed noise sources, correlations of noise as in equation (i) approximate interstation Green's functions, an important result that forms the basis of most ambient noise studies of the Earth's (time-dependent) internal structure. More general, emerging, approaches to noise interferometry make no assumptions on the nature of the ambient field, but also require the joint consideration of noise sources and Earth structure.

To the frustration of ambitious ambient field seismologists, the precious noise tends to be superimposed by transient signals with much higher amplitude, for instance, from earthquakes. The challenge of emphasizing noise so as to promote the emergence of correlation functions that reliably approximate a Green's function is the subject of Chapter 5 by Ritzwoller and Feng (2018). The authors describe many of the techniques that have been developed during the past decade, and that have proven to be effective in a wide range of settings.

Quasi-random wavefields may arise from quasi-random sources, such as ocean waves, but also from multiple scattering in the heterogeneous Earth. In this regard, scattering-generated coda waves and the ambient field are close relatives. As shown by Snieder et al. (2018) in Chapter 6, subtle changes of coda waves are valuable indicators of changes in Earth structure. Despite being diffuse in nature, coda waves may in fact be used to locate temporal velocity variations.

Chapter 7 by Shapiro (2018) is the first in a series of chapters focused on applications. It illustrates the use of surface waves in ambient noise to image Earth structure, at scales ranging from the top hundred meters to the upper hundred kilometers. Surface wave observables, such as frequency-dependent traveltimes and amplitudes, may be extracted from interstation correlations. When dense arrays with an interstation spacing smaller than the wavelength are available, ambient noise surface wave phase velocities can be extracted directly and used for subsurface velocity and anisotropy imaging.

While ambient noise correlations are often dominated by surface waves, coherent body wave arrivals tend to be more difficult to extract. In Chapter 8, Nakata and Nishida (2018) show that advanced processing techniques, partly developed for dense arrays, can promote the emergence of body waves in noise correlations. The extracted signals can be used in applications ranging from the imaging of subsurface reservoirs to the mapping of discontinuities at several hundred kilometers depth.

In contrast to transient signals from earthquakes or explosions, ambient noise is omnipresent, which enables repeated measurements and the monitoring of subsurface changes. In Chapter 9, Sens-Schönfelder and Brenguier (2018) explain how coda waves extracted from ambient noise correlations can be used in practice to detect and locate minute velocity changes in the Earth. Their survey of recent applications includes observations of time-variable Earth structure related to volcanic processes, earthquake-related stress adjustments, and environmental factors, such as local hydrology. Often, observed velocity changes are larger than expected for ideal rock-forming minerals, suggesting that micro-structures and their associated nonlinear effects play a significant role.

Finally, Chapter 10 by Hayashi (2018) provides an introduction to the use of ambient noise methods for near-surface engineering of the upper tens to hundreds of meters. This includes a review of the spatial auto-correlation (SPAC) method, which provides robust inferences of near-surface shear velocity structure, and applications for ground motion predictions based on the estimated 2D shear wave velocity structure.

A book intended to serve as an introduction to a dynamic and expanding field can never be complete. We nevertheless hope to have found a reasonable balance between observations, theory, and applications that whets the reader's appetite for more.

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