Improving the virtual source method by wavefield separation

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ABSTRACT
The virtual source method has recently been proposed to image and monitor below complex and time-varying overburden. The method requires surface shooting recorded at downhole receivers placed below the distorting or changing part of the overburden. Redatuming with the measured Green's function allows reconstruction of a complete downhole survey as if the sources were also buried at the receiver locations. Some challenges still need to be addressed in the virtual source method such as limited acquisition aperture and energy reflected downward from the overburden. We demonstrate that up-down wavefield separation can substantially improve the quality of virtual source data. First, it allows us to eliminate artifacts associated with the limited acquisition aperture typically used in practice. Second, it allows us to reconstruct a response in the absence of down-going multiples from the overburden. These improvements are illustrated on a synthetic dataset of a complex layered model modeled after the Fahud field in Oman, and on ocean bottom seismic data acquired in the Mars field in the deepwater Gulf of Mexico.

Key words: wavefield separation, multiple suppression, OBC, multi-component, dual-sensor summation

1 INTRODUCTION

The virtual source method (Bakulin and Calvert, 2004, 2006) is a technique to image and monitor below complex overburden without knowledge of overburden velocities or near-surface time-lapse changes. The virtual source method is closely related to seismic interferometry (Derode, et al., 2003; Schuster, et al., 2004; Snieder, 2004; Wapenaar, 2004; Wapenaar, et al., 2005); both use cross-correlation of the recorded wavefields at a given pair of receivers to estimate the Green's function between them. In practical applications challenges in virtual source method still need to be addressed. The goal of this study is to identify these challenges and demonstrate the usefulness of wavefield separation to overcome some of them.

The simplest approach to generating virtual source gathers is to cross-correlate the total wavefield recorded at the virtual source location with the total wavefield recorded at the receivers (Mehta, et al., 2006). The resultant virtual source gather includes all the responses between the virtual source and the receiver, some of which may not be of interest for geophysical applications. The current practice is to correlate the windowed direct arrival in the total wavefield recording at the virtual source with the total wavefield at the receivers (Bakulin and Calvert, 2006). This approach suppresses some of the unwanted responses as compared to the simplest approach. Neither one gives the true subsurface response for two reasons.

According to theory (Derode, et al., 2003; Bakulin and Calvert, 2006; Snieder, 2004; Wapenaar, 2004; Schuster, et al., 2004; Korneev and Bakulin, 2006), 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; hence simple cross-correlation and summing over a subset of sources does not provide the true response. Apart from the spurious events attributable to incomplete source aperture, both the approaches yield reflections from the overburden and the free-surface because both the up-going and the down-going waves are recorded at the receivers. These unwanted responses obscure the target reflections from beneath the virtual source and receivers.

Here, we attempt to suppress the artifacts caused by incomplete source aperture, and the reflections from the overburden and the free-surface. Up-down wavefield separation shows promise for improving virtual source data quality by removing the reflections from the overburden and non-physical events arising from incomplete source aperture. Similar up-down wavefield separation is done by Snieder et al. (2006b) in a different context applied to structural engineering. In the next section we illustrate this in a synthetic model, followed by an explanation of the need for wavefield separation before cross-correlating the recordings.

Apart from imaging below complex overburden, virtual source is also a powerful tool for time-lapse monitoring with permanently placed receivers. We apply the virtual source method to multi-component ocean-bottom cable (OBC) data recorded at the Mars field (*www.rigzone.com*), having 120 4-C sensors permanently placed on the sea-floor. We show in the final section how wavefield separation helps suppress the strong reflection from the sea-surface, hence unraveling the reflection response of the reservoir. This improves the repeatability for seismic monitoring by making the response independent of variations in the sea-level, sea temperature, source locations, and source signatures.

2 SYNTHETIC MODELING

Figure 1 shows vertical profiles of P- and S-wave velocities used for synthetic simulation by reflectivity modeling (Schmidt and Tango, 1986). The density varies between 2.1 and 2.5 g/cm^3. 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 horizonal well to suppress the distorting effects of the upper near surface (above 200 m), when trying to image the reservoir layers below. The complex overburden (i.e., the region above the receivers) consists of layers with extremely high velocity contrasts typical of the Middle East, and here modeled after the Fahud field in Oman.

If ideal redatuming is to be performed with seismic interferometry then the reconstructed response corresponds to a buried virtual source at any of the receivers. This response will contain reflections from the overburden layers as well as free-surface multiples.

Bakulin and Calvert (2006) showed how gating before cross-correlation can eliminate some of the overburden reflections. This makes the virtual source radiate predominantly downwards and provides cleaner response from deep target reflectors. Their approach, however, cannot suppress the free-surface and overburden-related multiples. Here we set a goal to completely eliminate from the virtual source data all the down-going multiples related to the overburden.

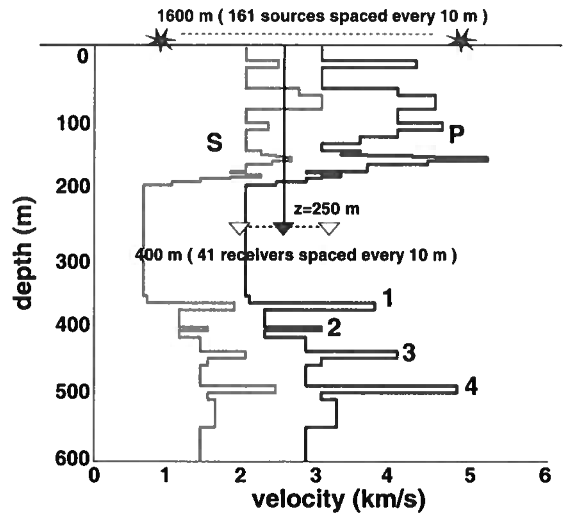

Figure 1. P- and S-wave velocity profiles and the acquisition geometry for a synthetic model inspired by Middle East field Fahud. 161 sources are spaced every 10 m on the surface, and 41 receivers are placed in a horizontal well at a depth of 250 m. Receiver spacing is 10 m.

Therefore, we benchmark the virtual source data against the "ground truth" response computed for a new model where all overburden above the well is replaced by a homogeneous half-space with the same velocities as just below the receivers (Figure 1).

We choose receiver 21 (middle receiver) as the virtual source, highlighted in red in Figure 1. The virtual source gather we generate should be equivalent to the response obtained by putting a physical source at the location of receiver 21. Figure 2 shows a comparison of the two responses. Figure 2a shows the virtual source gather generated by cross-correlating the total wavefield at the virtual source location (receiver 21) with the total wavefield at the receivers. Figure 2b shows the wavefield response of the receivers to a physical source (vertical force) at the virtual source location, after removing the laterally propagating shear waves. The laterally propagating shear waves are removed by using only the up-going energy at the receivers. For the rest of this paper, we refer to this response as the ground truth response. In addition to the four P-P reflection events, labeled 1 through 4 in Figure 1, which are present in both types of gather, the virtual source gather contains many other events.

For easier comparison we replot the ground truth response as shown in Figure 3. It shows the four P-P reflections labeled 1 through 4 and also an S-to-P con-

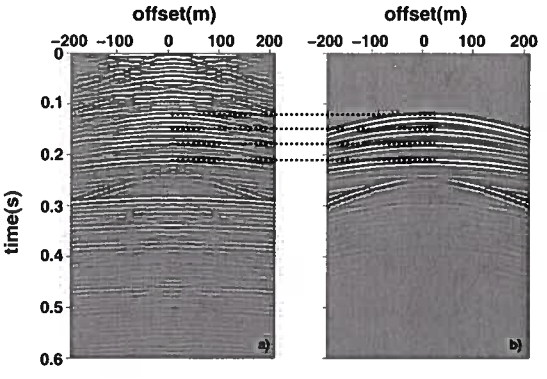

Figure 2. Figure (a) shows the virtual source gather generated by cross-correlating the total wavefield at the virtual source (receiver 21) with the total wavefield at the receivers. Figure (b) shows the shot gather generated by placing a physical source (vertical force) at the virtual source location (receiver 21) with a homogeneous half space above it. In Figure (b), the laterally propagating shear waves have been removed.

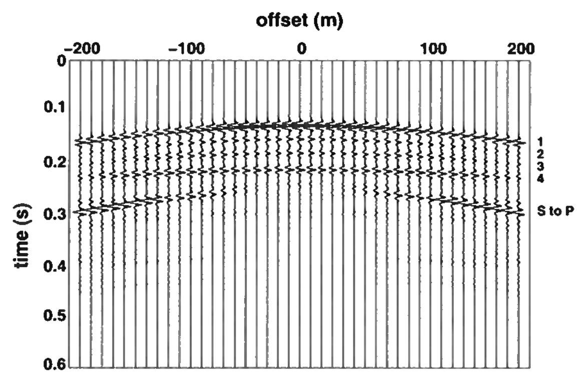

Figure 3. Ground truth response generated by putting a physical source (vertical force) at the virtual source location (receiver 21). The laterally propagating shear waves have been removed.

version. For further analysis we restrict ourselves to P-waves only. Figure 4 shows the virtual source gather, plotted in red, on top of the ground truth, plotted in black. As mentioned earlier, apart from the agreement in the reflection events, numerous other events exist in the virtual source gathers. Some of them are of physical nature (overburden-related response) and some are unphysical (artifacts arising from limited source aperture), but both represent unwanted responses, where the goal is to obtain only reflections from the subsurface. Next, we elaborate on their nature in layered media and demonstrate how wavefield separation can suppress both types of undesired response.

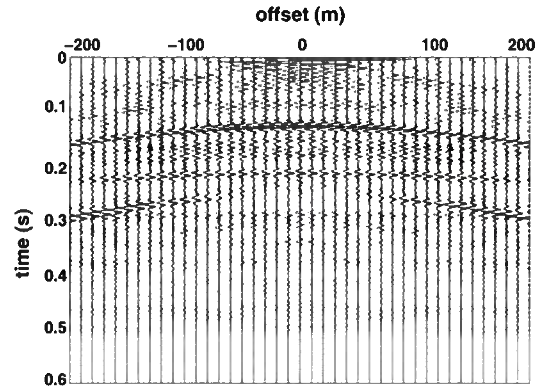

Figure 4. Black lines show the ground truth response. Red lines show the virtual source gather generated by cross-correlating the total wavefield at the virtual source (receiver 21) with the total wavefield at the receivers.

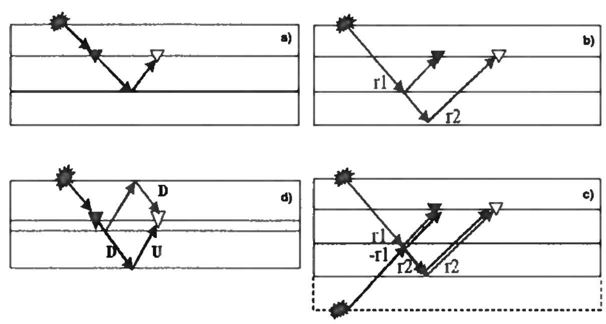

Figure 5. Depth-section cartoons explaining the need for wavefield separation. Figure (a) shows the source location that gives the stationary phase contribution for a physical arrival between the virtual source and the receiver. Figure (b) shows the source location that gives stationary phase contribution for a non-physical arrival between the virtual source and the receiver. Figure (c) shows the hypothetical source below the receivers, which, if present, would cancel the non-physical arrival. Figure (d) shows the presence of reflections from the overburden, in particular the free-surface multiples, here.

3 WAVEFIELD SEPARATION

Figure 5 shows depth-section cartoons for a three-layer model to illustrate the problem arising from incomplete source aperture and reflections coming from the overburden and the free-surface. In all the sub-figures, the red triangle is the virtual source and the yellow triangle is the receiver. They both are located at depth, and physical sources are excited at the surface. Figure 5a shows the source location along the surface that gives the stationary phase contribution (Snieder, et al., 2006a) for a physical arrival between the virtual source and the receivers as shown by the black arrows. By constitutive interference of the contributions from all other sources, only this source contributes to the true response between the virtual source and the receiver.

If, however, the source is placed as shown in Figure 5b, the virtual source and the receiver will record the wavefield propagating along the red arrows. Snieder, et al. (2006a) explains that even though this source gives a stationary phase contribution, cross-correlation of the two wavefields does not correspond to any physical arrival between them. Hence this source does not contribute to the true response. Such arrivals contribute to spurious events in the virtual source gather. Snieder, et al. (2006a) also show that if a source were placed below the receivers, as shown in Figure 5c, the waves propagating along the blue arrows will cancel the contribution of the waves propagating along the red arrows and hence the spurious event will not be a part of the response. In geophysical applications, however, we do not have the luxury to put a source in the subsurface, as shown in the cartoon.

In order to remove these spurious events, we resort to wavefield separation. As shown in Figure 5b, the wavefield propagating along the red arrows, recorded by the virtual source and the receivers is up-going. By restricting the wavefield at the virtual source to be only down-going, we can suppress these spurious events.

Even though the waves at the virtual source are only down-going, we still record reflections from the overburden and the free-surface, as shown by the red arrows in Figure 5d. 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 these arrivals from the data by restricting the waves at the receivers to be only up-going. Hence, we get the subsurface response by correlating the down-going energy at the virtual source location with the up-going energy at the receivers. The idea is similar to Noah's deconvolution as suggested by Riley and Claerbout (1976). If such separation is achievable without distortions, it would represent an improvement over the current best practice of time-windowing the direct arrival at the virtual source location and correlating that with the total wavefield at the receivers (Bakulin and Calvert, 2006).

3.1 Windowing in time

Figure 6 shows the virtual source gather (in red) generated by cross-correlating the windowed direct arrival in the total wavefield at the virtual source with the total wavefield at the receivers. The windowed direct arrival is obtained by placing a time gate of 40 ms around the direct arrival. The reflections are preserved and compared to Figure 4 many spurious events are suppressed. The suppression results from restricting the energy at the virtual source location to be mostly down-going P-wave energy (in the form of direct arrival). Time-windowing the direct arrival thus improves the virtual source gather, although a better wavefield separation approach is to decompose the wavefield into up- and down-going waves.

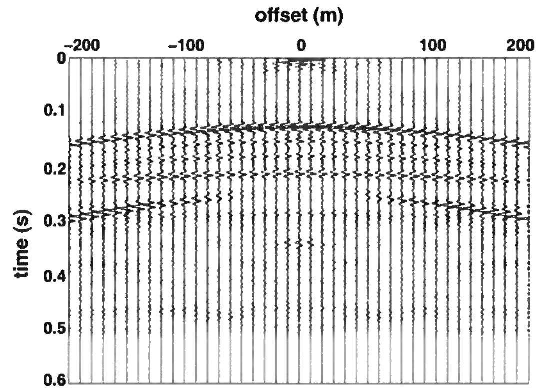

Figure 6. Black lines show the ground truth response. Red lines show the virtual source gather generated by cross-correlating the windowed direct arrival at the virtual source (receiver 21) with the total wavefield at the receivers.

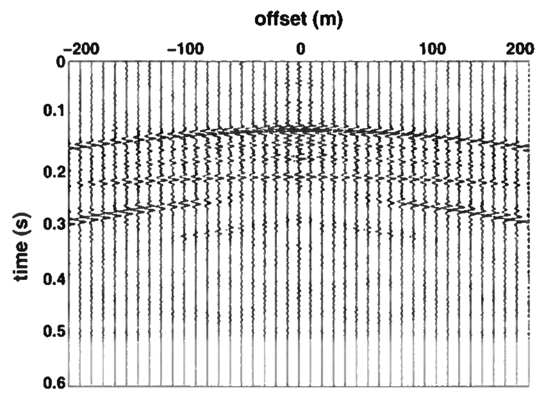

Figure 7. Black lines show the ground truth response. Red lines show the virtual source gather generated by cross-correlating the down-going waves at the virtual source (receiver 21) with the up-going waves at the receivers.

3.2 Up-down separation

As demonstrated by the cartoons in Figure 5, we get the desired subsurface response by correlating the down-going energy at the virtual source location with the up-going energy at the receivers. Instead of time-windowing, we separate the wavefields into up- and down-going waves and use those for correlation. Figure 7 shows the virtual source gather (in red) generated by correlating the down-going waves at the virtual source with the up-going waves at the receivers. The spurious events are suppressed and the virtual source gather closely matches the ground truth response. Hence, wave-

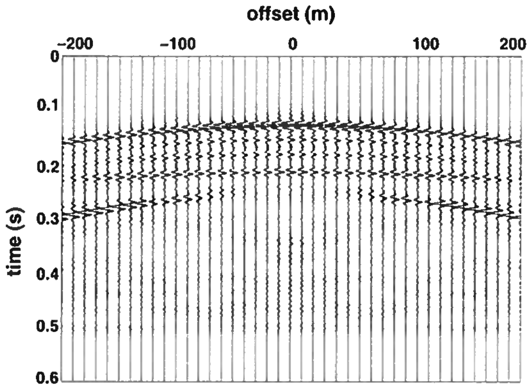

Figure 8. Black lines show the ground truth response. Red lines show the virtual source gather generated by cross-correlating the direct arrival windowed in the down-going waves at the virtual source (receiver 21) with the up-going waves at the receivers.

field separation is indeed a promising tool for suppressing down-going multiples in the process of generating the virtual source gather.

The up-down separation and time-windowing can also be combined to generate the virtual source gather as shown in Figure 8. This virtual source gather is generated by correlating the direct arrival windowed in the down-going waves at the virtual source location with the up-going waves at the receivers. For this synthetic model it shows an improvement over Figure 7.

For field data this improvement will become prominent once we separate the recorded wavefield into up- and down-going waves. For the synthetic modeling, the modeling program separated the wave-field into up- and down-going waves. For layered media, wavefield separation for field data can be done by dual-sensor summation (e.g., Robinson, 1999). According to dual-sensor summation, given hydrophone (H) and vertical component geophone (Z) recording of vertically propagating waves at the same sensor location, the sum H+Z yields the up-going energy and the difference H-Z the down-going energy. Before we apply this to field data, we compare the exact down-going and up-going waves, for our synthetic model with waves separated by the H-Z and H+Z approximations respectively.

Figure 9 shows the exact down-going waves for the raw data (plotted in black) and obtained from H-Z (plotted in red). Similarly, Figure 10 shows the exact up-going waves for the raw data (plotted in black) and from H+Z (plotted in red). In each plot, the wavefields obtained in the two different ways are practically identical, suggesting that despite being strictly valid for zero-offset data in horizontally layered media, dual-sensor summation technique provides a reasonable separation of the wavefield into up- and down-going waves for all offsets at hand.

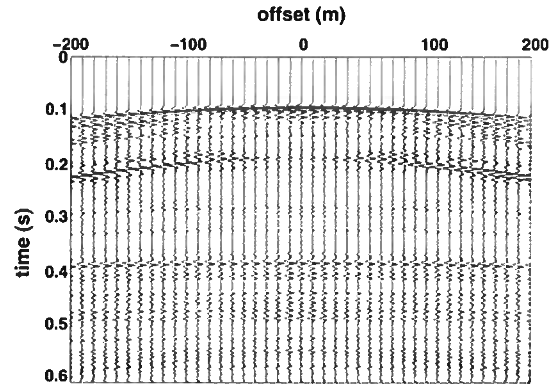

Figure 9. Comparison of the exact down-going waves (black lines) with the H-Z approximation (red lines).

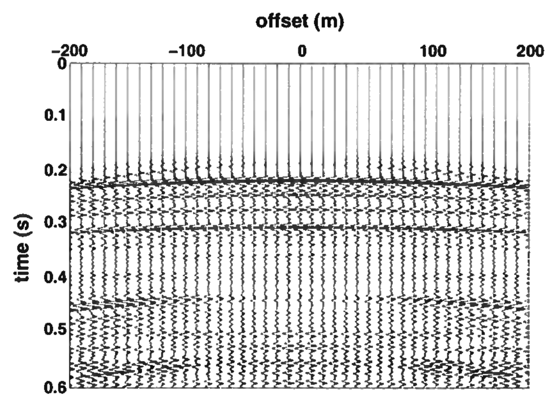

Figure 10. Comparison of the exact up-going waves (black lines) with the H+Z approximation (red lines).

4 FIELD EXAMPLE: REDATUMING OCEAN-BOTTOM SEISMIC AT MARS

We demonstrate the improvement in the virtual source gathers due to wavefield separation using the data recorded for seismic monitoring of the Mars field located in the Gulf of Mexico. Figure 11 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. Sea level, water velocity and shot locations change slightly between repeat acquisitions even though receivers remain fixed on the seabed. This creates a problem for seismic monitoring aimed to detect small timeshifts and amplitude changes related to field depletion. The virtual source method allows us to redatum OBC data to the sea bed without knowing any of these factors. Redatumed data should correspond to fixed (virtual) source and fixed receiver and exhibit

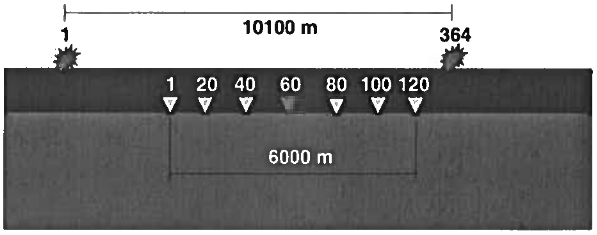

Figure 11. Cartoon showing the geometry of the Mars field OBC data acquisition. 120 receivers are spaced every 50 m on the sea-floor and 364 air guns (spaced every 25 m) are fired from the sea surface. Water depth in this cartoon is 1 km, close to that for the Mars field.

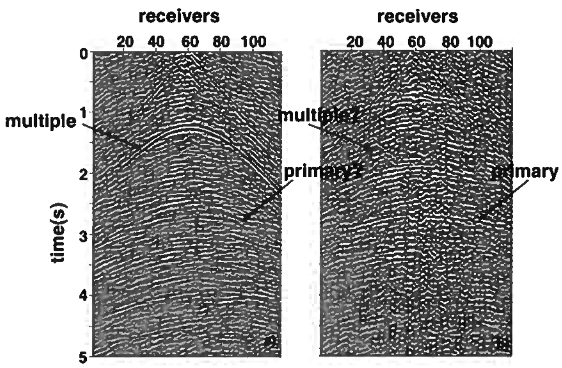

Figure 12. Virtual source gathers generated with receiver 60 as the virtual source. Figure (a) shows the virtual source gather generated by cross-correlating the total wavefields at both the virtual source and receiver locations. Figure (b) shows the virtual source gather generated by cross-correlating the down-going waves at the virtual source location with the up-going waves at the receivers. The label "multiple" refers to the reflection from the free-surface (overburden) and the label "primary" refers to a reflection from the subsurface. The "?" mark refers to the absence of the reflection event.

greatly improved repeatability between surveys. This was shown by Bakulin and Calvert (2006) for synthetic and real data of repeated vertical seismic profiles (VSP) acquired over time-varying overburden.

For the synthetic model, we demonstrated the improvement in the virtual source gathers by up-down separation. For the Mars field data, we use the dual-sensor summation technique for the separation of the wavefield into up- and down-going waves. We use these separate up- and down-going waves to generate the improved virtual source gathers.

We choose receiver 60 (middle receiver) as the virtual source and sum the correlation gather over all the sources. Figure 12a shows the virtual source gather, for the hydrophone component, generated by correlating the total wavefield recorded at the virtual source location with the total wavefield at the receivers. The

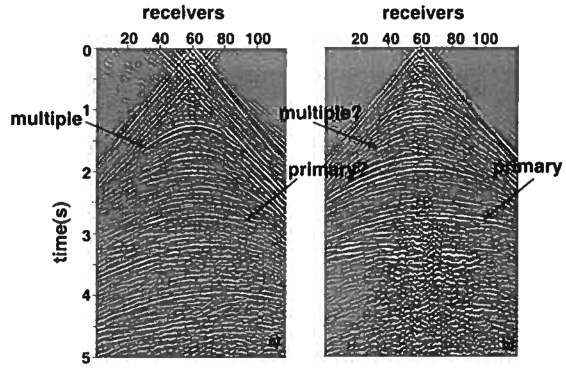

Figure 13. Virtual source gathers generated with receiver 60 as the virtual source. Figure (a) shows the virtual source gather generated by cross-correlating the direct arrival, windowed in the total wavefield at the virtual source, with the total wavefield at the receiver locations. Figure (b) shows the virtual source gather generated by cross-correlating the direct arrival, windowed in the down-going waves at the virtual source location, with the up-going waves at the receivers. The label "multiple" refers to the reflection from the free-surface (overburden) and the label "primary" refers to the reflection from the subsurface. The "?" mark refers to the absence of the reflection event.

most prominent reflection we see is the reflection from the sea-surface, labeled as "multiple". The arrow with the "primary?" mark is the location where we expect the strongest true reflection from the subsurface. Hence, even for a simple overburden, correlating the total wavefields gives a virtual source gather dominated by the reflection from the sea-surface.

Using the hydrophone and the vertical component geophone recording and the dual-sensor summation technique we separate the up- and down-going waves at all receivers. If instead of correlating the total wavefields, we correlate the down-going waves at the virtual source with the up-going waves at the receivers, we obtain virtual source gather shown in Figure 12b. The free-surface multiple is suppressed (highlighted by the arrow and "multiple?" mark). The reflections from the deeper subsurface are now visible and the strongest one is highlighted by an arrow and labeled as "primary." Although the reflections from the subsurface are visible, the virtual source gather is still noisy.

Figure 13a shows the virtual source gather obtained by the current best practice (Bakulin and Calvert, 2003, 2006): correlating the windowed direct arrival in the total wavefield at the virtual source location with the total wavefield at the receivers. The windowed direct arrival is obtained by placing a time gate of 400 ms around the direct arrival. Correlating the time windowed direct arrival makes the virtual source gather cleaner but the strongest reflection is still the free-surface multiple (labeled as "multiple"). To further improve the virtual source gather quality, we combine the up-down sepa-

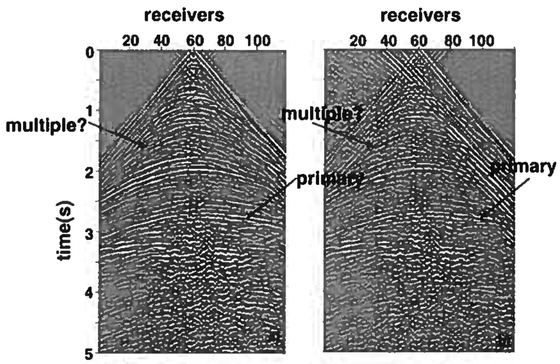

Figure 14. Virtual source gathers generated with receiver 60 as the virtual source. Figure (a) shows the virtual source gather generated by cross-correlating the direct arrival, windowed in the down-going waves at the virtual source location, with the up-going waves at the receivers. Figure (b) shows the virtual source gather generated by summing the *virtual source gathers*, generated for hydrophone and vertical component geophone: each of which is generated separately by cross-correlating the direct arrival, windowed in the total wavefield at the virtual source location, with the total wavefield at the receivers. The label "multiple" refers to the reflection from the free-surface (overburden) and the label "primary" refers to the reflection from the subsurface. The "?" mark refers to the absence of the reflection event.

ration and the time-windowing approach. As shown in Figure 13b, if we correlate the direct arrival, windowed in the down-going waves at the virtual source location, with the up-going waves at the receiver, the virtual source gather is cleaner and the true subsurface response (highlighted by the arrow and labeled as "primary") is clearly visible in the absence of the free-surface multiples. The free-surface multiple (labeled as "multiple?") is attenuated because we use only the up-going energy at the receivers. The early-time reflections are crisper in Figure 13b than in Figure 13a because we excluded any up-going energy that may have been left in the windowing approach. The near-offset jitter in Figure 13b around 3 to 4 s is the result of the wave scattering near the soft sea bottom. These scattered and mode-converted waves are sensed by the vertical component and show up in the virtual source gather when we include the vertical component for up-down wavefield separation.

We conclude that the combination of wavefield separation and gating produces the best of the responses [Figure 13b], as predicted by synthetic modeling. While wavefield separation restricts the radiation pattern of the virtual source to be strictly downward, additional gating imposes the virtual source to be P-wave and thus improves signal-to-noise ratio by eliminating unwanted shear-wave energy from the virtual source. This unwanted late energy might be used to generate virtual shear sources (Bakulin and Calvert, 2005).

Dual-sensor summation is strictly valid for zero-offset data over horizontally layered media. Therefore in many practical instances of large offsets or complex overburden structures in two or three dimensions it may fail to deliver separated wavefields with undistorted phase as required for virtual source generation. In cases such as for borehole observations below near surface, an alternative approach can be attempted to unravel an improved reflection response of the subsurface. First, one can generate two virtual source datasets using the current best practice, i.e. correlating the direct arrival, windowed in the total wavefield at the virtual source (VS), with the total wavefield at the receivers, both for the hydrophone (VS_H) and vertical component geophone (VS_Z) separately, and then extract the up-going waves ($VS_H + VS_Z$) for the downhole survey using dual-sensor summation applied to the virtual source data. Figure 14b, generated by such an alternative approach, reveals a gather similar in quality to our best response shown in Figure 14a [same as Figure 13b]. In Figure 14b, however, are distortions in early times and near the direct arrival because of windowing in the total wavefield instead of windowing in the down-going waves. As shown before, wavefield separation in the process of generating the virtual source gathers indeed gives the true subsurface response. This alternative approach with wavefield separation after generating the virtual source data, however, also gives reasonable reflection response and can be improved further by suitable combination of three-component (3-C) sources and 4-C geophones, i.e. by generating an elastic (vector) virtual source.

The up-down wavefield separation applied to the virtual source method suppresses the down-going multiples shown in the Figure 5. There are, however, waves that propagate downwards from the virtual source, reflect from the subsurface, propagate through the overburden and reflect back into the subsurface and are then sensed by the receivers as up-going waves. Such multiples are present in the virtual source data even after applying wavefield separation to the virtual source method.

5 CONCLUSIONS

The virtual source method as practiced to date can be improved upon to get mainly the reflection response from the deeper subsurface by using wavefield separation combined with gating of the direct arrival. Instead of correlating total wavefields as suggested by theory, in practice it is more beneficial to correlate down-going waves at the virtual source with the up-going waves at the receivers. In addition, time windowing or gating of the direct arrival in the down-going response further improves the signal-to-noise ratio.

Synthetic modeling in layered media inspired by the Fahud field in Oman reveals the nature of these improvements. Selecting down-going waves at the virtual source eliminates the reflections from the overburden and a free surface; in other words it restricts the radiation pattern of the virtual sources to downward directions only. Using up-going waves at the receivers suppresses the free-surface multiples and spurious events arising from the inability to put sources surrounding the receivers. Combination of the two provides a response in the absence of downgoing energy from the overburden. Additional gating of the down-going response restricts the virtual source radiation pattern to predominantly P-waves and avoids contamination by shear energy. A field data example confirms that combination of wavefield separation and gating leads to a greatly improved signal-to-noise ratio on virtual source data and thus a cleaner reflection response of target horizons.

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