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Analysis of intermediate period correlations of coda from deep earthquakes

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ABSTRACT

We aim at assessing quantitatively the nature of the signals that appear in coda wave correlations at periods >20 s. These signals contain transient constituents with arrival times corresponding to deep seismic phases. These (body-wave) constituents can be used for imaging. To evaluate this approach, we calculate the autocorrelations of the vertical component seismograms for the Mw 8.4 sea of Okhotsk earthquake at 400 stations in the Eastern US, using data from 1 h before to 50 h after the earthquake. By using array analysis and modes identification, we discover the dominant role played by high quality factor normal modes in the emergence of strong coherent phases as ScS-like, and P'P'df-like. We then make use of geometrical quantization to derive the constituent rays associated with particular modes, and gain insights about the ballistic reverberation of the rays that contributes to the emergence of body waves. Our study indicates that the signals measured in the spatially averaged autocorrelations have a physical significance, but a direct interpretation of ScS-like and P'P'df-like is not trivial. Indeed, even a single simple measurement of long period late coda in a limited period band could provide valuable information on the deep structure by using the temporal information of its autocorrelation, a procedure that could be also useful for planetary exploration.

1. Introduction

Recent advancement in seismology followed the discovery of the long range correlations in the seismic wave field (Paul and Campillo, 2001; Campillo and Paul, 2003). Analyzing coda waves, it was shown that correlation averaged on long time series leads to the recovery of elastic response between two stations. Similar results were obtained by analyzing long time series of seismic noise (Shapiro and Campillo, 2004) in the microseismic period band, primarily generated by ocean–atmosphere and solid Earth interaction (Longuet-Higgins, 1950). Given the surface-to-surface setup (both noise sources and stations are located on the Earth's free surface) the resultant correlation or Green's function is dominated by surface waves. This approach led to numerous applications of ambient noise surface wave tomography in various regions of the world and at different scales. More recently, body waves reconstructed from correlation of seismic noise have been reported at both regional and global scale, and over a wide range of frequencies (Zhan et al., 2010; Poli et al., 2012b,a; Olivier et al., 2015). For teleseismic propagation and deep Earth phases emergence of body waves from correlation has been shown stable and free of spurious signals (Boué et al., 2013) for relatively short periods (∼7 s), where significant scattering is produced by small scale heterogeneity. The long period counterpart (>25 s) shows a more complex signal with correlations largely polluted by spurious arrivals (Boué et al., 2014). Careful analysis of continuous data on a global scale (Nishida, 2013; Boué et al., 2014), showed the importance of removing ballistic and coda waves derived from large earthquakes in order to mitigate these spurious arrivals. Using correlation of antipodal stations, Lin and Tsai (2013) also reported evidence of earthquake influence in the emergence of long period body waves. The presence of spurious arrivals in the resulting correlations (for example large amplitude ScS observed on the vertical to vertical component correlation over short interstation distances), suggests an incorrect interpretation of the correlation as the Green's function. As spurious arrivals are observed on correlation stacked over large number of earthquakes (Nishida, 2013; Boué et al., 2014), they do not represent a local observation, and the use of several earthquakes does not help the azimuthal averaging of the observed wavefield, required to reduce the effect of spurious. Before exploiting the derived long period body waves for travel time measurements, it is necessary to assess the nature of the spurious signals. Improper interpretation of the correlations of ambient noise records results from the incorrect representation of the Green's function with a source distribution along the free surface (Ruigrok et al., 2008), in addition to the argument of uneven distribution of actual sources of noise. At long periods, the scattering is weak and one could not expect a recovery from diffuse waves (Lobkis and Weaver, 2001;

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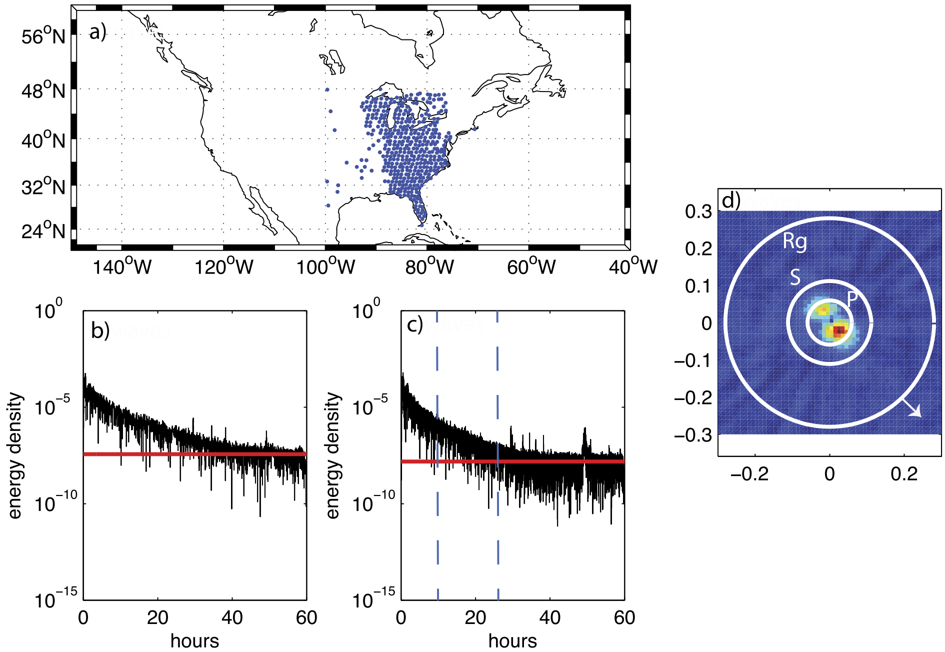

Fig. 1. Summary of coda waves observations. a) Map of the ∼400 Usarray stations available at the time of the sea of Okhotsk earthquake. The envelopes of signals for FB1 (7–12 mHz) (b) and FB2 (15–35 mHz) (c) are plotted together with estimated noise level (red line). The FK for FB2 is plotted in (d), together with velocity of slowness values for surface waves (Rg), direct P and direct S waves (white circles). The white arrow indicates the great circle path from the earthquake to the center of the network.

Campillo, 2006; Sens-Schönfelder et al., 2015) as in case of shorter period waves.

Independent studies (Maeda et al., 2006) showed that at large lapse time after big earthquakes, the coda signals at intermediate periods tend to be dominated by high Q spheroidal normal modes, whose eigenfunctions indicate propagation in the mantle and the core. The correlation indicates the properties of coherent propagation, that is, reverberations constituting normal modes in the late coda.

In this work our goal is to evaluate the accuracy of the reconstruction of the Green's function from the correlation of long period (>20 s) coda waves. To that scope we first analyze the constituents of the coda waves by array processing. We then perform sliding window correlations to observe which part of the coda wave contributes to the emergence of ScS or PKIKPPKIKP (P'P'df) that are suspected to be wrongly reconstructed at short interstation distances. We take advantage of a large array to perform spectral and velocity analysis of the correlation. This part of our study permits to individuate peaks on the spectrum of the correlations associated with particular apparent velocity. We can thus associate our observations with modes in well defined areas of the dispersion map. In complement to the eigenfrequencies of the modes, we present a geometric quantization approach, aimed at describing the set of rays associated with a mode, and thus illustrating access to time domain information such as reverberation times. Our results imply that direct interpretation of ScS and PKIKPPKIKP arrival is non-trivial, since long period coda correlation is not proportional to the Green's function. However, valuable information about the Earth's structure can still be extracted if alternative analysis of the times of correlation pulses (as our geometric quantization) is applied.

2. Long period coda wave properties

After large earthquakes, the signal with period larger than 20 s, remain above the noise level for several hours (Figs. 1b and c). To shed light on the waves forming the long period coda waves, we analyze the seismograms recorded at ∼400 vertical component broadband seismic stations composing the TA network in the continental US (Fig. 1a), after the Mw 8.4 Sea of Okhotsk earthquake. The expectation is that excitation of the surface waves in the late coda will be minimal due to the depth of the event (∼650 km), and therefore the body waves will be the dominant component of the signal.

The signals are filtered in two frequency bands: FB1: 7–12 mHz (142–83 s), FB2: 15–35 mHz (28–66 s). The 60 h envelopes, calculated using the Hilbert transform and no smoothing, for FB1 and FB2 are respectively shown in Fig. 1b and 1c. For FB1 we observe a stable decrease of energy from the maximum (∼ half an hour after the event) up to ∼35 h, when the signal goes below the noise level (Fig. 1). The signal filtered in FB2 shows a faster decay (Fig. 1b), with noise becoming dominant 30 h after the event. Both envelopes are characterized by slow decay with lapse time, and no evidence of late surface wave arrivals. Maeda et al. (2006) suggested that slow decay of the long-period coda is due to the contribution of spheroidal higher modes with large Q values.

We present in Fig. 1d the slowness (wavenumber) Fourier analysis of the coda records in the frequency band 2 for a time window between 10 to 24 h after the event. The result indicates the predominance of great circle propagation of high apparent velocity energy, as previously observed by Sens-Schönfelder et al. (2015). The lack of azimuthal spread of energy for the late coda is another indication of weak scattering for the intermediate period coda wave.

3. Coda correlation

Similar to previous studies (e.g Lin and Tsai, 2013) we aim to identify the part of the coda contributing to the emergence of long period body waves. We further study the propagation characteristics of the retrieved body waves, in order to asses the accuracy of travel time measurements.

The correlation of coda signal after the Mw 8.4 sea of Okhotsk earthquake is calculated for the 2 frequency bands using a 1 h moving window with 50% overlap. We used data from 1 h before and 50 h after the event, when the envelope of coda waves is well