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Virtual shear source makes shear waves with air guns

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ABSTRACT

We demonstrate a novel application of the virtual source method to create shear-wave sources at the location of buried geophones. These virtual downhole sources excite shear waves with a different radiation pattern than known sources. They can be useful in various shear-wave applications. Here we focus on the virtual shear check shot to generate accurate shear-velocity profiles in offshore environments using typical acquisition for marine walkaway vertical seismic profiling (VSP). The virtual source method is applied to walkaway VSP data to obtain new traces resembling seismograms acquired with downhole seismic sources at geophone locations, thus bypassing any overburden complexity. The virtual sources can be synthesized to radiate predominantly shear waves by collecting converted-wave energy scattered throughout the overburden. We illustrate the concept in a synthetic layered model and demonstrate the method by estimating accurate P- and S-wave velocity profiles below salt using a walkaway VSP from the deepwater Gulf of Mexico.

INTRODUCTION

The virtual source method (VSM) has been introduced (Bakulin and Calvert, 2004, 2005, 2006; Calvert, 2004) as a way to generate seismic sources at the location of downhole geophones using the actual excitation from a source array at the surface. VSM development represents a natural extension of the time-reversal ideas of Fink and Prada (2001) and Draeger et al. (1998). Here we show how to make a virtual source that excites predominantly shear waves using walkaway vertical seismic profiling (VSP) data acquired with air gun sources typical for offshore environments. Air guns do not excite shear waves in the water; therefore, VSP estimates of shear velocity are usually obtained by analyzing late arrivals of converted-wave energy that need to be identified, picked, and processed (Zhou et al., 2005). Such analysis becomes difficult in complex geological settings. Recently, a seabed shear source was introduced, but its practical deployment faces several challenges, and its suitability in deep water remains untested (Ackers et al., 2005).

Here we demonstrate that VSM can take advantage of conventional marine acquisition to automatically harvest all converted-wave energy and to effectively create downhole shear sources at suitably illuminated geophones. These shear virtual sources are created downhole, eliminating the distorting effects of the complex overburden. They give kinematically correct shear arrivals with approximately correct amplitudes. The virtual source creation is completely data driven and does not require knowledge of the overburden velocity. In fact, the more complex the overburden, the better the quality of the virtual shear source because it is fueled by more P-S conversions. In contrast to actual downhole sources available in the industry, the virtual shear source does not radiate direct P-waves; thus, the shear wave of interest becomes the first arrival. In the present implementation, this is accomplished by suitably gating the VSP arrivals to suppress P-wave energy, although a more fundamental approach based on wavefield separation can also be considered.

We first illustrate the concept on a synthetic example using a deviated well in a layered model inspired by a North Sea field. We then create virtual check shots for P- and S-waves using a walkaway VSP acquired in a subsalt prospect in the deepwater Gulf of Mexico and show that our P and S velocity profiles are in excellent agreement with the dipole sonic logs both in salt and below salt at 7 km depth.

METHODOLOGY

VSM is described in detail by Bakulin and Calvert (2004, 2006). Korneev and Bakulin (2006) show that VSM can be thought of as a special Kirchhoff redatuming with experimentally measured Green's functions. Alternative derivations recovering the response between a pair of receivers based on time-reversal arguments are given by van Manen et al. (2005) and Wapenaar (2004). Essentially, the goal is to obtain a virtual source at the location of each geophone by using energy from an array of surface sources. The acquisition is the same as conventional VSP with surface shots and downhole geophones. The output is a new data set equivalent to firing downhole

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(virtual) sources placed at existing geophone locations and recording the wavefield at all existing receiver locations.

Suppose we want to convert receiver α into a virtual source and record the signal from it in receiver β. The virtual source trace $D_{\alpha\beta}(t)$ can be computed from the equation given in Bakulin and Calvert (2004):

$$D_{\alpha\beta}(t) = \sum_{k=1}^{n} S_{k\alpha}(-t) * S_{k\beta}(t), \qquad (1)$$

where $S_{k\alpha}(t)$ and $S_{k\beta}(t)$ are traces from surface shot k to receivers α and β, respectively, and the asterisk denotes convolution. Note that convolution with a time-reversed series is equivalent to crosscorrelation. Equation 1 describes the time reversal or back propagation of recorded signals from each shot toward the geophone that will serve as a virtual source. Linearity and reciprocity are assumed in order to simulate a time-reversed experiment numerically on a computer rather than doing it physically as described by Fink and Prada (2001). Reverberations, diffractions, and multiples are all transmitted back with proper delays; all collapse at the geophone location, thus fueling the virtual source. In this paper, we only consider marine sources in a VSP configuration, but other sources and configurations can be handled in the same way. In this case, equation 1 describes time reversal that back propagates hydrophone recordings toward the virtual buried force. At negative times, equation 1 reconstructs the wavefield collapsing toward the source (acausal response); at positive times the equation recovers the outgoing wavefield (causal response) as if it emanated from the buried source (Korneev and Bakulin, 2006), which we call the virtual source. In this study, we focus on analyzing horizontal-component recordings in the well from an air gun source. Because of reciprocity, such acquisition is equivalent to a hydrophone recording at sea from a buried horizontal force. A real source representing a buried horizontal force has a radiation pattern that includes P- and S-waves (Figure 1a) that cannot be separated. With VSM, we can in principle create a radiation pattern of our choice. Bakulin and Calvert (2004, 2006) show how to create sources that radiate predominantly P-waves by using the vertical geophone component and time-reversing only downgoing P-waves. In this study, we modify the virtual source generation to obtain a virtual shear source.

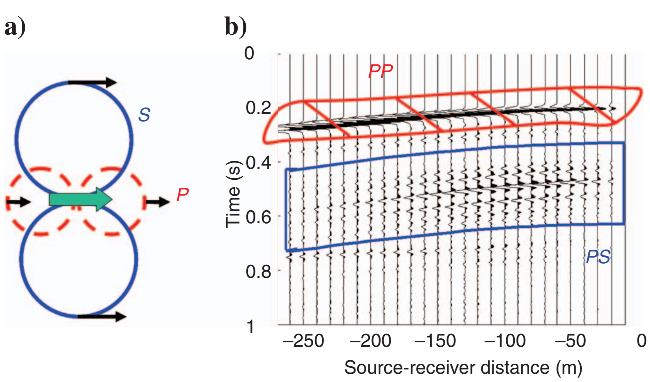

Figure 1. (a) Far-field radiation pattern of a horizontal force in a homogeneous elastic medium. (b) Horizontal component recorded by a geophone at 200 m depth in the sediment from an air gun array at sea. Blue box outlines data used for time reversal. First arrivals of P-P nature (red) have been muted.

- On the time-reversed portions we mute the strongest downgoing P-waves corresponding to the first arrivals and leave late arrivals that are rich in converted-wave energy.
- We use the horizontal (inline) component for recording, which further favors converted waves arriving as S-waves into the receiver.

In laboratory experiments at a solid-fluid interface, Draeger et al. (1998) demonstrate that selective time reversal of converted modes can result in a tighter focal spot for reconverted S-waves as a result of their smaller wavelength. We use a similar idea but with a different objective: We want to focus back only the desired shear wavefront and eliminate unwanted longitudinal wavefronts, so that, after focusing, the virtual source emits predominantly transverse energy.

SYNTHETIC 1D EXAMPLE: DEVIATED WELL IN THE NORTH SEA

Let us create a virtual shear source at a geophone buried 200 m below sea level using a marine walkaway VSP recorded in a well deviated at 27° with respect to the vertical direction. We use a realistic 1D velocity model from the Tommeliten field in the North Sea (Allnor et al., 1997). A buried horizontal geophone at 200 m depth records the wavefield shown in Figure 1b from an air gun array at sea. Shown is the simulated inline horizontal component of the full wavefield, containing all possible arrivals and multiples except those from the sea surface because the water layer was modeled as a half-space. Because of reciprocity, the same wavefield would be generated by a buried horizontal force and recorded by hydrophones in the water. Interference caused by fine layering near the seabed makes it difficult to identify the individual waves. The first arrivals represent transmitted P-P energy, while later arrivals contain various types of converted, scattered and reverberating energy.

The radiation pattern of the horizontal force consists of two P-wave lobes and two S-wave lobes (Figure 1a). Because we want the virtual source to emit only shear energy, we mute the first P-wave arrivals in the time-reversed portion and only back propagate data inside the blue gate outlined in Figure 1b. Note these later arrivals represent interference of different waves propagating as P- and S-waves through various parts of the section. Any arrival that passes through the geophone as a shear wave (P-…-S) will contribute to the creation of the S-wave lobe of the virtual source radiation pattern, while those waves passing as P-waves (P-…-P) through the virtual source location would fuel the P-wave lobe. By muting the first arrivals and using the horizontal geophone component, we eliminate the strongest downgoing P-wave energy and amplify converted-wave energy passing as S-waves through the receiver, thus enhancing the S-wave lobe of the virtual source radiation pattern and weakening the P-wave lobe. To generate a pure P-wave source, we do the opposite, i.e., we use a short gate around the first arrivals and mute later portions on the time-reversed traces (Bakulin and Calvert, 2004, 2006). Such simple wavefield separation splits the radiation pattern of the virtual source into detached P- and S-wave parts.

If exact wavefield separation were achievable, we would select the downgoing (converted) S-wave field for time reversal and convolve them with upgoing shear reflections. Such an accurate separation is difficult in practice, so we resort to simple gating. Through wavefield separation we can make a virtual source that radiates predominantly a desired mode (P or S). Through appropriate selection of VSP aperture, we can modify the direction of the virtual-source radiation. Such customized tuning is impossible to do with real downhole sources that have a fixed radiation pattern.

A check shot from a virtual shear source at 200 m depth, as recorded by deeper geophones in a deviated well (Figure 2a), reveals a direct arrival propagating along the well with the shear-wave velocity. This is seen easily by comparing it with a second set of waveforms that represents simulation of a real downhole source (horizontal force) placed at 200 m depth and recorded by horizontal geophones in the same well (black seismograms in Figure 2a). Despite some weak noise caused by limited aperture, the virtual-source wavefield is in good kinematic agreement with the true response. A small mismatch in the near-field is likely caused by the imperfect P-S separation. Note that the real shear source also radiates upward, and the reflection from the seabed produces a downgoing S-wave visible at 0.7–1.0 s. Virtual-source data do not contain this event because of their downward radiation pattern.

A horizontal force radiates the largest S-wave amplitude in the vertical direction (Figure 1a), but S-P conversion on a planar fluid-solid interface is zero at normal incidence. Therefore, some upgoing shear energy experiences perfect reflection and does not reach the limited aperture of the surface array. This suggests that the radiation pattern and amplitudes of the virtual source will be distorted and will not exactly match those of a horizontal buried force. Nevertheless, the virtual source constructively combines all mode-converted waves at nonvertical incidence, and their superposition generates a kinematically correct shear-wave arrival on the virtual-source records in a deviated well (Figure 2a) and even in a vertical well (Bakulin and Calvert, 2005).

Next, we show a real data example in which deviations from the flat-layered model create more abundant mode-converted energy at all angles of incidence, allowing us to create an even higher-quality virtual shear source than in the synthetic case.

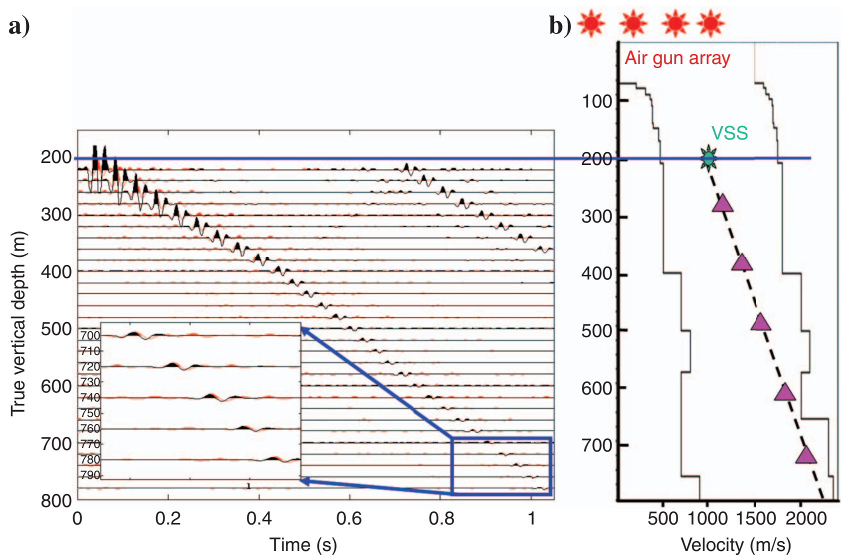

Figure 2. (a) Virtual-source check shot in a deviated well (27°) and (b) corresponding velocity model and acquisition geometry. Virtual source data are shown in red; seismograms from a directly simulated downhole source are shown in black. The virtual shear source is at 200 m depth. Note that the real shear source creates a ghost reflection from the seabed (around 0.75–1.0 s) that is absent on the virtual source data because of its downward radiation pattern.

FIELD DATA EXAMPLE: WALKAWAY VSP IN THE GULF OF MEXICO

A walkaway VSP was acquired in a vertical well through a massive salt body in the deepwater Gulf of Mexico (Figure 3 insert). The sources were air guns in the water column; the geophones were located in and below salt. The very diverse P-S conversions occurring above the receivers allow us to create high-quality virtual shear source data. Because S-wave arrivals register most strongly on the horizontal component, we used as input the inline horizontal (x) receiver component of the VSP data (Figure 3).

We muted remnants of the P-wave first arrivals on the horizontal component, taking care not to harm the strong S-waves that arrive later. Ray tracing suggests that the first event in this late-arriving S-wave package is produced by P-S conversion at the top of the salt (green dots in Figure 3), while following arrivals represent additional conversions and reverberations in the sediments above the salt. We emphasize that no such modeling or interpretation is required to create the virtual shear source, but some understanding of the nature of the arrivals is beneficial in selecting a useful gate (dashed in Figure 3) for time reversal in equation 1. We have yet to see a VSP data set where converted energy is not present in some form, any portion of which can be used for generation of the virtual shear source.

Figure 4a shows the virtual shear source data created from this Gulf of Mexico data set. For comparison, Figure 4b shows conventional P-wave virtual-source data generated from the vertical component of the VSP using a window around the first arrival for time reversal. It is clear that the first arrivals in Figure 4 correspond to different wave types, which are both very easy to pick to construct P- and S-wave virtual check shots. Picking the first arrivals on subsalt receivers gives the velocity profiles shown in Figure 5. They match the smoothed sonic logs very well. Note that although P-wave check

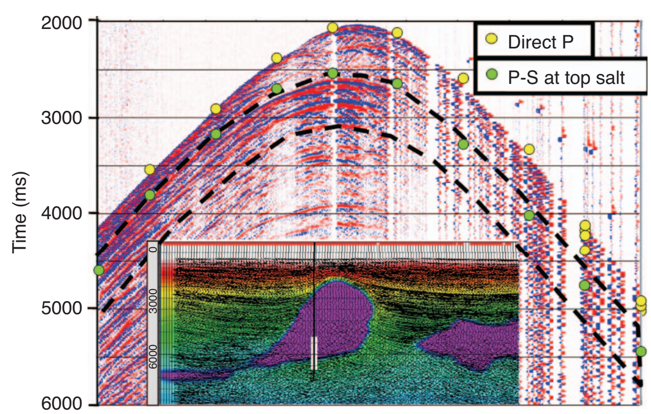

Figure 3. Common-receiver gather from the Gulf of Mexico walkaway VSP. Acquisition includes 612 air gun source locations (shown in red at the top of the insert) and 96 receiver positions (shown by white bar in the well). Shown is the inline horizontal (x) component for the topmost receiver. Yellow and green dots denote ray-traced traveltimes of the direct P-wave and the P-S-wave converted at top salt. Black dashes outline approximately the gate used for virtual shear source creation.

shots are acquired routinely, true S-wave check shots are rare and require a bulky and expensive seabed source (Ackers et al., 2005). Without the virtual shear source, we would not have been able to obtain such an accurate shear-wave profile in an offshore environment below salt at more than 7 km depth. Traditional (surface-source) check shots often give inaccurate velocity profiles below complex salt bodies.

Since the virtual check shot measures interval velocities, our primary focus was on the subsalt sediments rather than on the relatively homogeneous salt. But for the sake of completeness, we also used the virtual-source data to measure the average velocities of P- and S-waves in the salt. A linear regression through the virtual-source first arrivals in the salt gives $V_p = 4470 \pm 100$ m/s and $V_s = 2560 \pm 100$ m/s. Smoothed logs over the same depth interval give $V_p = 4465 \pm 20$ m/s and $V_s = 2540 \pm 10$ m/s, where the error bars reflect salt inhomogeneity rather than measurement uncertainty. Again, virtual check shot and well velocities are in excellent agreement.

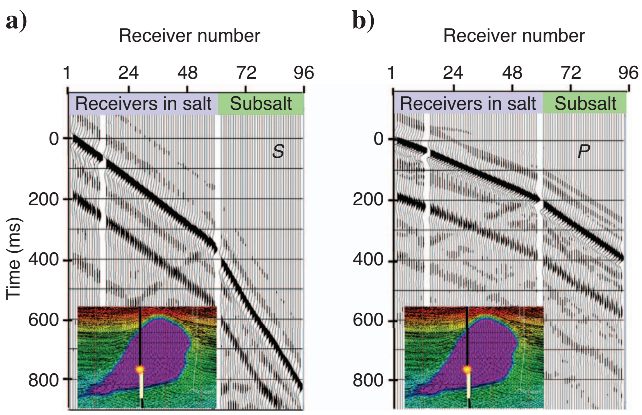

Figure 4. Common-shot gather for (a) an S-wave and (b) a P-wave virtual source. In both cases, the virtual-source location coincides with the topmost VSP receiver and fires at time zero.

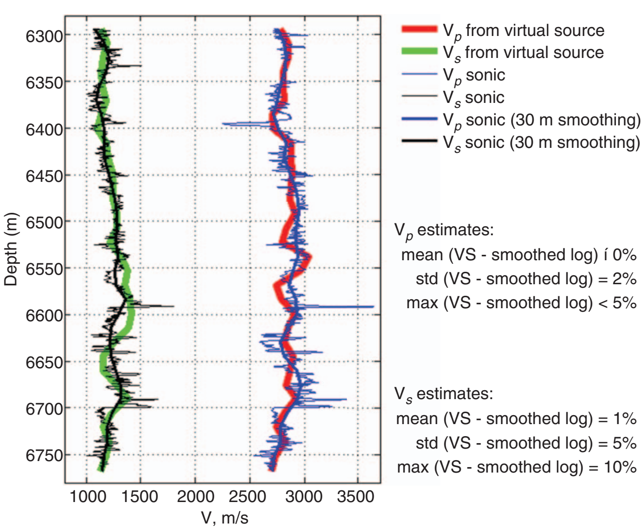

Figure 5. Comparison of P and S velocity profiles obtained with virtual sources and sonic logs. Virtual check shots are in very good agreement with the sonic logs smoothed to the VSP resolution of about 30 m (100 ft).

Creating S-wave velocity profiles along vertical or deviated wells is the simplest application of the virtual shear source. We could process the entire shear wavefield (Figure 4a) as a conventional VSP to obtain a high-resolution SS image of the medium below the receivers. Although amplitudes of virtual source data are expected to be inexact, they are sufficiently representative for most purposes. Examples of SS images obtained using virtual shear sources below complex overburden are shown in Bakulin and Calvert (2005).

CONCLUSION

VSM accurately redatums the full wavefield recorded through any complex overburden and allows the creation of virtual sources that radiate predominantly a desired wave mode (P or S). In this study, we focused on creating a virtual shear source that radiates predominantly S-waves, even when the physical sources in the water layer emit only P-waves. Theoretically, the S-wave radiation of the virtual source stems from converted P-S waves transmitted through the overburden. We show on synthetic and real data that S-wave energy intended for time reversal can be isolated by muting first arrivals that represent direct P-waves and enhanced by using the horizontal (inline) component. This differs from the procedure used for generating virtual P-wave sources, where we time-reverse only data around the first arrivals and use the vertical geophone component.

The current study was limited to the practically important task of reconstructing a virtual shear check shot from an air gun array at sea and estimating an S-wave velocity profile along wells with different inclinations. Examples of synthetic and real data are presented to confirm that the first arrival from the virtual shear source is an S-wave. The deepwater field example shows that the method is capable of delivering very accurate estimates of P- and S-wave velocities at great depths in and under salt. The more complicated the overburden, the better and more valuable the virtual shear source.

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