VIRTUAL REAL SOURCE

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Abstract

Estimation of the seismic source signature is an important problem in reflection seismology, especially in seismic imaging problems. Existing methods of source signature estimation (statistical methods and well-log-based methods) suffer from several drawbacks. Here, I introduce a method of extracting the source signature based on the theory of seismic interferometry, also known as the virtual source method. The only requirement for this method is to have a receiver location lie at the shot position whose source signature we want to estimate (not necessarily a zero-offset receiver). Through modeling examples, I show that the Virtual Real Source method produces accurate source signatures even for complicated subsurface and source signatures. Source signature of each shot can be extracted reliably if they all have similar amplitude spectra even though their phase spectra might be completely different. This method of source signature estimation not only gives accurate traveltimes and amplitudes of reflection events, but also has the potential to solve other issues, such as finding source radiation patterns, measuring intrinsic attenuation, and estimating statics.

Introduction

An accurate source signature deconvolved from the seismic data helps to correctly position reflectors and estimate reflection amplitudes. Amundsen (2000) notes that, “Areas where this knowledge (of source signature) is potentially of great value are on board source array QC, deconvolution, multiple attenuation, tying reflection data to wells, modeling and inversion, AVO analysis, reservoir monitoring, and analysis of marine multicomponent recordings.”

Because of the challenges and high cost in measuring the source signature directly in the field, researchers have proposed alternative methods and algorithms to estimate the source signature. Source signature estimation based on statistical methods (Robinson and Treitel, 1980) suffer from several drawbacks. For example, assumptions of whiteness of the earth response, stationarity of the data, and the phase characteristics of the wavelet have little theoretical justification and the extracted wavelets may not be reliable. Methods based on well-logs are prone to errors as well. Other approaches involve linear and non-linear inversion (Amundsen, 2000; Landrøand Sollie, 1992). These methods, however, need data to be recorded at a mini-streamer located below the source array and also assume that the scattered energy recorded by the mini streamer is negligible.

Here, I introduce a new method for determination of the seismic source signature which is based on the principle of seismic interferometry and is devoid of the above drawbacks. Through modeling examples, I show that this method produces accurate source signatures even for complicated subsurface structures and source signatures.

A simple idea

In seismic interferometry the Green’s function between any two receiver locations can be computed by cross-correlating the receiver recordings due to random sources in the medium (Lobkis and Weaver, 2001; Wapenaar, 2004). This principle has been applied to exploration seismology to remove overburden problems (Bakulin and Calvert, 2006; Mehta *et al.* , 2006) and in imaging the subsurface.

I use seismic interferometry for extracting the Green’s function between two receiver locations. Let us consider two receiver locations A and B as shown in Figure 1a. To determine the Green’s function between these two receiver locations, the recordings at these two locations are cross-correlated for every source i.e. the two receiver gathers are cross-correlated. The cross-correlations are summed for all the shots to obtain the Green’s function between the two receiver locations. This, however, is not the true Green’s function, since it is scaled by the power spectrum of the source wavelet. This is the scaled impulse response and is given by:

$$U_{virt}(\omega) \quad = \quad |S(\omega)|^2 G(\omega), \tag{1}$$

where $U_{virt}(\omega)$ is the scaled impulse response, $S(\omega)$ is the seismic source wavelet, and $G(\omega)$ is the Green's function between A and B. Note that this wave field does not depend on the phase spectrum of the source.

Equation (1) is valid strictly for a closed source aperture, i.e. the true scaled impulse response between the two receivers can be obtained if there are sources on a closed surface surrounding the two receivers. In reality, the receivers are not usually surrounded by sources. This incomplete source aperture can result in some spurious events (Mehta *et al.* , 2006) which can be removed through some special processing (K. Mehta, personal communication, 2007).

If location A also coincides with a shot location, then at receiver B there is a direct recording due to the shot at A (Figure 1b); this direct recording is given by

$$U_{real}(\omega) \quad = \quad S(\omega) G(\omega). \tag{2}$$

From the equations (1) and (2) it is clear that deconvolving the real recording (equation 2) with the scaled impulse response (equation 1) gives the true source signature. In practice, I perform this operation in the frequency domain by dividing the spectra of the two recordings

$$\left[\frac{U_{virt}(\omega)}{U_{real}(\omega)}\right]^* \quad = \quad S(\omega), \tag{3}$$

where $*$ represents the complex conjugate.

Thus, deconvolving the real recording with the scaled impulse response gives the source signature and so this method is named as "Virtual Real Source (VRS)". Note that the only requirement for this method is to have a receiver at the location previously occupied by the shot (the shot whose source signature we are interested in), but not necessarily a zero-offset receiver. This is a common scenario and is found in most seismic surveys. Apart from this requirement and the imperfect scaled impulse response due to an incomplete source aperture, there are no assumptions for this method to work; we do not need any prior information about the subsurface.

Modeling tests

A simple three-layer model used for testing the idea described in the previous section. The top boundary is a free-surface and the other three sides are absorbing boundaries. The shots are on the surface at an equal spacing of 10m spanning a total length of 7.5km. I do SH-wave modeling for this example and for all the examples that are to follow. The theory, however, is valid for all components of excitation and recording. The snapshot of the wavefront at a particular instant of time is shown in the figure. A 30Hz dominant frequency ricker wavelet is used as the source wavelet.

The wavelet extracted using VRS from the full record spanning over 5 seconds is given in Figure 2a. The wavelet is well-recovered as can be seen from the good match with the actual wavelet. However, there are some spurious events after the main lobe which might be caused due to the imperfect scaled impulse response. To suppress the spurious events, wavelets can be extracted from different windows and then summed. Through this operation, only the true signals are stacked while the spurious events would be mis-stacked and thus suppressed. This is evident from Figure 2b where stacking of wavelets extracted from many windows has greatly improved the estimation of the source signature. The algorithm was tested on more complex models and in every case the source signature was extracted with acceptable accuracy.

Conventional methods for source signature estimation do not work well especially for complicated signatures. So this algorithm was tested extensively on complicated source signatures. Even for complicated wavelets, the method produced accurate results as evident from an air-gun-type signature, shown in Figure 3.

Source variability

Strictly this method of source signature estimation works well if all the sources are the same, i.e. they have the same source wavelet. But this is not usually the case in the field where source signatures can vary widely. What happens if the source signatures vary within the survey? A closer inspection of the interferometry process reveals that source variability does not pose a big problem. This is because after cross-correlations and summations, the source wavelet for the virtual source function is an average over all source signatures (Snieder *et al.* , 2007). Equation (3) can now be rewritten as

$$\left[\frac{U_{virt}(\omega)}{U_{real}(\omega)}\right]^* = \left[\frac{|S_{avg}(\omega)|^2}{S(\omega)}\right]^* = \left[\frac{|S_{avg}(\omega)|^2}{|S(\omega)|^2}S^*(\omega)\right]^* \approx S(\omega). \tag{4}$$

From equation (4) it is clear that if the amplitude spectrum of the source signature of interest does not deviate significantly from the average amplitude spectrum of all the source signatures in the survey (which is commonly the case in most surveys), then the source signature can be extracted accurately. All the phase information comes from the phase of the source signature of the shot we are interested in (denominator in equation 4).

This was tested by randomly changing the phase spectrum of the source wavelet from one shot to the next, keeping the amplitude spectrum the same. A receiver gather from this survey is shown in Figure 4. As proved above, as long as all the sources have the same amplitude spectrum, every source signature can be extracted accurately. It is clear from Figure 5 that even for a complicated change in phase spectrum of the sources in the survey, the source signatures can be extracted reliably as long as they all have similar amplitude spectra. In a survey where the amplitude spectrum varies between sources, the amplitude spectra of all the sources gets averaged during cross-correlation. Under these conditions, the closer the amplitude spectrum of the desired source signature is to the average amplitude spectrum, the more accurate will be the extracted source signature.

Discussion and conclusion

Apart from the limited source aperture, there are no assumptions involved in source signature extraction using the Virtual Real Source method. No prior information about the subsurface or the seismic survey is needed. The only requirement for the method, however, is that the source location must coincide with a receiver location. Note that we do not need a zero-offset receiver, rather a receiver location lie near the shot whose source signature we want to estimate. The method is valid for all components of excitation and recording. The Virtual Real Source method can extract source signatures accurately even if the phase spectra of the source signatures are completely different but as long as their amplitude spectra are similar. Because of the lack of any assumptions, Virtual Real Source works well for complicated sub-surfaces and source signatures. As already mentioned, it is important to keep in mind is that the quality of the extracted wavelet depends on the quality of the scaled impulse response. The true scaled impulse response between two receivers is obtained only when there is a full coverage of sources surrounding the receivers. This, however, is not the case in most seismic surveys. So for extracting the source signatures accurately, we need a large survey area and adequate coverage of sources and receivers.

This method of seismic source signature estimation not only gives accurate traveltimes and amplitudes of reflection events, but also has the potential to solve other issues, such as finding source-receiver radiation patterns, measuring attenuation, and estimating statics. The Virtual Real Source method can also be applied in crustal seismology to find the source signature of earthquakes. There might also be potential applications in other fields of science and technology dealing with wave propagation.

References

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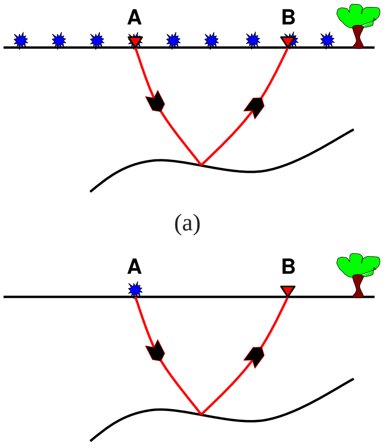
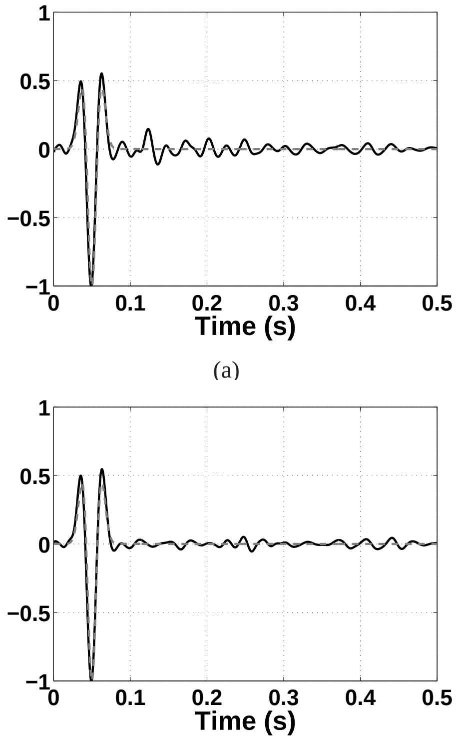


(a)

(b)

Figure 1: Scheme for (a) scaled impulse response and (b) real recording between two receiver locations A and B.



(a)

(b)

Figure 2: The true source signature (gray dashed line) and the wavelet extracted (black solid line) using (a) the full seismic record and (b) a windowing-stacking procedure.

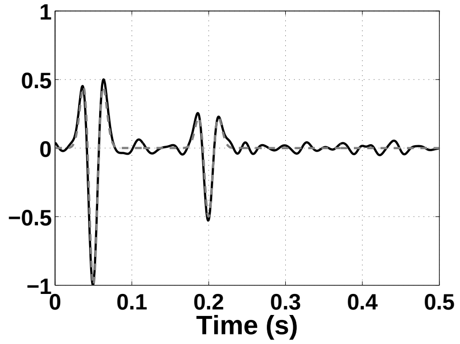


Figure 3: The true source signature (gray dashed line) and the wavelet extracted (black solid line) for a air-gun-type signature.

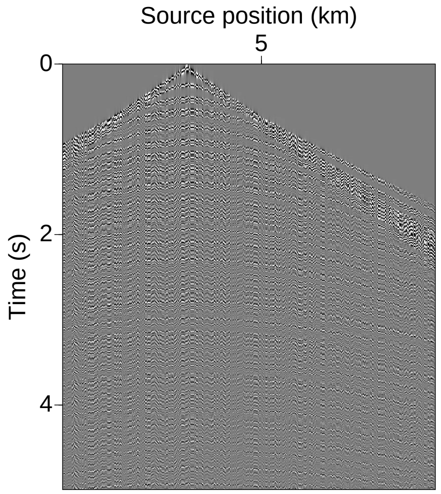


Figure 4: Receiver gather with the sources having different phase spectra but having the same amplitude spectrum.

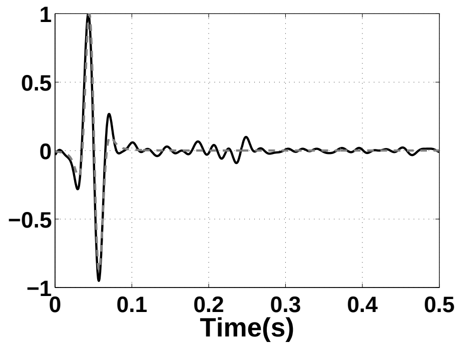


Figure 5: The true source signature (gray dashed line) and the extracted signature (black solid line) for a shot in the random-phase-spectra test.