Retrieving reflections from seismic background-noise recordings: theory and results

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Abstract

We review a general representation for retrieving seismic Green's functions between two observation points in lossless arbitrary inhomogeneous media and evaluate its application for passive seismic exploration. The theory is validated with a field example, in which several coherent events are retrieved from seismic background-noise recordings in a desert area. Results match well with events in an active exploration data set at the same location. The retrieval of the Earth's reflection response from crosscorrelations of seismic noise recordings can provide valuable information, which may otherwise not be available due to limited spatial distribution of seismic sources, difficult terrain conditions, economical reasons, etc.

Introduction

Seismic Interferometry (SI) is the process of generating new seismic responses by crosscorrelating seismic observations at different receiver locations. A first version of this principle was derived by Claerbout (1968), who showed that the reflection response of a horizontally layered medium could be synthesized from the autocorrelation of its transmission response. Later, he conjectured that in order to retrieve the reflection response of a 3D medium one needs to cross-correlate the transmission responses measured at different receivers. Wapenaar (2004) proved Claerbout's conjecture for a 3D inhomogeneous medium.

One application of Seismic Interferometry is to generate seismic reflection responses from passive noise recordings. Draganov et al. (2004) modeled transmission responses measured at the free surface of a 2D inhomogeneous medium in the presence of white noise sources in the subsurface. By cross-correlating these transmission responses at two surface locations A and B, they successfully retrieved the reflection response of the medium, as if measured at point A in the presence of an impulsive source at point B. They showed that the quality of the retrieved results depends strongly on the whiteness of the noise and the distribution of the noise sources.

In 2005, a small field experiment was carried out by SRAK with Shell's technical advice and support with the idea to test the applicability of the SI method for retrieval of seismic reflections. Draganov et al. (2007) cross-correlated 10 hours of the recorded background-noise, interpreted the results as seismic reflections and concluded that Seismic Interferometry proved successful in retrieving the Green's function from a passive survey.

In this paper we review theory and some applications of seismic interferometry for the purpose of passive seismic exploration, using a representation theorem by Wapenaar and Fokkema (2006).

Green's function representation

We consider an arbitrary inhomogeneous lossless medium in which we define an arbitrary-shaped closed surface ∂D with outward pointing normal vector $\mathbf{n} = \begin{pmatrix} n_1 & n_2 & n_3 \end{pmatrix}$. Inside this surface we define two points $\mathbf{x}_A$ and $\mathbf{x}_B$. In the frequency domain, the Green's function between these two points, $\hat{G}_{p,q}^{v,f}(\mathbf{x}_A, \mathbf{x}_B, \omega)$, can be represented as (Wapenaar and Fokkema, 2006):

$$2\Re\left\{\hat{G}_{p,q}^{v,f}(\mathbf{x}_A, \mathbf{x}_B, \omega)\right\} =$$
$$-\oint_{\partial D}\left(\left\{\hat{G}_{p,i}^{v,f}(\mathbf{x}_A, \mathbf{x}, \omega)\right\}^* \hat{G}_{q,ij}^{v,h}(\mathbf{x}_B, \mathbf{x}, \omega) + \left\{\hat{G}_{p,ij}^{v,h}(\mathbf{x}_A, \mathbf{x}, \omega)\right\}^* \hat{G}_{q,i}^{v,f}(\mathbf{x}_B, \mathbf{x}, \omega)\right)n_j d^2\mathbf{x} \tag{1}$$

The superscripts of the Green's functions represent the observed quantity (v = particle velocity) and the source quantity (f = force source, h = deformation source), respectively. The subscripts represent the components of the observed quantity and the source quantity, respectively. Further $\Re$ denotes the real part and ω the angular frequency. The terms $\hat{G}_{p,i}^{v,f}$ and $\hat{G}_{p,ij}^{v,h}$, under the integral in the right hand side of equation 1, represent responses of force and deformation sources at $\mathbf{x}$ on ∂D. The products $\left\{\hat{G}_{p,i}^{v,f}\right\}^* \hat{G}_{q,ij}^{v,h}$, etc. correspond to crosscorrelations in the time domain. Hence, the right-hand side can be interpreted as the integral of the Fourier transform of crosscorrelations of observations of wavefields at $\mathbf{x}_A$ and $\mathbf{x}_B$, respectively, due to impulsive sources at $\mathbf{x}$ on ∂D; the integration takes place along the source coordinate $\mathbf{x}$. The left-hand-side of equation 1 is the Fourier transform of $G_{p,q}^{v,f}(\mathbf{x}_A, \mathbf{x}_B, t) + G_{p,q}^{v,f}(\mathbf{x}_A, \mathbf{x}_B, -t)$, which is the superposition of the response at $\mathbf{x}_A$ due to an impulsive source at $\mathbf{x}_B$ and its time-reversed version. Since the Green's function $G_{p,q}^{v,f}(\mathbf{x}_A, \mathbf{x}_B, t)$ is causal, it can be obtained by taking the causal part of this superposition (or, more precisely, by multiplying this superposition with the Heaviside step function). Alternatively, in the frequency domain the imaginary part of $\hat{G}_{p,q}^{v,f}(\mathbf{x}_A, \mathbf{x}_B, \omega)$ can be obtained from the Hilbert transform of the real part.

The retrieved Green's function is exact and contains, apart from the direct wave between $\mathbf{x}_B$ and $\mathbf{x}_A$, all scattering contributions (primaries and multiples) from inhomogeneities inside as well as outside ∂D. When ∂D is a sphere with sufficiently large radius, and the medium along and outside ∂D is homogeneous and isotropic, equation 1 can be approximated by (Wapenaar and Fokkema, 2006),

$$2\Re\left\{\hat{G}_{p,q}^{v,f}(\mathbf{x}_A, \mathbf{x}_B, \omega)\right\} \approx \frac{2}{\rho c^K}\oint_{\partial D}\left\{\hat{G}_{p,K}^{v,\phi}(\mathbf{x}_A, \mathbf{x}, \omega)\right\}^* \hat{G}_{q,K}^{v,\phi}(\mathbf{x}_B, \mathbf{x}, \omega)d^2\mathbf{x}. \tag{2}$$

Upper-case Latin subscripts take on the values 0,1,2 and 3; the repeated subscript K represents a summation from 0 to 3. The Green's functions in the right-hand side

represent the observed particle velocities at $\mathbf{x}_A$ and $\mathbf{x}_B$ due to sources at $\mathbf{x}$ on ∂D. The superscript ϕ denotes that these sources are P-wave sources (for $K=0$) and S-wave sources with different polarizations (for $K=1,2,3$). Hence, the summation over the repeated subscript K represents a summation over P- and S-wave source responses. Finally, ρ is the mass density and c^K corresponds to the P-wave velocity for $K=0$ and to the S-wave velocity for $K=1,2,3$ along ∂D. Since the right-hand side contains one crosscorrelation product of monopole responses only, this representation is better suited for seismic interferometry than equation 1. For a detailed analysis of the approximations in equation 2, see Wapenaar and Fokkema (2006). Evaluation of either equation 1 or 2 requires that sources are available on a closed surface ∂D around the observation points $\mathbf{x}_A$ and $\mathbf{x}_B$.
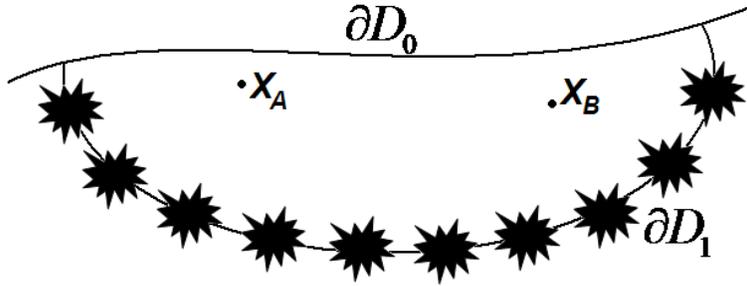
Figure 1: Configuration for passive data.

Configuration for passive data
For the situation of passive data we assume that natural sources are available in the subsurface and that the responses of these sources are measured by receivers at or below the free surface. We divide the closed surface ∂D into a part ∂D_0 coinciding with the free surface and a part ∂D_1 containing the sources in the subsurface, see Figure 1. For this situation equation 1 needs to be evaluated over ∂D_1 only. This is exact as long as ∂D_0 and ∂D_1 together form a closed surface. Hence, the direct wave as well as the primaries and multiples in $\hat{G}_{p,q}^{v,f}(\mathbf{x}_A,\mathbf{x}_B,\omega)$ are correctly retrieved by the integral along the sources on ∂D_1. A more intuitive explanation is that the free surface ∂D_0 acts as a mirror, which obviates the need of having sources on a closed surface. When the sources at ∂D_1 are uncorrelated noise sources, the right-hand side of equation 2 reduces to a direct crosscorrelation of the observed wavefields at $\mathbf{x}_A$ and $\mathbf{x}_B$; that is

$$2\Re\left\{\hat{G}_{p,q}^{v,f}(\mathbf{x}_A,\mathbf{x}_B,\omega)\right\}\hat{S}(\omega) \approx \frac{2}{\rho c_P}\left\langle\hat{v}_p^{obs,*}(\mathbf{x}_A,\omega)\hat{v}_q^{obs}(\mathbf{x}_B,\omega)\right\rangle, \tag{3}$$

where $\langle . \rangle$ denotes a spatial ensemble average, $\hat{S}(\omega)$ the power spectrum of the noise, c_P is the P-wave velocity, $\hat{v}_p^{obs}$ and $\hat{v}_q^{obs}$ are the observed p- and q-component of the particle velocity.

Example

Draganov et al. (2007) succeeded in retrieving seismic reflections from passive noise recordings. Ten hours of background-noise data were recorded along an array of 17 three-component geophones in a desert area. The specific place for the array was chosen to be along a line of an active exploration survey.

The panels were energy normalized and cross-correlated. The result was bandpass-filtered between 2 and 10 Hz. The retrieved source-receiver pairs with the same offset were summed. In Figure 2A we show the resulting common-offset stack panel after energy normalization. The same procedure was applied to the active data, using 17 common-source gathers with source positions around the corresponding locations of the geophones from the passive array. To eliminate the surface wave the result had to be f-k filtered and low-cut filtered at 20 Hz, yielding Figure 2B. Still the retrieved surface waves in Figure 2A hampers the good comparison between the datasets. Due to the very narrow frequency band of the retrieved data, f-k filtering could not be applied, but it was chosen to suppress the inclined coherent events in a different way. By simply summing the retrieved common-source gathers (a so-called brute stack) a response of a line source along the passive array was created – see Figure 2C. The retrieved coherent events show good arrival-time agreement with the reflected hyperbolae in the active data, as indicated with the red lines between Figure 2B and Figure 2C. It can thus be concluded that the retrieved coherent events in Figure 2C are retrieved reflection arrivals.

Conclusion

We have reviewed a general representation of Green's functions in terms of crosscorrelations of wavefields at two observation points in lossless, arbitrary inhomogeneous media. We have discussed the application of this representation for extracting Green's functions from passive background-noise recordings. The theory is validated with a field example, where several coherent events were retrieved that aligned well with events in active exploration data at the same location.
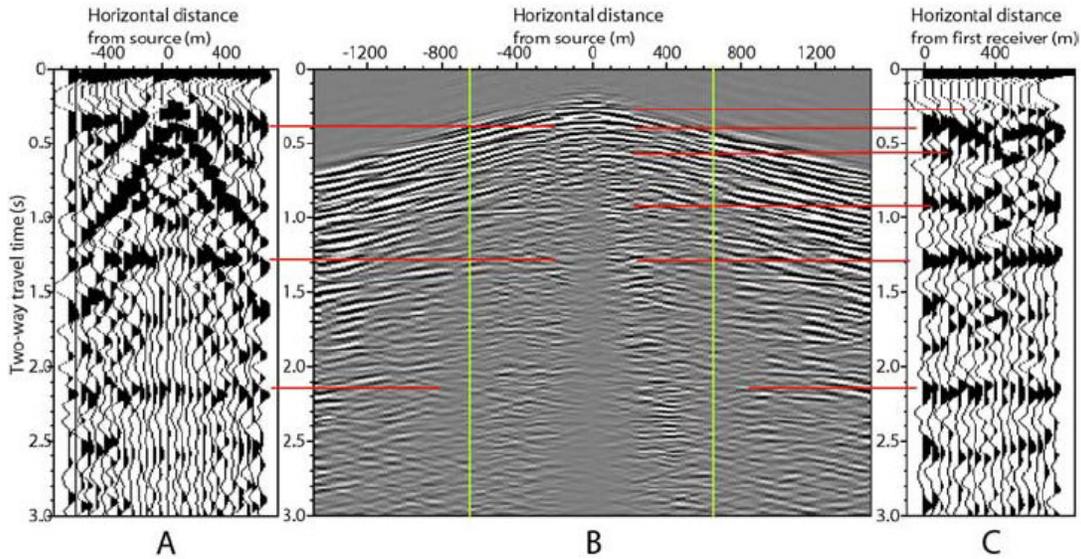
Figure 2: (A) Common-offset stack panel obtained from the common-source gathers retrieved from the passive data. (B) Common-offset stack panel after surface wave elimination in the active survey. (C) Line-source response obtained by summing the common-source panels retrieved from the passive data (brute stack).

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