Comparing virtual versus real crosswell surveys

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Summary

The virtual source method (VSM) is a useful tool for imaging below complex overburden and monitoring in the presence of time-varying overburden. This concept, when extended to crosswell geometry produces data comparable to real crosswell data. Using a field data example we demonstrate that virtual crosswell data is kinematically comparable to real crosswell data, but the virtual crosswell method possesses flexibilities, which are difficult to achieve in a real crosswell survey. Some of these flexibilities include the ability of the virtual source to radiate either horizontally or vertically and the possibility for the virtual source to radiate only P- or only S-waves. It is also possible to create virtual crosswell data that contain only the direct arrivals or only the reflections. These features of the virtual crosswell method should make it useful for crosswell tomography, imaging and reservoir monitoring for moderate interwell distances.

Introduction

The VSM (Bakulin and Calvert, 2004; 2006) or seismic interferometry (Wapenaar, 2004; Schuster, et al., 2004; Snieder, et al., 2006) is useful for redatuming a surface seismic survey below the near-surface overburden by creating virtual sources at downhole receiver locations. The VSM, when applied to VSP and OBC acquisition geometries (Bakulin and Calvert, 2004; Mehta, et al., 2007), gives data that is independent of the near-surface overburden and the time-lapse changes therein. Some initial examples of crosswell data with virtual source have been presented by Shiraishi and Matsuoka (2005) and Minato, et al. (2007). In this study we compare virtual and real sources in a crosswell configuration and apply best practices that include gating and wavefield separation before correlation (Mehta, et al., 2007), to illustrate the benefits of virtual crosswell survey.

What is a virtual crosswell survey?

Real crosswell acquisition geometry (Figure 1a) consists of two wells: well 1 with borehole receivers (red circles) and well 2 with borehole sources (yellow star). Waves excited by the borehole sources propagate between the two wells and are then recorded by the borehole receivers. The recorded wavefield include the direct arrivals and the reflections from the subsurface (ray tracing in Figure 1a). The direct arrivals and the reflections can then be used separately for tomography and imaging respectively (Tura, et al., 1994). Unlike the real crosswell survey, the virtual crosswell (Figure 1b) requires receivers (red circles) in both wells and surface shooting (yellow stars) to allow wave propagation between the downhole receivers in wells 1 and 2. After cross-correlating the wavefields recorded by the receivers in wells 1 and 2 and summing the correlation gather (Mehta, et al., 2008) over the surface shots, the resulting virtual source data resembles the recording by the receivers (red circles) in well 1 due to virtual source in well 2 (white star). As described later in the article, depending on the wavefield selected for correlation, the virtual crosswell data can contain only reflections, only direct arrivals or both. This flexibility of the virtual crosswell survey provides crosswell data containing the desired wavefield only. Such a clean approach to wavefield separation is difficult for real crosswell data, hence providing a reason to pursue the virtual crosswell method.

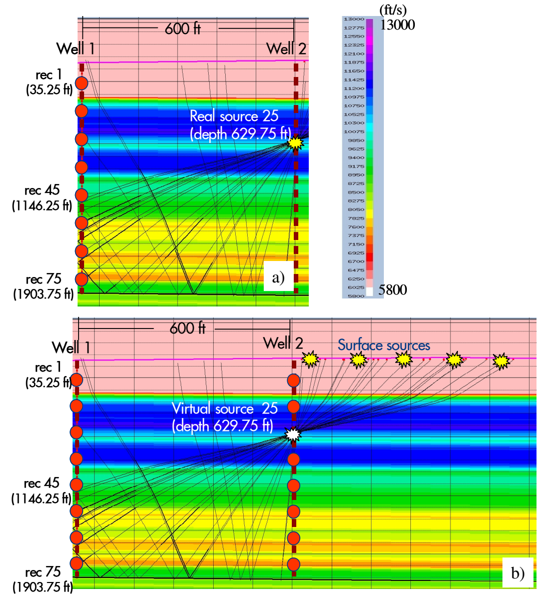

Figure 1: (a) shows the acquisition geometry for a real crosswell. Red circles are the receivers and the yellow star is a real borehole source (located at 629.75 ft; same depth level as receiver 25). (b) shows the same for a virtual crosswell. The virtual source (white star) is also placed at 629.75 ft; same depth level as receiver 25. (a) and (b) also show the possible wave propagation between the two wells, in the form of ray-tracing.

Direct arrivals in virtual and real crosswell data

As a part of a seismic acquisition program onshore US, downhole seismic data was recorded for both the real and the virtual crosswell geometries, as described in Figures 1 and 2. The downhole source (Z-Trac) was operated by Z-Seis whereas dual-well recording was done by Reservoir Imaging Inc. Wells 1 and 2 are 600 ft apart. For the virtual crosswell, waves are excited by vertical vibrators (stars in Figure 2) on the surface. These waves are recorded in wells 1 and 2 that contain respectively 75 and 77 3-C receivers at a depth interval of 25.25 ft (Figure 1b). For the real crosswell survey, the sensors in well 2 are replaced by real downhole source (yellow star in Figure 1a).

The first step towards comparing the real and the virtual crosswell data is to look at the direct arrivals. Figure 3a shows the crosswell data with the Z-Trac source (Figure 1a) recorded by the vertical component of the downhole receivers. The Z-Trac source has radiation pattern similar to that of in-line horizontal force. The display shows only the bottom 30 receivers (45 to 75) in order to make the display comparable to the virtual crosswell data (discussed later). The dashed yellow line in Figure 3a highlights the timing and the moveout of the direct P-wave arrival.

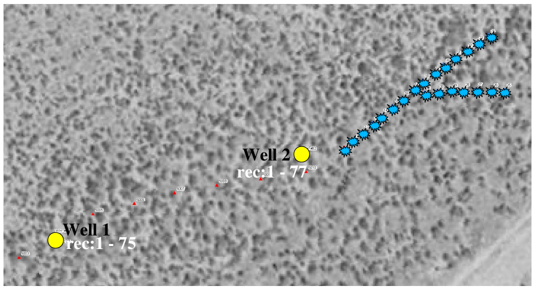

Figure 2: Map view of the crosswell acquisition geometry. Wells 1 and 2 are 600 ft apart and there are about 20 surface shots as indicated by the stars. The real source was deployed in well 2.

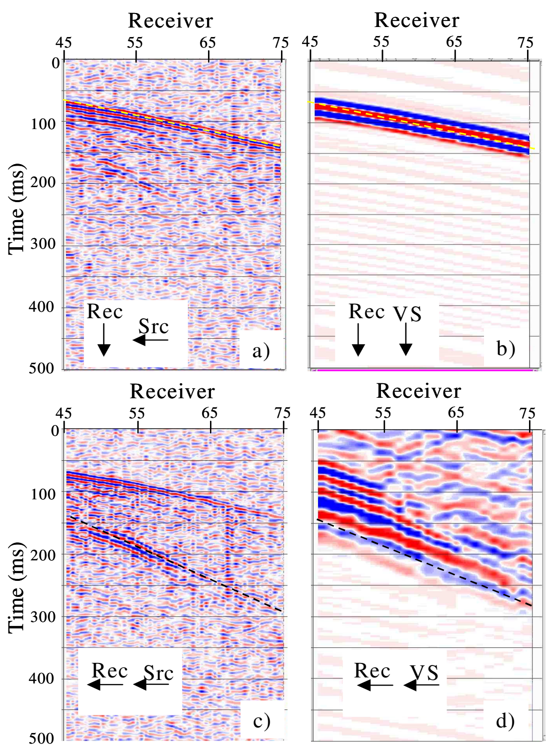

Figure 3: (a) and (c) show the real crosswell data recorded due to a downhole source (depth 629.75 ft; same depth level as receiver 25) into the bottom 30 receivers. (b) shows, for the same source-receiver combination, the virtual crosswell data generated by correlating direct P-wave arrivals at the receivers in both wells. (d) shows the virtual crosswell data generated by correlating direct S-wave arrivals at receivers in both wells. In the panels, the dashed yellow line depicts the direct P-wave arrival and the dashed black line depicts the direct S-wave arrival. The arrows show the orientation of the (real and virtual) source and the receivers.

An important advantage of the virtual crosswell survey over the real crosswell survey is the ability to correlate separate wavefields to obtain only the desired virtual crosswell data. For example, gated direct P-wave arrivals recorded by the vertical components at both the virtual source and the receivers, when correlated and summed over the physical sources, give only the direct P-wave propagating between the virtual source and the receivers (Figure 3b). For the virtual crosswell data the display is limited only to the bottom 30 receivers (45 to 75) because for the given surface shot distribution that feed the virtual source to produce direct arrivals, only the bottom 30 receivers record the stationary phase response (Snieder, et al., 2006; Mehta, et al., 2008). This explanation is visual in the form of rays (Figure 1b) that propagate as direct arrivals from the virtual source to the receivers. The timing and the moveout of the direct P-wave arrival in Figure 3b (dashed yellow line) agree with those for the real crosswell data (Figure 3a). The virtual crosswell data (Figure 3b) is generated by correlating and summing the downhole recording due to surface shots. The frequency band of the virtual crosswell data (10 to 80 Hz) is, hence, comparable to the data generated by a VSP type survey in a similar setting. The real crosswell data, on the other hand, has much higher frequency content (80 to 700 Hz) because of the specifications of the downhole sources and shorter propagation distances. Figure 3a shows the band-pass filtered real crosswell data (80 to 200 Hz) in order to make the real and the virtual crosswell data as comparable, in frequency content, as possible. The difference in the frequency content of the real and the virtual crosswell data is evident in Figures 3a and 3b.

Figure 3c shows the same real crosswell data recorded by the horizontal component. Apart from the direct P-wave, the horizontal component also records the direct S-wave (dashed black line). Similar to the P-wave virtual source (Figure 3b), correlating the direct arriving S-wave as recorded by the horizontal components at both the virtual source and the receivers creates a direct S-wave arrival between the virtual source and the receivers (Figure 3d). The timing and moveout (dashed black line) agree with those for the real crosswell data, suggesting that unlike the real downhole source, we can create a downhole virtual source that radiates only S-waves. Apart from the direct S-wave arrival, Figure 3d also shows numerous low-amplitude events at earlier times. These could be spurious events caused by incomplete destructive interference, while summing the correlation gather. Limited surface shot aperture (Figure 2) is a possible reason for the incomplete destructive interference.

Reflections in virtual and real crosswell data

Let us now compare the reflection response for the virtual and the real crosswell survey. Figure 4a shows the real crosswell data that correspond to a real downhole horizontal force recorded by the vertical component of the downhole receivers. For comparison with the virtual crosswell data, the display shows all the downhole receivers, because for reflections all the receivers record the stationary phase response from the virtual source (rays in Figure 1b). A red bar indicates the bottom 30 receivers, where the direct arrival for the virtual crosswell data is comparable to that for the real crosswell data.

If we cross-correlate the total wavefield recorded by the vertical component at both the virtual source and the receivers, the resulting virtual crosswell data (Figure 4b) contain direct arrivals and reflections between the two wells. The moveout and the timing of the direct arrival (yellow line) agree with those for the real crosswell data (Figure 4a). Since we correlate the total wavefields, Figure 4b also contains the direct S-wave arrival (solid black line) between the virtual source and the receivers. The reflection response can be further highlighted by correlating the gated direct P-wave arrival at the virtual source with the total wavefield at the receivers (Figure 4c). The direct P-wave arrival is preserved (yellow line). Apart from that the reflections (dashed black lines) are stronger than those in Figure 4b. Since we use only the direct P-wave arrival at the virtual source, Figure 4c does not contain the direct S-wave arrival. The reflections in Figure 4c are still contaminated by the later arriving downgoing waves, which can be suppressed by creating virtual crosswell data that contain only reflections. Such virtual crosswell data (Figure 4d) can be created by correlating the direct arrival at the virtual source with only the upgoing waves at the receivers. For a vertical well, the up-down wavefield separation is possible using f-k filtering.

Comparison of Figures 4a and 4d suggests that the real crosswell data is devoid of strong reflections for a source at 629.75 ft depth. However, moving the real source deeper (Figure 4e) reveals the direct arrivals and also strong reflections (black dashed line). Since the real downhole source radiates mostly horizontally, it is difficult to get a response from the strong reflectors that are at a considerable depth from the real downhole source. To illustrate this point using the virtual crosswell method, Figure 4f shows the virtual crosswell data obtained by correlating the direct P-wave arrival in the horizontal component of the virtual source with the total wavefield in the vertical component recording of the receivers. This is equivalent to a virtual source radiating mostly horizontally and hence, comparable to the real downhole source. Similar to the real crosswell data (Figure 4a), Figure 4f is dominated by downgoing waves. Reflections are present in Figure 4f but they are weak compared to those in Figure 4c. This limitation of the real crosswell survey is overcome by the virtual crosswell method. The virtual crosswell method allows us to create data due to virtual source radiating either vertically (Figure 4c) or horizontally (Figure 4f), provided that the receivers that act as the virtual sources have 3-C recordings.

Features of virtual crosswell surveys

A real crosswell recording includes the direct arrivals and the reflections from the subsurface between the wells. These two wavefields can be used separately for tomography and reflection imaging respectively. A virtual crosswell survey can provide the crosswell data in two sets: one with only the direct arrivals (Figure 3b or 3d) and one with only the reflections (Figure 4d). This is an important advantage of the virtual crosswell over the real crosswell. In a real crosswell survey we get the total wavefield recordings, which need to be further separated into direct arrivals and reflections.

For a vertical borehole, most real downhole sources (Z-Trac, piezoelectric) radiate horizontally and hence, not enough energy propagate down to the desired depths. The real crosswell data is, hence, dominated by the direct arrivals for a shallow downhole source (Figure 4a). The reflections are visible only when we lower the downhole source to bring it closer to the strong reflectors (Figure 4e). This limitation can be overcome by the virtual crosswell method, provided that the downhole receivers (acting as the virtual source) contain 3-C recordings.

Since the real downhole source has radiation pattern similar to a horizontal force, it radiates both P- and S-waves simultaneously. Using virtual crosswell, we can create a source that radiates only P- or only S-waves (Figures 3b and 3d), enabling us to separate the response of the subsurface to a P-wave source and to an S-wave source. Such a separation is much more difficult in real crosswell data.

Potential Applications

Crosswell surveys can be used for reservoir monitoring. Time-lapse real crosswell requires at least one dedicated well (for downhole sources). These sources cannot be permanently placed in wells, and hence the time-lapse survey may not be well repeatable. Virtual crosswell survey may overcome both of these limitations because it only requires instrumenting wells with receivers. This can be done by placing permanent fiber-optic hydrophones behind the casing or tubing in producing wells, making the survey very repeatable and non-intrusive. Other possible non-repeatabilities in time-lapse real crosswell surveys include changes in orientation and signature of the downhole source between surveys. Time-lapse virtual crosswell data becomes independent of these issues once we deconvolve the correlation gather by the (surface) source power spectrum. These features of the virtual crosswell survey make it useful for time-lapse crosswell monitoring.

Apart from time-lapse monitoring, virtual crosswell survey is useful for large interwell distances (greater than 500 m), for which the real crosswell does not produce reliable data. Due to the possibility to creating a P- or an S-wave virtual source, we can perform a Por S-wave tomography and reflection imaging using the virtual crosswell data. This technique is also useful for applications that require undershooting obstacles, such as near-surface distortions, salt or gas clouds. In terms of frequency content, the virtual crosswell data is comparable to a conventional VSP data. Main advantages of virtual crosswell over VSP include wider coverage and removal of time-varying overburden effects and hence better repeatability. The price to pay is dual-well recording.

Conclusions

The concept of the virtual source can be extended to crosswell geometry. For similar acquisition geometry, virtual crosswell data is comparable to the real crosswell data. Because of the way it is created, the virtual crosswell data has lower frequency content as compared to the real crosswell data at short interwell distances. Apart from this limitation, the virtual crosswell approach has a number of advantages over the real crosswell method, such as the radiation pattern of the virtual downhole source, ability of the virtual downhole source to radiate only P- or only S-waves and well repeatable surveys for time-lapse monitoring.

This study is just a proof of concept for the virtual crosswell method, and hence we do not go into the details of comparing the reflection imaging and tomography results. Apart from that, Figures 3 and 4 show that comparison of the real and virtual crosswell data was reliable only in certain depth range, suggesting that the field acquisition geometry was not ideal (especially in terms of surface shot distribution) to perform virtual crosswell method. In order to maximize the benefits of the virtual crosswell method, first step is to conduct a proper pre-survey modeling. In case of complex overburden best insurance is to have wide shooting geometry with areal shots or several shot lines.

Acknowledgements

We are thankful to Shell for permission to publish this paper. We thank Z-Seis and Reservoir Imaging Inc. for acquiring the cross-well surveys and assistance with data processing. We also appreciate the useful discussions with Patsy Jorgensen and Michael Costello.

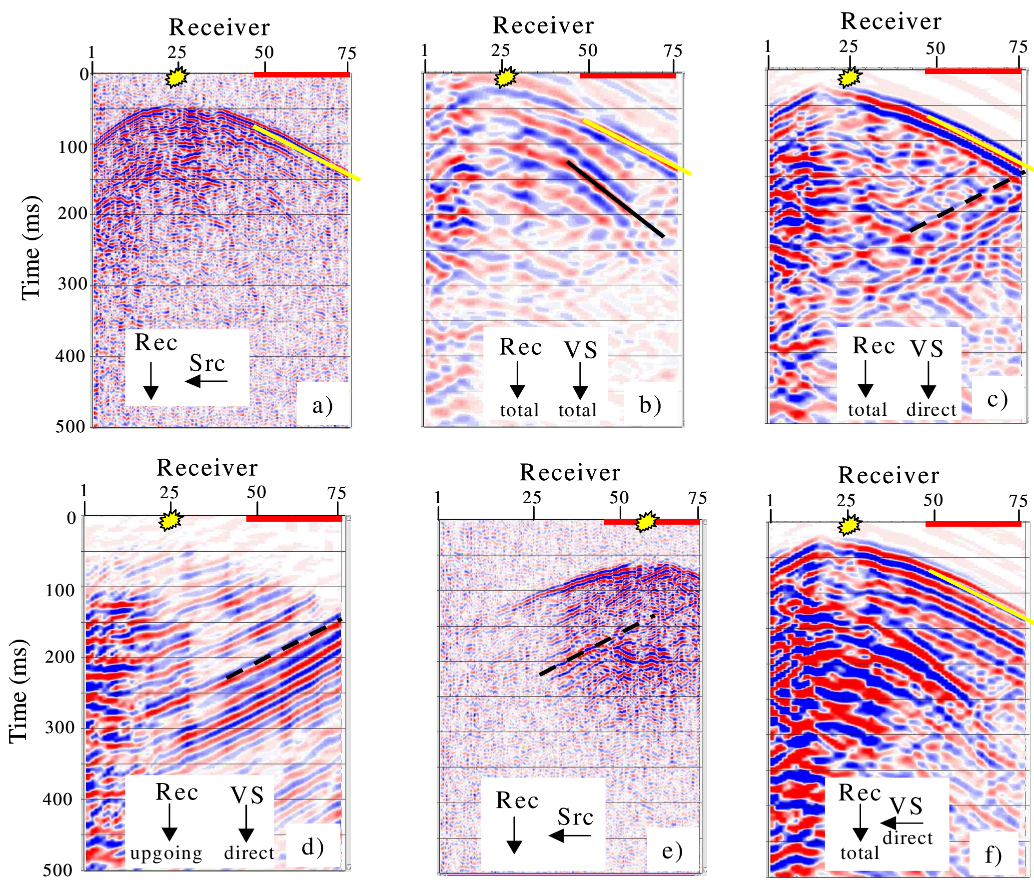

Figure 4: (a) shows the real crosswell data with a downhole source 629.75 ft deep (same depth level as receiver 25) recorded by downhole receivers. Yellow line highlights the direct P-wave (for bottom 30 receivers indicated by red bar). The arrows in all the panels show the orientation of the (real and virtual) source (Src, VS) and the receivers (Rec). Figures (b), (c), (d) and (f) show the virtual crosswell data, for which the text below the arrows indicate the wavefield used for correlation. Yellow and the solid black lines highlight the direct P- and S-wave arrivals, and the dashed black line highlights the reflections. (e) shows the real crosswell data for a deeper downhole source (1513.5 ft; same depth level as receiver 60). Apart from the direct arrival, it shows reflections (dashed black line). Compared to (c), Figure (f) is dominated by downgoing waves more than reflections.

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