Improving the virtual source method by wavefield separation

Kurang Mehta¹, Andrey Bakulin², Jonathan Sheiman², Rodney Calvert² & Roel Snieder¹

¹Center for Wave Phenomena, Department of Geophysics, Colorado School of Mines, Golden, CO 80401
²Shell International Exploration and Production Inc., 3737 Bellaire Blvd. Houston, TX 77001

Summary

Virtual source method has recently been proposed to image and monitor below complex overburden without knowledge of overburden velocities and near-surface changes. We demonstrate that up-down wavefield separation can substantially improve the quality of virtual source data. It allows us to eliminate artifacts associated with the limited acquisition aperture and to reconstruct a new optimized response in the absence of first order multiples/reflections from the overburden. These improvements are illustrated on a synthetic dataset, and on OBC data acquired in the Mars field in the deepwater Gulf of Mexico.

Introduction

Virtual source (VS) method (Bakulin and Calvert, 2004, 2006) is a technique to image and monitor below complex overburden without knowledge of overburden velocities and near surface changes. VS method is closely related to seismic interferometry (Derode, et al., 2003; Schuster, et al., 2004; Snieder, 2004; Wapenaar, 2004; Wapenaar, et al., 2005; Korneev and Bakulin, 2006); both are based on correlating the recorded wavefields at a given pair of receivers to estimate the Green’s function between them. The simplest approach to generate VS gather is to correlate total wavefield recorded at virtual source with total wavefield recorded at receivers (Mehta, et al., 2006). The resultant VS gather includes all the responses between virtual source and receiver, some of which may not be of interest for geophysical applications. The current practice is to correlate the gated direct arrival in total wavefield at virtual source with total wavefield at receivers (Bakulin and Calvert, 2006). Neither the simplest approach nor the current practice gives the true sub-surface response because according to the theory, we get the true response between a given pair of receivers by correlating the wavefields recorded at the two receivers and summing the correlated signal over sources that populate a closed surface enclosing the two receivers. For geophysical applications, we cannot have sources all around the receivers and this limitation leads to spurious events in the VS data. Apart from the spurious events due to incomplete source aperture, for both the approaches we get reflections from the overburden and the free-surface. We attempt to suppress these unwanted events using wavefield separation.

Synthetic modeling

Fig. 1 shows P- and S-wave velocity profile used for synthetic simulation by reflectivity modeling (Schmidt and Tango, 1986). 161 sources (vertical forces) are placed, every 10 m, on the surface and 41 receivers are placed, every 10 m, in a horizontal well at a depth of 250 m. The objective is to create virtual sources along the horizontal well. We choose receiver 21 as the virtual source, highlighted in red in Fig. 1. This VS gather should be equivalent to the response generated by putting a physical source at receiver 21, i.e. ground truth response (Fig. 2). We see the four P-P reflections labeled 1 through 4 and also a S to P conversion. For further analysis we restrict ourselves to P-waves only. Fig. 3 shows in red (plotted on top of ground truth in black) the VS gather generated by correlating total wavefield at virtual source (receiver 21) with total wavefield at receivers. Apart from four P-P reflection events that are present in both cases, there are other events in VS gather. Some of them are of physical nature (overburden-related) and some are unphysical (artifacts due to limited source aperture) but both represent unwanted responses in geophysical applications.

Bakulin and Calvert (2006) showed how gating before correlation can eliminate some of the overburden reflections by making virtual source radiate predominantly downwards. However their approach cannot suppress free-surface and overburden-related multiples. Fig. 4 shows the VS gather (in red) generated by gating before correlation. The reflections are preserved. As compared to Fig. 3 a lot of spurious events are, however, suppressed. Gating, thus, improves the VS gather, although a better wavefield separation approach is to decompose the wavefield into up- and down-going waves.

Wavefield separation

Fig. 5 shows cartoon for a three-layer model to illustrate the effect of incomplete source aperture and reflections coming from overburden and free-surface. Red triangle is virtual source and yellow triangle is receiver. Fig. 5(a) shows the source location that gives the stationary phase contribution (Snieder, et al., 2006) for a physical arrival between virtual source and receiver as shown by the black arrows. Hence, this source contributes to the true response between virtual source and receiver. If, however, source is placed on the other side of the virtual source and the receiver, as shown in Fig. 5(b), virtual source and receiver will record the waves propagating along the red arrows. Even though the source gives a stationary phase contribution, correlation of the two wavefields does not correspond to any physical arrival between them. Such arrivals contribute to spurious events in VS gather. If we would have a source below receivers, as shown in Fig. 5(c), the waves propagating along the blue arrows will cancel the effect of the waves propagating along the red
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arrows and hence the spurious event will not be a part of the response. However, for geophysical applications we do not have the luxury to put a source in the sub-surface. We can suppress these spurious events by restricting the waves at virtual source to be down-going.

Even though the waves at virtual source are down-going, we get reflections from overburden and free-surface as shown by red arrows in Fig. 5(d). These correspond to physical arrivals and would be a part of the response if we had a physical source at the virtual source location. We can suppress the effect of these arrivals by restricting waves at the receivers to be up-going. Hence, we get the sub-surface response by correlating down-going energy at virtual source with up-going energy at receivers. This represents an improvement over the current practice of relating the direct arrival before correlation (Bakulin and Calvert, 2006). Fig. 6 shows the VS gather (in red) generated by correlating down-going waves at virtual source with up-going waves at receivers. The spurious events are suppressed and VS gather is practically on top of ground truth response. Hence, wavefield separation is indeed a promising tool for generating the VS gather containing true sub-surface response. The up-down separation and gating can be combined to generate the VS gather as shown in Fig. 7. Additional gating imposes the virtual source to be P-wave and thus improves signal-to-noise ratio by eliminating unwanted shear-wave energy which might be used to generate virtual shear sources (Bakulin and Calvert, 2005).

Field example: Mars OBC data

We demonstrate improvement in VS method, due to wavefield separation, using data recorded for seismic monitoring in the Mars field. Fig. 8 shows a cartoon of the acquisition geometry. The geometry consists of 364 air guns fired (spaced every 25 m) on the sea-surface with 120 four-component sensors (spaced every 50 m) permanently placed on the sea floor at one kilometer depth. VS method allows us to redatum OBC data to the sea bed without the knowledge of water level, water temperature and source location.

For Mars field data, we use the dual-sensor summation technique (e.g., Robinson, 1999) for the separating wavefield into up- and down-going waves. We choose receiver 60 as the virtual source and sum the correlation gather over all the sources. Fig. 9(a) shows VS gather, for hydrophone component, generated by correlating total wavefield recorded at virtual source with total wavefield at receivers. The most prominent reflection we see is the reflection from sea-surface, labeled as “primary”. Hence, even for a simple overburden, correlating the total wavefields gives a VS gather dominated by the reflection from overburden.

If instead of correlating total wavefields, we correlate down-going waves at virtual source with up-going waves at receivers, the resulting VS gather is shown in Fig. 9(b). Free-surface multiple (FSM) is suppressed (highlighted by the arrow and “multiple” mark). Reflections from deeper sub-surface are now visible and strongest one is highlighted by an arrow and labeled as “primary”. Fig. 10(a) shows VS gather obtained by current practice. Correlating the gated direct arrival makes VS gather cleaner but strongest reflection is still FSM. To further improve VS gather quality, we combine up-down separation and gating. As shown in Fig. 10(b), if we correlate direct arrival gated in down-going waves at virtual source with up-going waves at receiver, the VS gather is cleaner and we do see true sub-surface response (highlighted by the arrow and labeled as “primary”) in absence of FSM.

Dual-sensor summation is strictly valid for zero-offset data over layered media. In many practical instances of large offsets or complex (2D and 3D) overburdens it may fail to deliver separated wavefields. In such cases, an alternative approach can be attempted to unravel improved reflection response. We generate two VS gathers using the hydrophone and vertical component geophone separately, and then extract the up-going waves for downhole survey using dual-sensor summation. Fig. 11(b), generated by such an alternate approach, reveals a gather very similar in quality to our best response shown in Fig. 11(a) [same as Fig. 10(b)]. There are, however, distortions in early times and near the direct arrival because of gating in total wavefield instead of gating in down-going waves.

Conclusions

Virtual source method can be improved to get only the reflection response from the deeper sub-surface using wavefield separation combined with gating. Instead of correlating total wavefields as suggested by theory, in practical cases it is more beneficial to correlate down-going waves at virtual source with up-going waves at receivers. In addition gating of down-going response further improves signal-to-noise ratio.

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Fig. 1: P- and S-wave velocity profiles and acquisition geometry for synthetic model.
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Fig. 2: Ground truth response generated by putting a physical source (vertical force) at the virtual source location (receiver 21).

Fig. 3: Ground truth response plotted in black. In red is the VS gather generated by correlating the total wavefield at the virtual source (receiver 21) with the total wavefield at the receivers.

Fig. 4: Ground truth response plotted in black. In red is the VS gather generated by correlating the windowed direct arrival at the virtual source (receiver 21) with the total wavefield at the receivers.

Fig. 5: Cartoon explaining the need for wavefield separation. Fig. (a) shows the source location that gives the stationary phase contribution for a physical arrival between virtual source (red) and receiver (yellow). Fig. (b) shows the source location that gives stationary phase contribution for a non-physical arrival between virtual source and receiver. Fig. (c) shows the hypothetical source below receivers, which if present, would cancel the effect of the non-physical arrival. Fig. (d) shows the presence of reflections from the overburden and/or the free surface multiples (FSM).

Fig. 6: Ground truth response plotted in black. In red is the VS gather generated by correlating the down-going waves at the virtual source (receiver 21) with the up-going waves at the receivers.

Fig. 7: Ground truth response plotted in black. In red is the VS gather generated by correlating the direct arrival windowed in the down-going waves at the virtual source (receiver 21) with the up-going waves at the receivers.
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Fig. 8: Cartoon of the geometry of the Mars field OBC data acquisition. Water depth = 1 km. VS gather is generated with receiver 60 as the virtual source.

Fig. 9: VS gather generated (a) by correlating the total wavefields at both the virtual source and receiver locations and (b) by correlating the down-going waves at the virtual source location with the up-going waves at the receivers.

Fig. 10: VS gather generated (a) by correlating the direct arrival windowed in the total wavefield at the virtual source with the total wavefield at the receiver locations and (b) by correlating the direct arrival windowed in the down-going waves at the virtual source location with the up-going waves at the receivers.

Fig. 11: VS gather generated (a) by correlating the direct arrival windowed in the down-going waves at the virtual source location with the up-going waves at the receivers and (b) by summing the VS gathers generated for hydrophone and vertical component geophone: each of which is generated separately by correlating the direct arrival windowed in the total wavefield at the virtual source location with the total wavefield at the receivers.