Virtual Shear Checkshot with airguns

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Summary

We present a new application of the Virtual Source Method that simulates shear-wave checkshot from conventional walkaway Vertical Seismic Profile thus giving the name Virtual Shear Checkshot. Since Virtual Source is "manufactured" to our specifications, we can design a pure shear radiation pattern without longitudinal part. This would be impossible with a real source. We demonstrate that this shear radiation results from the superposition of abundant converted-wave arrivals and we focus on obtaining shear-wave checkshots in challenging offshore environment where shear sources are usually not available. We present synthetic and field data examples of Virtual Checkshots where vertical *P*- and *S*-velocity profiles are recovered under complex overburden using arrays of airguns.

Introduction

The Virtual Source Method (VSM) has recently been introduced (Bakulin and Calvert, 2004) as a way to generate seismic sources at the location of downhole geophones utilizing actual excitation from the source array at the surface. Bakulin and Calvert (2005) further suggested that one can make Virtual Source that excites only shear waves using Vertical Seismic Profiling (VSP) with airgun sources typical for offshore environment. Airguns do not excite direct shear waves and any VSP estimate of shear velocity is usually obtained using late arrivals of converted energy that need to be identified, picked and processed (Zhao et al., 2005). Recently seabed shear source was introduced but its deployment has a lot of challenges and suitability for deep waters is unknown (Ackers et al., 2005). We illustrate that VSM can automatically harvest useful converted energy abundant in real data and effectively create a downhole shear source at one of the geophone locations using conventional acquisition with airguns. This process is completely data-driven and does not require knowledge of overburden velocity. In fact, the more complex the overburden, the better the quality of the Virtual Shear Source. In contrast to actual downhole sources, Virtual Shear Source does not radiate *P*-waves and thus the shear wave of interest becomes the first arrival. First, we illustrate the concept on a synthetic example using layered model from a North Sea field. Then we create Virtual Shear Checkshot using deepwater VSP dataset from the Gulf of Mexico and obtain shear-velocity profile that is in very good agreement with the dipole sonic log both in salt and below salt.

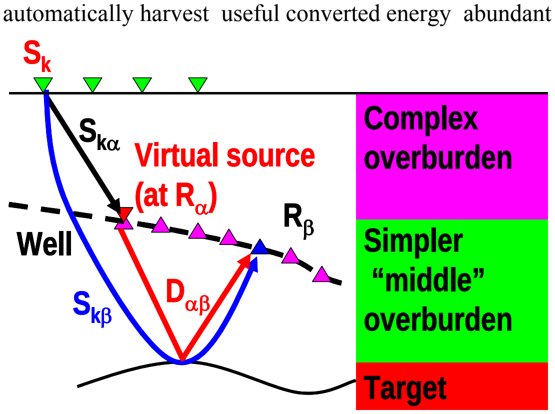

Figure 1: Virtual Source principle.

Theory

The Virtual Source Method has been described in detail by Bakulin and Calvert (2006). The essence of the method is to obtain a Virtual Source at the location of each geophone by utilizing energy from an array of surface sources (Figure 1). The acquisition is as for conventional VSP with surface shots and downhole geophones. The output is a new dataset with both downhole sources and receivers at the same locations. Downgoing signals recorded by geophones are time-reversed and re-sent back from each shot. Linearity and reciprocity are assumed in order to simulate a time-reversed experiment numerically on the computer rather than doing it physically as done by Fink and Prada (2001).

The Virtual Source trace $D_{\alpha\beta}(t)$, can be computed according to the equation of Bakulin and Calvert (2004)

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

where $S_{k\alpha}$ (t) and $S_{k\beta}$(t) are traces from a surface shot k to receivers α and β respectively, and the star denotes convolution. Since no velocity model is required to perform the generation of Virtual Source data, VSM can image through extremely complex overburdens (Bakulin and Calvert, 2004). Reverberations, diffractions, multiples are all re-transmitted back with proper delays and all collapse at the geophone locations, thus fueling the Virtual Source. Since our objective is to generate shear-wave Virtual Source data, we modify the VS process as follows:

- We record the horizontal component;
- On the time-reversed portions we mute the strongest downgoing *P*-waves corresponding to first arrivals.

Draeger et al. (1998) demonstrated in a laboratory experiment at a solid-fluid interface that selective time-reversal of converted modes can result in a tighter focal spot for backpropagated S-waves due to their smaller wavelength. Using similar idea we backpropagate converted wavefronts and mute unwanted longitudinal wavefronts. As a result, the Virtual Shear Source emits only transverse energy.

Synthetic example on realistic 1D model from North Sea

Let us attempt to create a Virtual Shear Source at a geophone buried 200 m below sea level during vertical VSP in a marine environment. We utilize a real 1D velocity from Tommeliten field in North Sea (Allnor et al. 1997) depicted on Figure 2b. The wavefield recorded from an airgun array in the water layer on the horizontal component

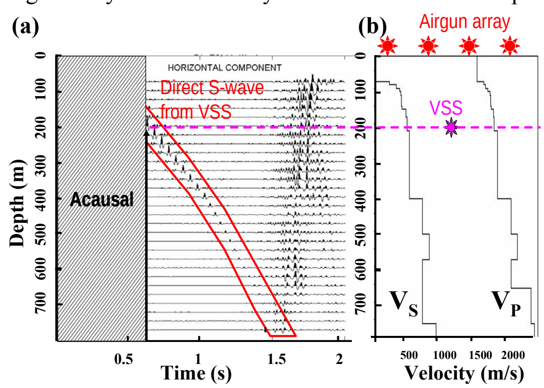

Figure 2. Virtual Source gather (a) and velocity section (b). VS is at 200 m depth. Both causal and acausal parts are shown. Note that most of the contamination occurs either in the acausal part or later in the causal part.

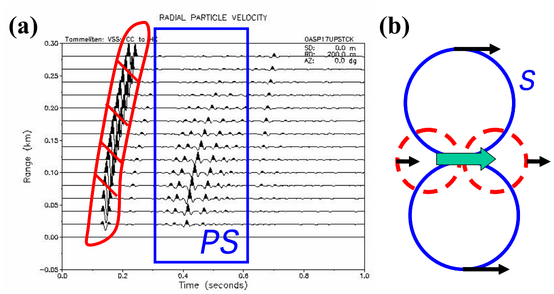

Figure 3: (a) Horizontal component recorded by a geophone at 200 m depth inside the sediment from an airgun array at sea. (b) Radiation pattern of horizontal force in homogeneous medium.

of a downhole geophone at 200 m is depicted in Figure 3a. The full wavefield, computed with a reflectivity code, contains all possible arrivals and multiples except those from the sea surface since water layer was modeled as a half-space. By reciprocity the same wavefield would be generated with a buried horizontal force and recorded by hydrophones at sea. Thin layering of shallow sediments makes it difficult to separate the individual waves. First arrivals are easily identified as scattered *P-P* arrivals while later energy consists of various transmitted and converted arrivals and reverberations. For a real source representing buried horizontal force, the radiation pattern consists of a *P*-wave lobe and two *S*-wave lobes (Figure 3b). To create Virtual Shear Source we mute the strongest downgoing *P*-wave energy in the time-reversed portion and only backpropagate the packet of interfering waves inside the blue rectangular gate that should contain most of the converted *PS* arrivals (Figure 3a). Selecting properly separated dowgoing (converted) S-wave field for time reversal may be preferable. However simple gating seems to work well for real data and avoids any phase distortion of the time-reversed traces that typically happens during wave separation procedures.

The resulting Virtual Shear Checkshot with Virtual Source at 200 m is shown in Figure 4. Clear dowgoing arrival is observed on all seismograms' horizontal component. This arrival has shear-wave velocity, as can be seen by comparing it with a second set of waveforms representing the firing of an actual downhole source placed at 200 m depth (Figure 4). We can even see a strong upgoing reflection from an interface at 400 m visible on both wavefields (Figure 4) which is consistent with the downward radiation pattern of the Virtual Shear Source.

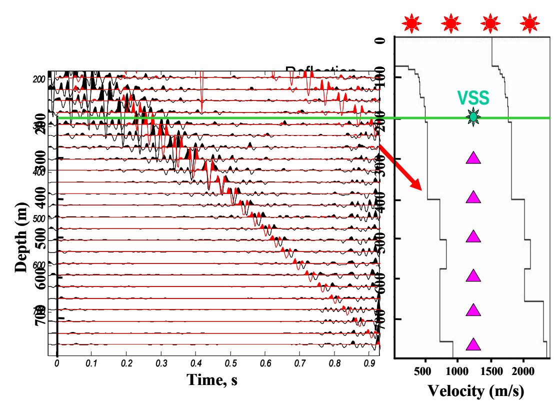

Figure 4: Virtual Source checkshot (left) and corresponding velocity model (right). Virtual Source data is in black and the seismograms from a simulated real downhole source are in red.

The obtained results are somewhat surprising if we recall that a horizontal force does not excite any shear waves in a strictly vertical direction (Figure 3b) and also that *P-S* conversion is zero at a fluid-solid interface. It implies that the radiation pattern of the Virtual Shear Source is likely to deviate from that of Figure 3b. Nevertheless data at non-zero offsets contain abundant converted energy and VS rigorously collects that energy and provides reasonable shear radiation even in the vertical direction. Of course real subsurface is always more heterogeneous than in this example and we will show next on field data how a deviation from the homogeneous plane-layered model will create more mode-converted energy enhancing the Virtual Shear Source at vertical incidence.

Deepwater field example of Virtual Shear Source

A walk-away VSP was acquired in a vertical well through a massive salt body in the deepwater Gulf of Mexico (Figure 5). The sources were airguns in the water column, i.e., pure *P*-sources. However, *P-S* conversions occur above the receivers - notably, at top salt – that allow us to create Virtual Shear Source data. Since *S* arrivals register most

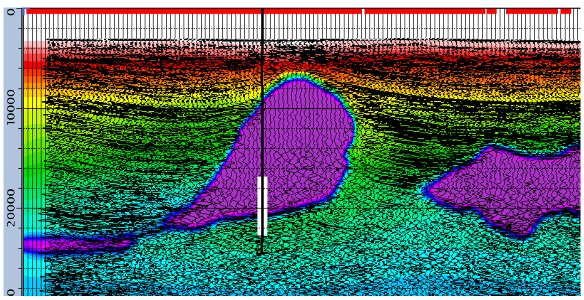

Figure 5. Walk-away VSP acquisition: airgun source, 612 shot points - shown in red at the top; 96 receiver positions shown by a white bar in the well.

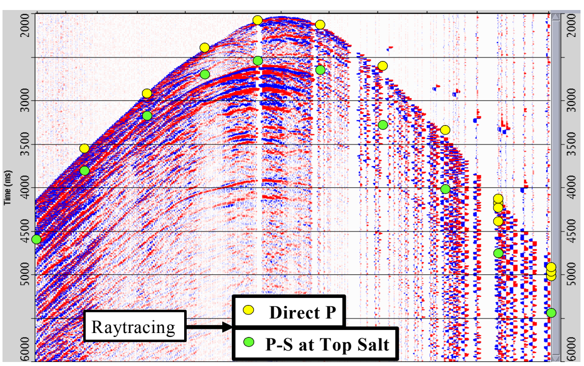

Figure 6. Common receiver gather – X (in-line) receiver component.

strongly on the horizontal component, we used as input the in-line (X) receiver component of the VSP (Figure 6). We muted remnants of the first arrival (*P*) on the X component taking care not to harm a later strong *S* arrival interpreted as *P-S* conversion at the top of salt (Figure 6). Figure 7a shows the resulting Virtual Shear Source data. For comparison, Figure 7b shows "conventional" Virtual Source data (*P*) generated from the Z component of the same VSP. It is obvious that the first arrivals in the two plots in Figure 7 correspond to different wave types – *P* and *S*. They are both very easy to pick to construct *P* and *S* Virtual Checkshots (Mateeva et al., 2006). Picking the first arrivals on sub-salt receivers gives the velocity profiles shown in Figure 8. They match the smoothed sonic logs very well. Note that while *P*-wave checkshots are routinely acquired with surface sources, conventional *S* checkshots do not exist. Without the Virtual Shear Source it would have been impossible to obtain such an accurate Vs profile at more that 7 km depth below salt, in an offshore environment.

Since the Virtual Checkshot measures interval velocities, our primary focus was on the sub-salt 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 *P* and *S* velocities in the salt. A linear regression through the Virtual Source first arrivals in salt gave Vp = 14660 ± 330 ft/s and Vs = 8390 ± 350 ft/s. Smoothed logs over the same depth interval gave Vp=14650 ± 60 ft/s, Vs = 8340 ± 35 ft/s, where the error bars reflect inhomogeneity rather than measurement uncertainty. So, once again, Virtual Checkshot and well velocities are in excellent agreement.

Of course, creating an *S*-velocity profile is the simplest application of the Virtual Shear Source. We could process the entire shear wavefield shown in Figure 7a as a conventional VSP to obtain a high-resolution *S-S* image of the medium below the receivers.

Conclusions

We present the Virtual Checkshot concept in which each receiver in a well is converted into Virtual Source and records from the Virtual Source to other receivers provide us with undistorted velocity estimate along the well that does not suffer from any overburden complexity above the receiver array. This is analogous to acquiring checkshot with a downhole seismic source that can be placed at every receiver location. The Virtual Source Method allows us to achieve similar results by having only receivers in a well and shooting a walkaway source line at the surface, i.e. using conventional walkaway VSP acquisition. As a result we obtain improved velocity profile along the well that can be used for well ties, velocity model building and other purposes. Virtual Sources are much more flexible than real ones. In particular we can manufacture Virtual Source that radiates pure shear energy without any *P*-wave contamination. This is achieved by using a horizontal component and muting the most energetic downgoing *P*-waves (first arrivals) in the time-reversal process. We prove the concept of Virtual Shear Checkshot using a synthetic and a real data example from the deepwater Gulf of Mexico. In the data example we can separately obtain two sets of wavefields: one having *P*-waves as a first arrivals and another having *S*-waves as a first arrival. Estimated *P*- and *S*-velocity profiles are in very good agreement with the sonic logs both in salt and sediment sections. We confirm that the more complicated the overburden, the better and more valuable the Virtual Shear Checkshot.

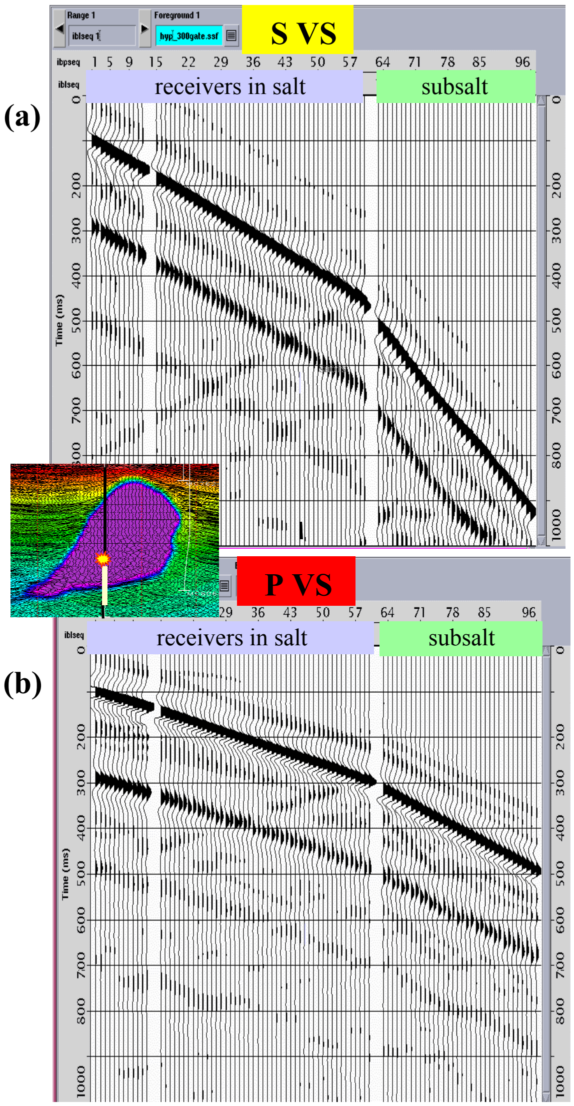

Figure 7. Common shot gather with an *S* (a) and a *P* (b) Virtual Source at the top-most VSP receiver. The Virtual Source "fires" at t=100 ms.

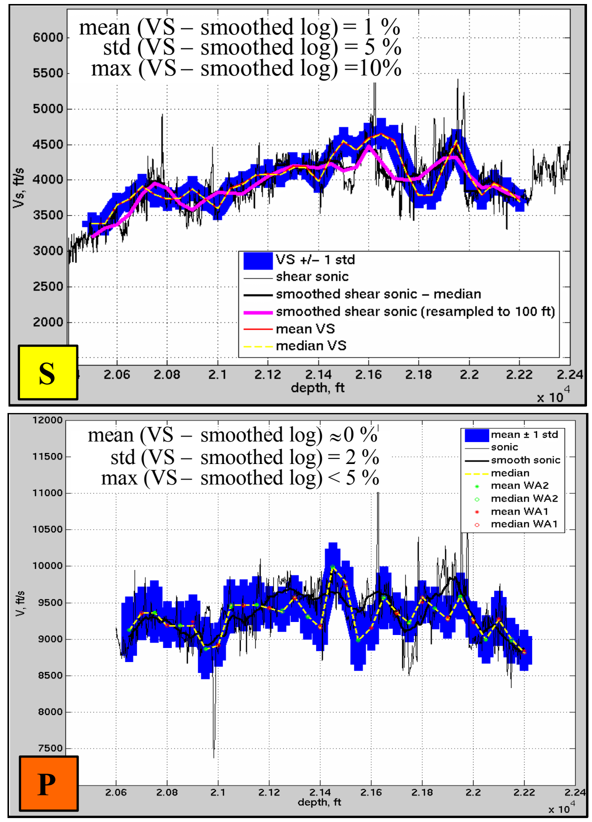

Figure 8. Virtual Checkshot vs. sonic log: (top) *S*-wave velocity, (bottom) *P*-wave velocity.

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