

Seismic interferometry by multi-dimensional deconvolution for passive transient sources

Joost van der Neut, Kees Wapenaar and Elmer Ruigrok
Delft University of Technology, Delft, the Netherlands.

It has been shown that cross-correlation of passive seismic recordings at the earth surface can yield a Green's function as if both sources and receivers were at the surface. One of the important underlying assumptions is that the passive sources are uniformly distributed throughout the subsurface. This assumption is generally not fulfilled. We present an alternative approach that can be applied to transient passive seismic recordings registered by an array of receivers, where Cross-Correlation (CC) is replaced by Multi-Dimensional Deconvolution (MDD). We show that MDD can correct implicitly for a non-uniform source distribution and demonstrate this with a synthetic example. The main drawback of our methodology is that individual transient events need to be identified and isolated in the shot records.

Introduction

In Seismic Interferometry (SI) we generally cross-correlate the registrations at two receiver locations to retrieve a Green's function as if one of these receivers is a (virtual) source and the other is a receiver (Schuster, 2001; Wapenaar and Fokkema, 2006). One application of this theory can be found in passive seismics, where passive subsurface sources are exploited to retrieve a Green's function between two receivers without requiring any active source power (Draganov et al., 2006). Assumed is that the sources are equally distributed along some closed boundary in the subsurface. However, passive sources generally do not obey this assumption, causing improper convergence to the desired reflection response and the emergence of spurious artifacts. In this abstract we show that replacing Cross-Correlation (CC) by Multi-Dimensional Deconvolution (MDD) can overcome this problem in some cases, given that the noise sources have a transient character and are detectable in the noise gathers individually. First we discuss the theory of passive SI by CC and MDD. To demonstrate some of the benefits of MDD, we compare the results of both methodologies on a simple synthetic acoustic example with an irregular passive source distribution.

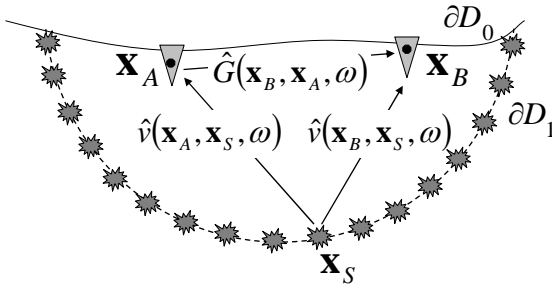


Figure 1: Configuration for a typical passive survey as discussed in this abstract.

Seismic Interferometry by Cross-Correlation (CC)

We assume that passive sources are distributed along some boundary in the subsurface ∂D_1 . Together with the free (earth) surface ∂D_0 , that acts as an elastic 'mirror' (Draganov et al., 2006), ∂D_1 constructs a closed surface $\partial D = \partial D_0 + \partial D_1$, surrounding the receiver locations \mathbf{x}_A and \mathbf{x}_B . It can now be shown that summation of the cross-correlations of the particle velocity registrations at \mathbf{x}_A and \mathbf{x}_B results in a Green's function between these receivers. This has formally been derived by Wapenaar and Fokkema (2006) as

$$\left\{ \hat{G}(\mathbf{x}_B, \mathbf{x}_A, \omega) + \hat{G}^*(\mathbf{x}_B, \mathbf{x}_A, \omega) \right\} |S(\omega)|^2 \approx \int_{\partial D_1} \hat{v}(\mathbf{x}_B, \mathbf{x}_S, \omega) \hat{v}^*(\mathbf{x}_A, \mathbf{x}_S, \omega) d\mathbf{x}_S. \quad (1)$$

On the right hand side, $\hat{v}(\mathbf{x}_i, \mathbf{x}_j, \omega)$ is the particle velocity registered at \mathbf{x}_i , due to a source at \mathbf{x}_j in the frequency domain, ω denotes the angular frequency and superscript $*$ stands for complex conjugation. On the left hand side we can recognize the causal Green's function $\hat{G}(\mathbf{x}_B, \mathbf{x}_A, \omega)$ between a source at \mathbf{x}_A and a receiver at \mathbf{x}_B . We also find the complex conjugate of $\hat{G}(\mathbf{x}_B, \mathbf{x}_A, \omega)$, corresponding to the acausal (or time-reversed) counterpart of this Green's function. Finally, $|S(\omega)|^2$ is the auto-correlation of the average passive source wavelet. Berkhout (1982) proposed an effective way to discretize integral equations in the frequency domain. To apply his methodology to equation 1, we formulate matrices $\hat{V}(\omega)$ and $\hat{G}(\omega)$, containing wavefields $\hat{v}(\mathbf{x}_i, \mathbf{x}_j, \omega)$ or $\hat{G}(\mathbf{x}_i, \mathbf{x}_j, \omega)$, respectively, with each column

containing a fixed source position \mathbf{x}_j and variable receiver positions \mathbf{x}_i at frequency ω . Equation 1 can then be discretized as

$$\hat{G}(\omega) + \hat{G}^*(\omega) \approx \frac{2}{\rho c} |S(\omega)|^{-2} \hat{V}(\omega) \hat{V}^H(\omega), \quad (2)$$

where superscript H denotes the Hermitian or complex conjugate transposed. We use equation 2 to redatum the passive sources in the subsurface to the receiver array by CC. Note that this method requires an estimate of the average source wavelet spectrum, which in practice can be hard to obtain. Further we assumed a uniform sampling of the source integral in equation 1, which may not be fulfilled in practice.

Seismic Interferometry by Multi-Dimensional Deconvolution (MDD)

In some cases we may be able to distinguish transient sources in the passive noise recordings (Draganov et al., 2007). The total recordings \hat{v} may thus be separated into direct arrivals \hat{v} and their multiples $\Delta\hat{v} = \hat{v} - \hat{v}$. Similarly, the pressure field at the receiver array \hat{p} can be separated in direct arrivals \hat{p} and their multiples $\Delta\hat{p} = \hat{p} - \hat{p}$. If we convolve the direct pressure field with a Green's function $\hat{G}(\mathbf{x}_B, \mathbf{x}_A, \omega)$ and integrate over the receiver locations at the surface ∂D_0 , we can construct the multiples of the particle velocity field according to

$$\Delta\hat{v}(\mathbf{x}_B, \mathbf{x}_S, \omega) = \int_{\partial D_0} \hat{G}(\mathbf{x}_B, \mathbf{x}_A, \omega) \hat{p}(\mathbf{x}_A, \mathbf{x}_S, \omega) d\mathbf{x}_A. \quad (3)$$

The aim of MDD is to retrieve the Green's function $\hat{G}(\mathbf{x}_B, \mathbf{x}_A, \omega)$ by inverting equation 3. If the medium is laterally invariant, we can construct the direct pressure field from \hat{v} through the relation $\tilde{p} = \rho/q\tilde{v}$, where the tilde denotes the frequency-wavenumber domain and q is the vertical slowness. Next we can discretize integral equation 3, in a similar fashion as we did for equation 1, yielding

$$\Delta\hat{V}(\omega) = \hat{G}(\omega) \hat{P}(\omega), \quad (4)$$

where $\hat{P}(\omega)$ contains $\hat{p}(\mathbf{x}_A, \mathbf{x}_S, \omega)$, with each column containing a fixed source position \mathbf{x}_S and variable receiver positions \mathbf{x}_A at frequency ω ; \hat{G} and \hat{P} are similar discretizations of \hat{G} and \hat{p} . We can solve equation 4 for each frequency component separately by least-squares inversion, according to

$$\hat{G}(\omega) \approx \Delta\hat{V}_3(\omega) \hat{P}^H(\omega) \left[\hat{P}(\omega) \hat{P}^H(\omega) + \varepsilon^2 \mathbf{I} \right]^{-1}, \quad (5)$$

where ε^2 is a stabilization parameter and \mathbf{I} is an identity matrix. We use equation 5 to retrieve the Green's function by MDD. Note that the average source wavelet is not required and no assumptions have been made on the sampling and aperture of the source array. However, sufficient illumination and sufficient receivers need to be present, to provide a complete representation of the integral in equation 3.

Numerical example

In Figure 2a we show the geometry of a 2D synthetic acoustic model. 51 receivers are placed at the earth surface, with 40 m spacing. In the subsurface we find a number of reflectors. Under these reflectors, 250 subsurface sources are present, distributed quasi-uniformly, with two clusters of relatively high source density. The source wavelets vary randomly with peak frequencies ranging between 10 and 30 Hz. A typical passive record is shown in Figure 2b. Note that we can clearly differentiate the direct arrivals from the multiples in this example. Our aim is to retrieve a shot record as if there was a virtual source at the central receiver location. We will compare results of CC and MDD based methodology. In Figure 3a we show the shot record retrieved by CC (equation 2) in solid red, overlaying a reference response in dashed black, obtained by placing an active source at the virtual source location. Due to the presence of the noise clusters, the central integral in equation 1 is not well sampled and the retrieving the Green's function by CC is non-ideal. We observe improper amplitudes, improper kinematics and the presence of spurious artifacts. For the application of MDD, we time-gate the direct fields (Figure 2b) and deconvolve the multiples (as described by equation 5). Results are shown in Figure 3b. Notice that the artifacts as appearing in the CC based method have completely been removed almost completely by the deconvolution procedure.

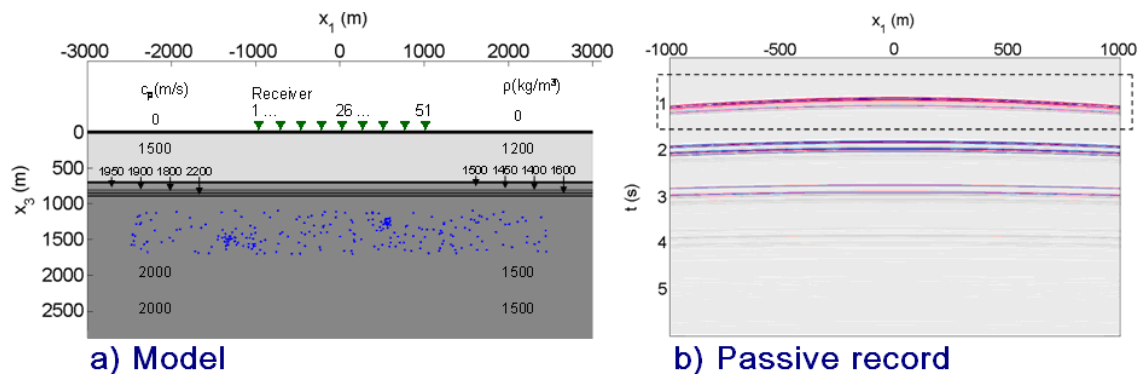


Figure 2: (a) Configuration of the numerical example; 250 transient subsurface sources are present in the subsurface (indicated by blue dots), distributed randomly with two clusters of high source density; 51 geophones are located at the earth surface. (b) A typical passive transmission record for an arbitrary subsurface source, including the time-gate that was used to isolate the direct wavefield.

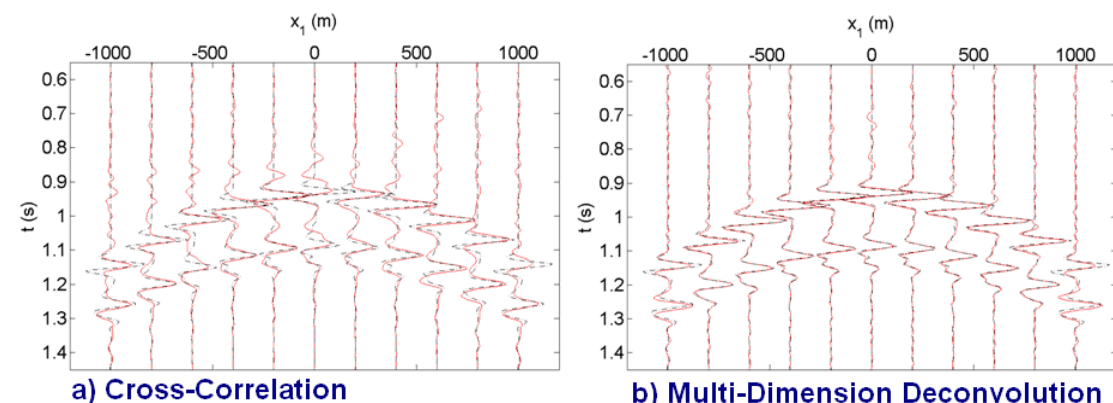


Figure 3: (a) Retrieved shot record by CC based SI (solid red), overlaying the reference response (dashed black); (b) Retrieved shot record by MDD based SI (solid red), overlaying the reference response (dashed black).

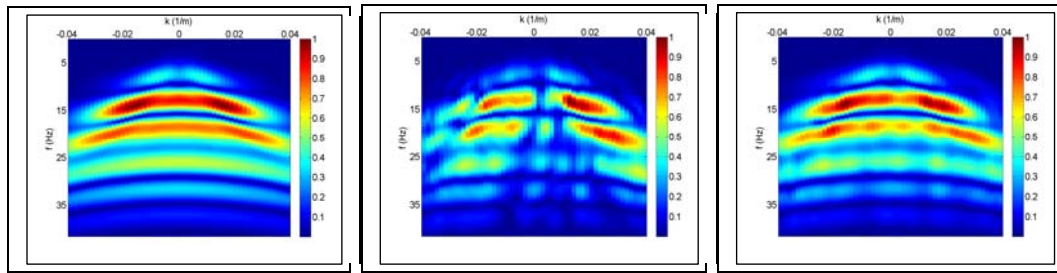


Figure 4: (a) Directly modeled shot record in the FK-domain; (b) Retrieved shot record by CC based SI in the FK-domain; (c) Retrieved shot record by MDD based SI in the FK-domain.

The strength of MDD can also be observed in the frequency-wavenumber- or FK-domain. In Figure 4a we show the FK-representation of the directly modeled reference response of the central shot record. In Figure 4b we show the retrieved response by CC. Notice that particular parts of the spectrum have stronger illumination than others in the CC based response. If we study the FK-representation of the data obtained through MDD (Figure 4c) we can see that these incoherencies have been averaged by the deconvolution of the wavefields, yielding a better convergence to the reference response.

Conclusion

We have shown that the problem of non-uniform distribution of passive sources that hampers many applications of Seismic Interferometry may in some cases be overcome by replacing Cross-Correlation by Multi-Dimensional Deconvolution. We illustrated this with a simple synthetic example. The proposed method of Multi-Dimensional Deconvolution works in general inhomogeneous anisotropic media and even loss terms can be taken into account. Knowledge of the source wavelet is not required and can vary from source to source. However, the greatest drawback is that the passive sources need to be of transient nature and should be detectable in the data. Moreover, the waveforms need to be sufficiently simple such that the direct fields can be separated from their multiples.

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