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Reverberations, coda waves and ambient noise: Correlations at the global scale and retrieval of the deep phases

P. Boué [a,*], P. Poli [b], M. Campillo [a], P. Roux [a]

[a] *Institut des Sciences de la Terre, Université Joseph Fourier and CNRS, Grenoble, France*
[b] *Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA, USA*

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ABSTRACT

Cross-correlation of continuous broadband records allows the retrieval of body waves at teleseismic distances. These continuous records mainly contain low-amplitude background noise that comes from ocean–crust interactions, although there are also many transient events of different magnitudes and their coda associated with reverberation and/or scattering. We present an analysis at the global scale of these different contributions in the context of body-wave retrieval using the cross-correlation technique. Specifically, we compare the correlation of long codas after strong earthquakes with those of the quietest days. In the long period range (25–100 s), several phases that propagate in the deep Earth are observed in the correlations of the signals recorded after earthquakes, with some of these phases showing non-physical polarization. At the same time, the global section of correlations shows a series of spurious branches. These features are reproduced with synthetic correlations. A stack of the quietest days of the year shows that body waves are still present, with relative amplitudes that are closer to those expected for the actual Earth response. When considering shorter periods (5–10 s), the reconstruction of the deep phases is not affected by the earthquake coda, due to the dominance of scattering over reverberation.

1. Introduction

From the regional to the global scale, ambient seismic noise primarily refers to the wavefield that is continuously produced by the interactions of the fluid envelopes, as mainly through ocean waves, and the solid Earth. The source mechanisms of these interactions are frequency dependent. Short-period noise (4 s to 30 s) is dominated by the two microseism peaks (e.g., Longuet-Higgins, 1950; Ardhuin et al., 2011). At longer periods (above 30 s), other mechanisms take place, which are also known as Earth hum (Kedar and Webb, 2005), such as the proposed shear-wave generation by infragravity waves (Fukao et al., 2010). Here the term "noise" is defined through its difference from the earthquake records. The duration of an earthquake record is defined with respect to a particular signal-to-noise ratio (SNR) threshold, and it varies with frequency for a given event magnitude. Furthermore, depending on the frequency, the scattering strength governs the ratio between the randomly scattered waves and the ballistic waves that reverberate between the main boundaries (i.e., the Earth surface, the core–mantle boundary).

It has been demonstrated that the elastic response between two stations can be evaluated by correlation of the records of scattered waves (Campillo and Paul, 2003) or long ambient noise records (Shapiro and Campillo, 2004). As expected from the theoretical Green's function between two points at the free surface, the correlations of continuous records are dominated by surface waves. The application of this approach has led to numerous examples of surface-wave imaging (e.g. Shapiro et al., 2005; Sabra et al., 2005a; Ritzwoller et al., 2011). The extension of the approach to body waves is indeed appealing, although the level of the remaining random fluctuations in the correlations makes the identification and exploitation of weak signals difficult. Furthermore, the sources of ambient noise are likely located at the surface, which results in a dominance of surface waves in the noise records. However, teleseismic body-waves have been observed in noise records (e.g. Vinnik, 1973; Gerstoft et al., 2008; Landès et al., 2010). The search for body waves in the correlations has been successful in the last few years, which started with the crustal phases (Zhan et al., 2010; Ruigrok et al., 2011; Poli et al., 2012a). Then, deep vertical reflections were detected from the mantle transition zone (Poli et al., 2012b) and from the core (Lin et al., 2013), with data from regional arrays. The complete teleseismic section was reconstructed by cross-correlation using a worldwide combination of arrays at short to long periods (5 s to 100 s; Boué et al., 2013) and at long to very long periods (30 s to

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* Corresponding author. Tel.: +33 (0)4 76 63 52 39.
E-mail address: pierre.boue@ujf-grenoble.fr (P. Boué).

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300 s; Nishida, 2013). These last studies demonstrated the feasibility of ambient noise body-wave imaging. Lin and Tsai (2013) also discussed core-phase retrievals using antipodal station pairs.

Different processing has been used in all of these studies, and especially regarding the removal of transient signals. Nishida (2013) applied the most rigorous processing, using the Global Centroid Moment Tensor catalog (Ekström et al., 2012) to systematically remove long time windows corresponding to earthquakes and the following few days, the number of which depended on the event magnitude (Nishida and Kobayashi, 1999). Lin et al. (2013) and Boué et al. (2013) used less restrictive criteria. At the global scale, both Nishida (2013) and Boué et al. (2013) observed mantle body waves but obtained different results for the amplitudes of the core phases, which are weaker, and were more realistic in the correlation computed by Nishida (2013). Note that large-amplitude core phases were also reported by Lin et al. (2013).

Boué et al. (2013) questioned the relevance of these high-amplitude phases, and suggested that they show non-physical features. By non-physical, we mean here that these features do not appear in the natural Green's function. For example, the phase in the correlation corresponding to ScS is observed at short distances with strong amplitudes for the vertical component, which leads to an obvious problem of polarization. The presence of spurious arrivals in the correlation section challenges the applicability of noise imaging to body-wave problems in the deep Earth. We address this problem here, by analyzing the conditions under which reliable information can be extracted from noise correlations.

On the other hand, Lin et al. (2013) observed a strong correlation between the phases that reach the deepest parts of the Earth (ScS, P′P′df) and the seismicity. They suggested that earthquakes mainly excite these body waves. Finally the observations of Lin et al. (2013) and Boué et al. (2013) included spurious phases that are not in the Earth response, or at least, have different relative amplitudes. The problem of spurious arrivals due to multiples was discussed on a smaller scale by Snieder et al. (2006). Concerning wave propagation at the global scale, Ruigrok et al. (2008) discussed the imperfect reconstruction of the Green's function from surface source records, which reveals the presence of spurious arrivals (ghost events). They derived an elastodynamic relation from the representation theorem showing that knowledge of the responses of the medium with and without the effects of the free surface is required to retrieve the exact Green's function. They verified this theoretical statement numerically with acoustic simulations.

By investigating the temporal evolution of the reconstructed Green's function after large seismic events, it is shown in the present study that the processing used can explain these observations at long periods. The structure of this report is the following. First, the dataset used and the processing applied are shown. Then we compare the quality of the reconstruction of some of the phases with the seismicity and the microseism excitation over a whole year. We present a synthetic example of the reconstruction of the partial Green's functions using a simulated long time reverberated coda wavefield to explain the characteristics of spurious arrivals. Finally, the study focuses on the particular propagation geometry between Finland and Japan.

2. Data and processing

In this study, one year was selected (2008) for the vertical-component records from a set of 420 stations distributed worldwide (Fig. 1). The BH channels are used after removal of the instrumental response, and decimation to a 5-Hz sampling frequency. Note that some of these stations are not available during the whole of the year period. All of the networks involved are detailed in Appendix A. The continuous records were processed similarly to Boué et al. (2013), which includes spectral normalization of the noise traces (whitening). Cross-correlations are computed for 4-h time windows, with a correlation lag of 4000 s, and normalized through the square root of the energy of both of the traces. They are directly stacked over one day, in the 5 s to 100 s period band. With this processing, we can detect and choose to remove the 4-h time window that contain ballistic arrivals of strong transient events (Boué et al., 2013). At the same time, the scattered and reverberated coda waves from earthquakes are retained. Eventually, the dataset contained more than 80 000 correlations per day, which corresponds to each possible station pair. These correlations can then be stacked either over a given period (e.g., days, weeks), which results in one correlation per station pair, or over space, which results to one correlation for a given average distance (bin) per day. The combination of both stacks corresponds to the global section, for which correlations are sorted as a function of distance from 0° to 180° with a bin size of 0.1°, and stacked over the year. This is shown in Fig. 2b, as the resulting vertical–vertical correlations, which represent the global average propagation. It is therefore justified to compare this with the synthetic Green's function computed in a spherical Earth using the Preliminary Reference Earth Model (Dziewonski and Anderson, 1981). Fig. 2a shows the synthetic seismograms computed using the spectral element method (Nissen-Meyer et al. 2007, 2008). We simulate a simple vertical point force with a Gaussian-shaped dominant period of 40 s. Although we note a general visual agreement that indicates that numerous deep phases are emerging from the correlation, there are some noticeable discrepancies, some of which have non-physical characteristics. The comparison between Fig. 2a and 2b should remain qualitative, as the 3D Earth structure favors the emergence of some phases after the spatial stack on the real data section (Fig. 2b). For example, Rayleigh waves can stack destructively, particularly at short periods, due to heterogeneities in shallow structures of the Earth.

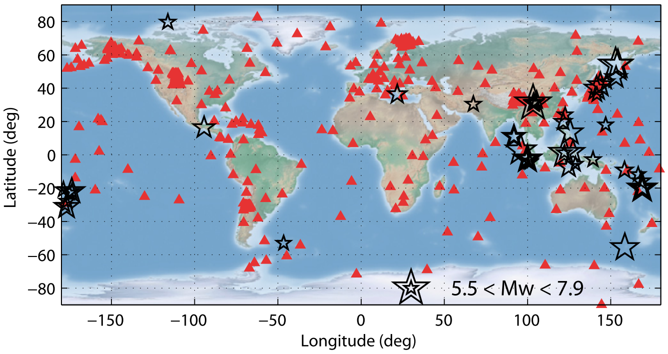

Fig. 1. Map of the network used in this study (see Appendix A for details). Triangles, location of the 420 seismic stations; stars, earthquakes (Mw > 5.5) that corresponds to HCDs.

In the global correlation section, some arrivals are present before the direct P-wave (Fig. 2b). As already noted, the ScS phase has too high relative amplitude. Even if the section representation with correlations stacked over distance bins enhances small move-out phases with a more constructive stack compared to large move-out phases like Rayleigh waves, it remains that ScS should not be visible on a vertical-component section at a distance close to 0°. Other deep phases, such as PKP and P′P′df, have high amplitudes relatively to the mantle, or even to the Rayleigh wave. Finally, there are some low-frequency spurious arrivals between the ScS and the P′P′df. In the following, we study how reverberated waves that follow large earthquakes affect the correlations. As the daily correlation for a given pair does not show a sufficient SNR, it is necessary to stack the correlations over space to produce