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Retrieval of Reflections from Ambient Noise Using the Incident Fields (Point-spread Function) as a Diagnostic Tool

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SUMMARY

Seismic interferometry (SI) enables the retrieval of virtual-shot records at the location of receivers. SI with ambient noise allows the retrieval of the reflection response of the subsurface without the need of any active source. The quality of the retrieved response is dependent on the illumination characteristics of the ambient noise.

For the exploration frequency band of interest, in low-seismicity regions most of the energy in the recorded noise comes from sources at or near the surface. Such sources would mainly contribute to retrieval of surface waves, which would show up as the most energetic arrivals in the retrieved results. Because of that, the generally weaker retrieved reflections would be buried by the retrieved surface waves. Aiming at improving SI retrieved reflections, we propose a diagnostic tool applied after cross-correlation that separates the correlated noise panels into surface-wave dominated and body-wave dominated. We show results of the application of the tool to modelled data for noise sources acting separately in time and for noise sources overlapping in time. Finally, we show results from the application of the diagnostic tool to ambient noise recorded in Northern Netherlands.

Introduction

Seismic interferometry (SI) is the process that enables the retrieval of the impulse response (Green's function) between receivers as if a virtual source were at one of the receiver locations. The retrieval may be achieved through correlation, convolution or deconvolution processes using recordings originating from active or passive sources (for an overview, see, e.g, Schuster, 2009). SI with passive sources requires only ambient-noise recordings in order to retrieve the reflection response of the subsurface. The quality of the retrieved response depends on the characteristics of the noise and the source distribution (in conjunction with the complexity of the subsurface), and the recording time length.

SI by cross-correlation with ambient noise has successfully retrieved surface waves (e.g., Shapiro and Campillo, 2004) and more recently even reflections (Draganov *et al.*, 2009). The dominant types of retrieved waves depend on the dominant waves in the recorded noise. When the predominant energy illuminating the recording (passive) array consists of surface-wave noise, generated by sources close to or at the Earth's surface, the retrieved results will exhibit surface waves, that will drown out the retrieved weaker reflections. In such a case, to retrieve reflections, one needs to process the ambient noise with the aim to suppress the surface-wave arrivals in it. Even when reflections are retrieved, they might not be obtained correctly due to preferential illumination of the recording array with body waves from certain directions.

Because of the above reasons, we propose here a fast method to evaluate the illumination characteristics of the ambient noise. The method is based on the evaluation of the so-called virtual source function. The results of the evaluation can be used to improve the qualtity of the retrieved reflection response. We explain the approach using modelled data from transient and continuous noise sources. We also show preliminary results from the application of the method to ambient-noise recordings from the North of the Netherlands.

Method

To retrieve the Green's function $G(\mathbf{x}_A,\mathbf{x}_B,\omega)$ between a receiver at $\mathbf{x}_A$ and a virtual source at $\mathbf{x}_B$ from recordings at these two points due to separately acting in time transient sources with an equal power spectrum $S_0(\mathbf{x}_S,\omega)$ at points $\mathbf{x}_S$ along a boundary $\partial\mathbb{D}$, one can use the relation (Wapenaar and Fokkema, 2006),

$$\Re\left\{G(\mathbf{x}_A,\mathbf{x}_B,\omega)\right\}S_0(\omega) \approx \frac{1}{\rho c}\oint_{\partial\mathbb{D}} \left\{p^{obs}(\mathbf{x}_A,\mathbf{x}_S,\omega)\right\}^{*}\, p^{obs}(\mathbf{x}_B,\mathbf{x}_S,\omega)\, d\mathbf{x}_S, \tag{1}$$

where $\Re$ stands for real part, ρ and c are the constant mass density and velocity, respectively, of the medium at and outside $\partial\mathbb{D}$, and ω is the angular frequency; $\hat{p}^{obs}(\mathbf{x}_A,\mathbf{x}_S,\omega)$ is the observed wave field at $\mathbf{x}_A$ due to a transient source at $\mathbf{x}_S$, and the asterisk denotes complex conjugation. If noise sources are acting simultaneously, then one can use the relation:

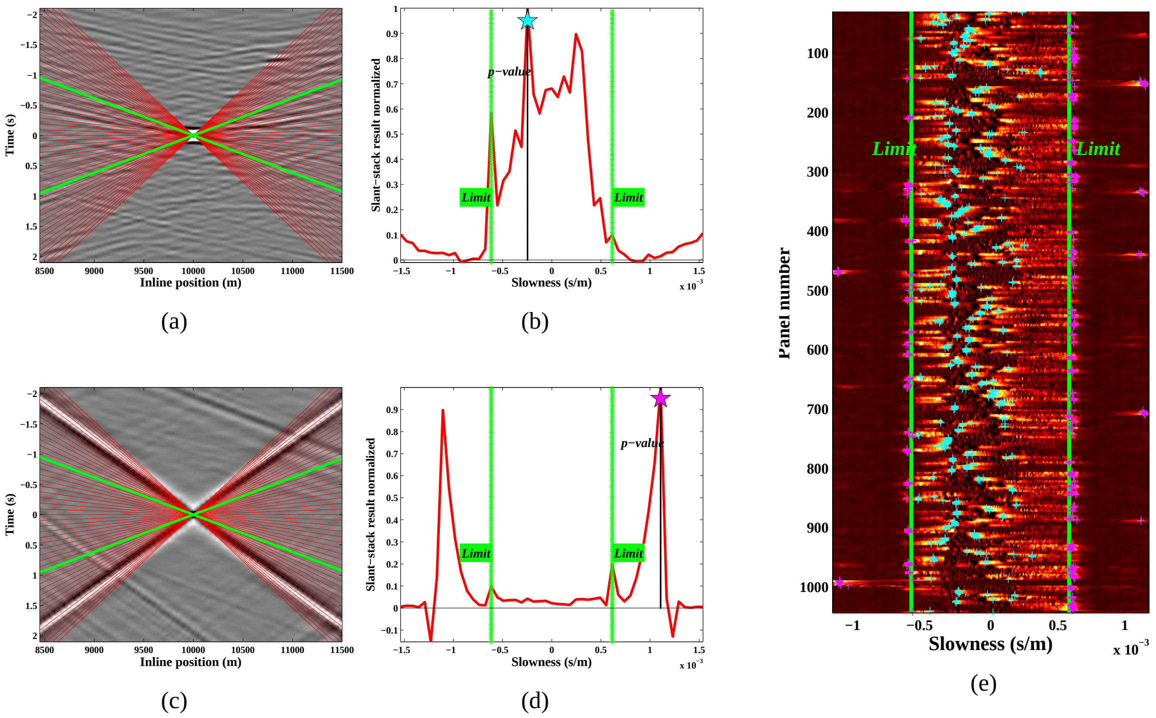
$$\Re\left\{G(\mathbf{x}_A,\mathbf{x}_B,\omega)\right\}\, S_0(\omega) \approx \frac{1}{\rho c}\left\langle \left\{p^{obs}(\mathbf{x}_A,\omega)\right\}^{*}\, p^{obs}(\mathbf{x}_B,\omega)\right\rangle. \tag{2}$$

It was assumed that the noise sources are white and uncorrelated, $p^{obs}(\mathbf{x}_A,\omega)$ stands for the total recorded noise at $\mathbf{x}_A$ due to all the noise sources, and $\langle\cdot\rangle$ denotes spatial ensemble average.

The correlation in the right-hand side of equations 1 and 2 for one virtual source (at $\mathbf{x}_B$) and a number of receivers (at $\mathbf{x}_A$) gives a correlation gather with causal and anticausal parts. The events in this gather that pass through $t = 0$ s and the position of the virtual source are informative of the illumination characteristics of the sources along the boundary $\partial\mathbb{D}$. We call the collection of these events the virtual-source function. Note that this function is an approximation of the point-spread function (Wapenaar and van der Neut, 2010).

Virtual-source functions of each of the transient sources from correlation panels with transient sources illustrate the illumination characteristics of each of these transient sources. The extracted characteristics could be used to decide if a correlation panel, that is the integrand in equation 1, from a certain source on $\partial\mathbb{D}$ would contribute to retrieval of mainly body waves or of mainly surface waves and therefore be kept or discarded, respectively. With continuous noise recordings, the virtual-source functions is dependent on the noise acting during the recording time. Evaluation of the virtual-source function for a relatively short time window would diagnose the illumination characteristics of the noise sources active during that time window.

There are several ways to study the illumination characteristics using the virtual-source function. One approach is to make use of $\tau - p$ or slant-stack transform of field u: $\tilde{u}(\tau, p) = \int u(\tau + px, x)\, dx$, This



(a) (b)

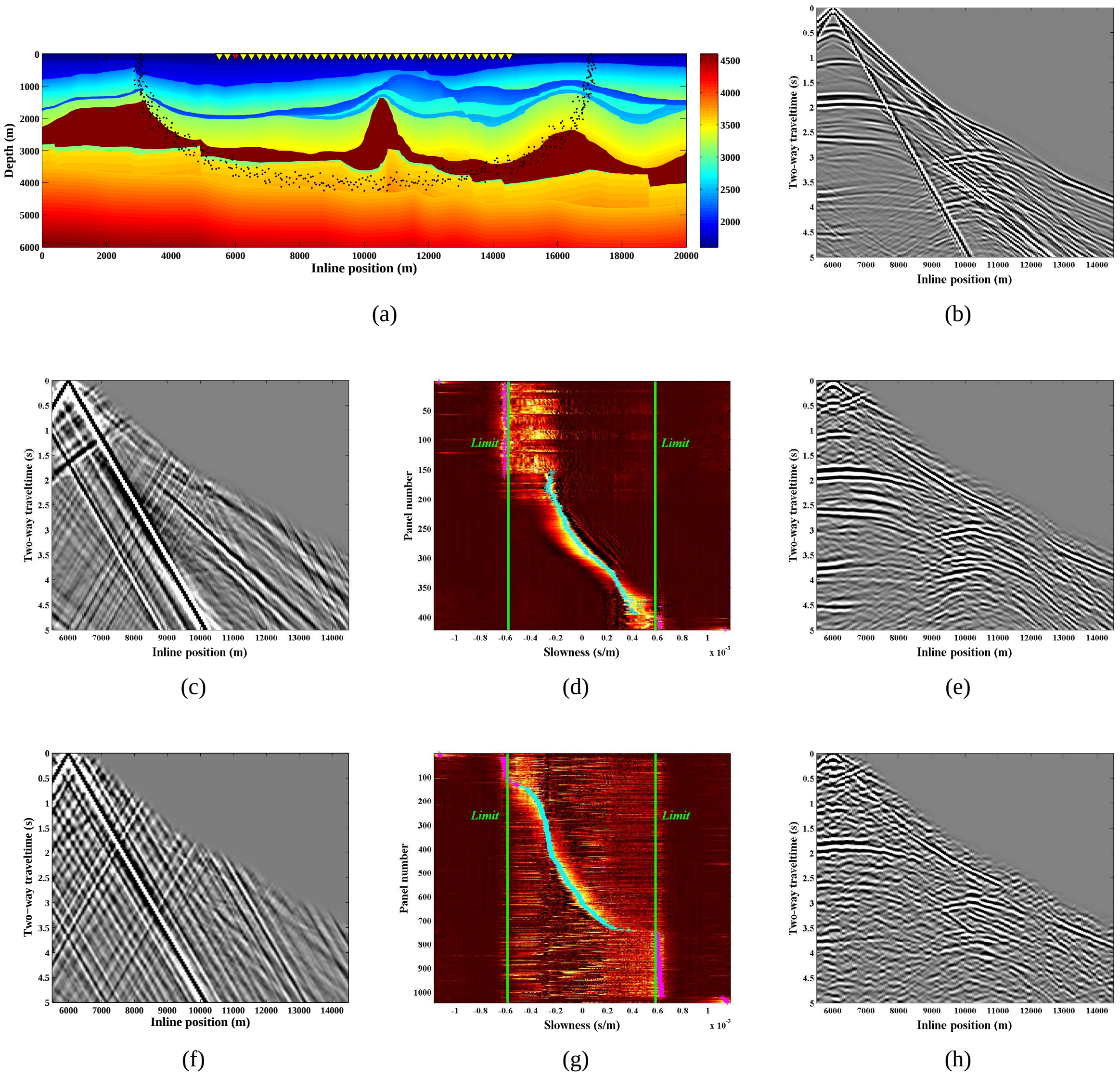
(c) (d)

(e)

Figure 1: ***(a)*** *Correlation panel from relatively deep transient sources.* ***(b)*** *The slowness-distribution diagram for (a). The red lines indicate slownesses, while the green lines indicate limits between body-wave and surface-wave events in the virtual-source function.* ***(c)*** *as in (a), but for sources close to the surface.* ***(d)*** *as in (b), but for (c).* ***(e)*** *A succession of slowness-distribution diagrams with correlation panels that are discarded (pink stars) and those that are kept (blue stars).*

representation has the advantage of speed when compared to frequency-wavenumber approaches, which require Fourier transforms. In the correlation panel, the events in the virtual-source function are summed along slownesses taken to pass through the time origin ($\tau = 0$). Figure 1a illustrates a correlation panel, with causal and anticausal parts and the source function in the middle, for relatively deep transient sources in Figure 2a. Figure 1c shows a correlation panel from sources relatively close to the Earth's surface in Figure 2a. The red lines represent slownesses or p-values that are analyzed at the source function for $\tau = 0$. The resulting slowness-distribution diagrams are displayed in Figure 1b and 1d. To use the diagram for discrimination between body-wave and surface-wave energy, we define as a limit the slowness of the direct P-wave (the green lines in Figure 1). If the maximum of a diagram is at a slowness value between the defined limits, as is the case in Figure 1b, then the concerned correlation panel is kept for further use in the integration process in equation 1 for the retrieval of a virtual source gather. For the case in Figures 1c and 1d, the correlation panels will be discarded from further use. For a continuous recording, calculation of slowness-distribution diagrams for successive time windows allows the build up of a panel (Figure 1e) that illustrates which correlated time windows are suitable for retrieval of reflections and which are not.

Results



(a) (b)

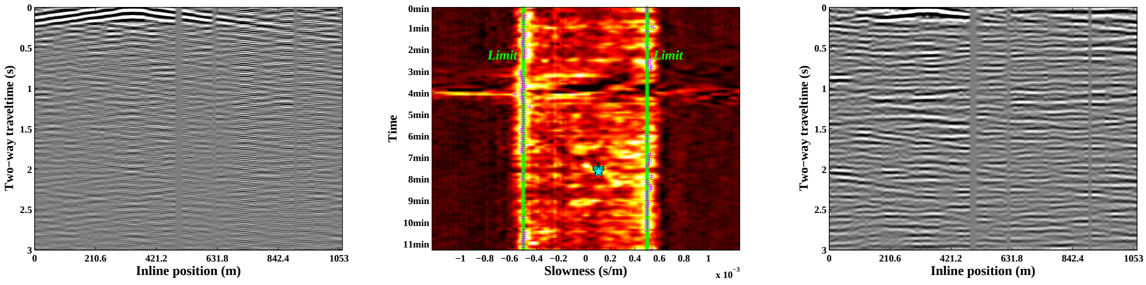
(c) (d) (e)

(f) (g) (h)

Figure 2: ***(a)*** *Subsurface velocity model (only the P-wave velocity shown) with 421 subsurface sources along a semi-elliptic boundary. 181 receivers are placed at 50 m depth with spacing of 50 m.* ***(b)*** *Directly modelled reflection response for a surface source located at* $x = 6000$ *m (the red triangle in (a)).* ***(c)*** *Retrieved common-source gather for a virtual source at* $x = 6000$ *m obtained using all panels for all transient sources.* ***(d)*** *Panel with slowness values of all correlation panels with transient sources.* ***(e)*** *Same result as in (c) after discrimination and discarding of panels with dominant surface waves.* ***(f)***, ***(g)*** *and* ***(h)*** *show the same as (c), (d) and (e), respectively, but for noise sources. The colour coding in (d) and (g) is like in Figure 1.*

We applied the above-described method to three different data sets. Two of them were obtained from an elastic numerical modelling using the geometry from Figure 2a - one consists of recordings from separately acting in time transient sources, while the other represents a continuous recording of noise sources that become active at random. Figures 2c,f show the retrieved common-source gathers when all subsurface sources are used. Comparing them to the directly modelled result in Figure 2b, we see that we have retrieved only surface waves. Using the slowness panels of the virtual-source functions in Figure 2d,g to discriminate surface-wave contributions and eliminate them, we obtain the retrieved results in Figure 2f,h, which exhibit clear retrieved reflections.

The third data set comes from continuous noise recording with a stationary array of 92 four-component receivers, spaced at 12 m, and buried 50 m below the surface, located near Annerveen, in the North of the Netherlands. We obtained preliminary results by applying equation 2 to 12 minutes of ambient-noise, which was divided in windows of 10 s each, with 5 s overlap. Figure 3a shows the retrieved common-source gather for a virtual source at 348 m after stacking all correlated time windows. The result exhibits only surface waves. The slowness distribution panel in Figure 3b shows the nearly total dominance of energy with surface-wave slowness. Only two correlated time windows contain predominant body-wave energy. The result of using only these 2 correlation panels is shown in Figure 3c.



(a) (b) (c)

Figure 3: *Annerveen stationary array field results. (a) Virtual shot gather with surface waves. (b) Slowness distribution diagram of 12 min of noise. (c) Virtual shot gather without the dominant surface waves from 3a.*

Due to the low slowness values in the used two correlated panels, the retrieved result exhibit predominantly nearly flat events, like the one just above 1.5 s. To conclude if these events are body or surface waves, we have to use the particle-velocity components to make polarization analysis or use the available crossline receivers.

Conclusions

We proposed a method to describe the illumination characteristics of records for seismic interferometry. The method makes use of events in the correlation panels that pass through the virtual-source position at zero time. We applied the method to noise recordings with the aim to improve the retrieval of reflections. The original retrieved results exhibited only surface waves. After the application of the method, parts of the recordings that were dominated by surface waves were identified and discarded. The newly obtained results were dominated by retrieved reflections.

Acknowledgements

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