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Virtual Shear-Wave Source Delivers a Reliable S-Wave Velocity Model for VSP Imaging

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Summary

Land walkaway VSP data acquired with vibroseis data contains abundant amounts of converted waves. Their imaging requires an accurate shear-wave velocity model that is often not available. Here, we apply seismic interferometry to create a virtual shear-wave checkshot with first arrivals representing the direct downgoing shear wave along the borehole. Testing on a field data example demonstrates the ability of the redatuming approach to reconstruct accurate virtual gathers and deliver reliable shear-wave velocity from first-break time picks. Using the retrieved shear-wave velocity profile, the mode-converted VSP field data were migrated to obtain a reliable subsurface image consistent with the image obtained from PP data.

Introduction

Seismic interferometry, also known as the virtual source method (VSM), has been widely used to create virtual source/receiver gathers. It transforms seismic data from the original field geometry to another desired geometry without knowing the underlying velocity model. In seismic interferomertry, the seismic wavefields are cross-correlated, or convolved with each other to produce the redatumed gathers as these recorded seismic traces act as natural wavefield extrapolators (Wapenaar and Fokkema, 2006; Schuster, 2009).

In walkaway VSP acquisition geometry, the recorded wavefields often contain a significant amount of mode-converted PS reflections. Shear-wave velocities are required to obtain reliable subsurface images using mode-converted reflection arrivals. Bakulin et al. (2007) demonstrated how the VSM can be used to create a shear-wave source at the location of buried geophones. They showed how the virtual shear-wave (VS) checkshot could yield an accurate shear-velocity profile.

In this study, we apply the VSM to create a virtual shear-wave source placed at a downhole receiver position using a land data example. The walkaway vibroseis sources are effectively redatumed using the interferometric transformation from the earths surface to the downhole location. Land walkaway VSP data contains many downgoing PS conversions in the near surface and overburden that feed virtual source with S-wave energy. To suppress the redatuming artifacts, we used the stationary phase analysis to optmize the summation aperture around the physical shots providing the most significant contributions. The first-break arrival times of the virtual downhole gather are picked to reconstruct the shear-wave formation velocities. This velocity profile is used for successful imaging of mode-converted PS waves.

Theory

Land walkaway VSP datasets are conventionally acquired using vibroseis sources along the surface and recording the wavefields at downhole geophones. Bakulin et al. (2009) proposed an interferometric approach to obtain a virtual source emitting shear-waves from the recorded physical shot records acquired in a marine acquisition environment using airgun sources. The transformed acquisition geometry is that of a single-well profile (SWP), where the virtual shot is fired at downhole receiver positions and the wavefield is recorded by the remaining downhole geophones.

The reciprocity equation of the correlation type can be used to redatum surface shots in VSP acquisition geometry to virtual SWP shots. Mathematically, obtaining a virtual downhole shear source can be computed in the frequency domain as follows (Bakulin and Calvert, 2005; Wapenaar and Fokkema, 2006; Schuster, 2009):

$$G(B|A,\omega) = \sum_s G(B|s,\omega)G(A|s,\omega)^*, \quad (1)$$

where $G(B|A,\omega)$ represents a virtual SWP trace recorded at receiver station B due to a virtual downhole shear source at A. $G(B|s,\omega)$ is the recorded seismic trace containing the extracted mode-converted PS arrivals recorded at B due to a source at s. $G(A|s,\omega)^*$ is the complex conjugate of the recorded trace recorded at a borehole station A due to a source at s. A schematic ray diagram in Figure 1 shows how cross-correlating a mode-converted PS arrival recorded at A due to a source at s with a mode-converted PS arrival recorded at B due to a source at s yields a new downhole trace for a virtual shear-wave source fired at A and recorded at B. The traveltime associated with the common ray path subtracts, and the arrival time of the virtual event is that of a direct shear energy propagating from A to B. Note that the virtual trace is retrieved by the data-driven cross-correlation operation between recorded traces without knowledge of the subsurface velocity model.

Figure 2 shows the workflow used to compute the virtual shear shot gathers. The recorded inline x-component VSP gathers are used in the transformation as they capture most of the mode-converted PS energy. We muted around the first-break (i.e., P-wave direct arrivals) to extract the conjugated green's function, $G(A|s)^*$, which is used for the backpropagation of the mode-converted data, $G(B|s)$. The interferometric redatuming is applied to all the physical shots. Each physical shot yields a redatumed virtual shot at the borehole receiver positions. Lastly, the energy from the contributing physical shots, based on the stationary phase analysis, are summed together to lessen the effect of cross-correlation artefacts and to obtain cleaner virtual shot records. Thus, the modified interferometric datuming equation becomes:

$$G(B|A,\omega) = \sum_{L} G(B|s,\omega) G(A|s,\omega)^*, \quad (2)$$

where L denotes the sources, which yields significant physical contributions based on stationary phase analysis, selected on the cross-correlogram prior to stacking (Korneev and Bakulin, 2006; Poliannikov and Willis, 2011).

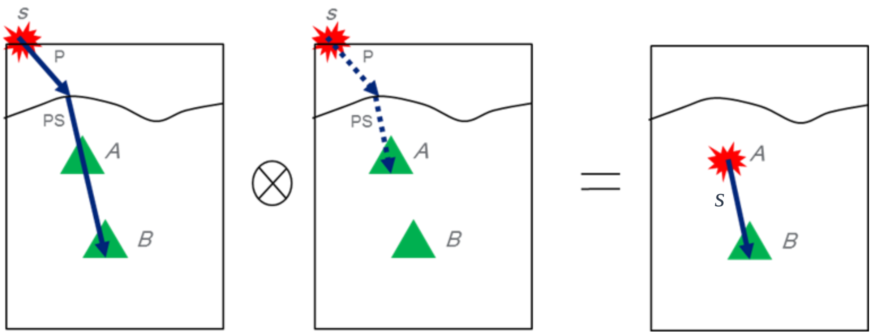

Figure 1 A schematic ray diagram: the virtual shear-wave source placed at the downhole receiver location at *A* is constructed by cross-correlating the mode-converted energy received at *B* due to a source *s* with the mode-converted energy received at *A* due to a source at *s*. Note that the traveltime associated with the common ray path subtracts (dashed segment).

Figure 2 The proposed workflow to extract virtual SWP shot gathers.

Field Data Example: land walkaway VSP in a desert environment

The VSP acquisition geometry is shown in Figure 3 (left), and it consists of 244 shots and 95 downhole receivers marked by the red and blue dots, respectively. The shot and receiver spacings are 82 ft and 50 ft, respectively. The challenge here is to retrieve a time-depth profile of shear-wave formation velocities in the vicinity of the well. Figure 3 (right) shows a representative x-component VSP common shot gather after horizontal rotation. Whereas the first arriving waves (i.e., direct P-wave) can easily be picked in this gather, the shear-wave is not easily traced to reconstruct an accurate shear-wave time-depth curve. Nevertheless, the x-component VSP walkaway gathers are rich in mode-converted PS energy.

The proposed interferometric datuming is used to create a virtual shear source using equation (1). The initial VS checkshot is reconstructed by summing the redatumed data over all available shots, and it is plotted in Figure 4 (right). The reconstructed virtual shear source is placed at the topmost downhole receiver position (black star in Figure 4 [left]). The source emits shear-wave arrivals received by all the 95 physical receivers below (blue dots in Figure 4 [left]). The shear-wave first arrivals become altered by non-physical contributions at deeper receiver stations showing an event interfering with the actual first arrivals marked by the blue arrow in Figure 4 (right). Therefore, this would yield an inaccurate shear-wave velocity profile.

To alleviate this problem, the modified equation (2) is used to sum the data only over the shots with stationary contributions. The stationary phase analysis is conducted by first creating cross-correlograms. The virtual trace, $G(B_{last}|A_{topmost})$, is the trace received at the last receiver station emitted by the virtual shear source placed at the topmost receiver position. According to the reciprocity equation of the correlation type, equation (1), this response, $G(B_{last}|A_{topmost})$, can be constructed by each physical shot. The cross-correlogram consists of the all the virtual responses from every shot. We can find out the contributing shots within a range L and can sum the data over these stationary points only.

The cross-correlogram for $G(B_{last}|A_{topmost})$ is plotted in Figure 5 (left), whereas the virtual shear shot gather using the modified summation in equation (2) is presented in Figure 5 (right). It is reconstructed by summing the redatumed data over the stationary shot points. The stationary points are marked by the blue arrow in the cross-correlogram and they extend from shot #50 to shot #150 in the vicinity of the well located close to shot #125. The first arrival shear-wave energy at the deepest receiver due to the "virtual" shot placed at the top borehole receiver is marked by the red arrow in the cross-correlogram. The far offset physical shots yield non-stationary contributions, which distort the construction of the virtual shot gather as their first-arrival times are earlier than the stationary point contributions.

First arrivals on the virtual shear checkshot were picked to retrieve a velocity profile as shown in Figure 5 (right). The resulting S-wave velocity model shown in Figure 6 (left) was used (together with the P-wave velocity model) to migrate the VSP mode-converted upgoing PS reflections. Figure 6 (middle) shows the VSP PS migrated image clearly revealing two target reflectors. For comparison, the VSP PP migrated image is shown in Figure 6 (right). We observe the same two target reflectors in the same subsurface position validating the accuracy of the S-wave velocity model.

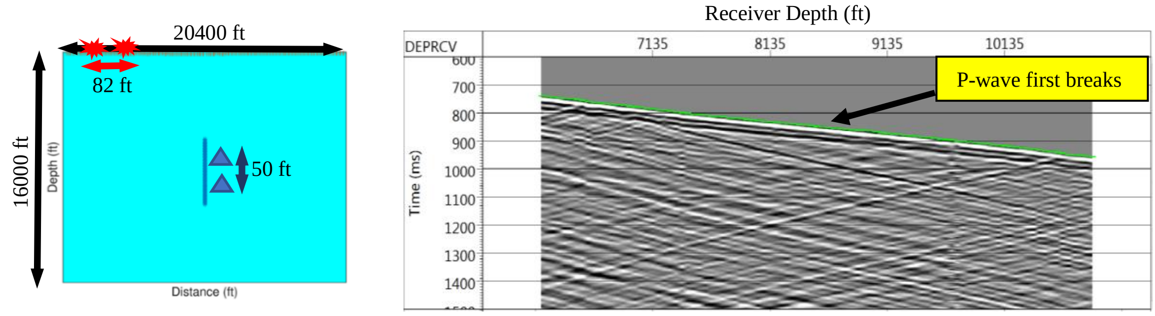

Figure 3 *The walkaway VSP acquisition geometry (left) and a representative x-component VSP common-shot gather showing clear first-break picks of P-wave direct arrivals (right).*

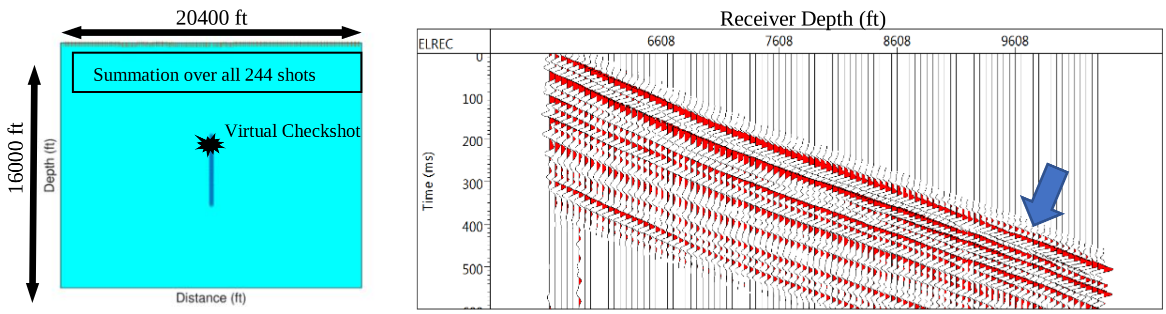

Figure 4 *The virtual shear-wave source using summation over all 244 shots: The source is placed at the topmost receiver position denoted by the black star while the energy is received by all the receivers denoted by the blue dots (left). The virtual shear shot gather shows the inaccurate first-arrival of shear-wave energy, especially at the deeper receiver stations, marked by the blue arrow (right).*

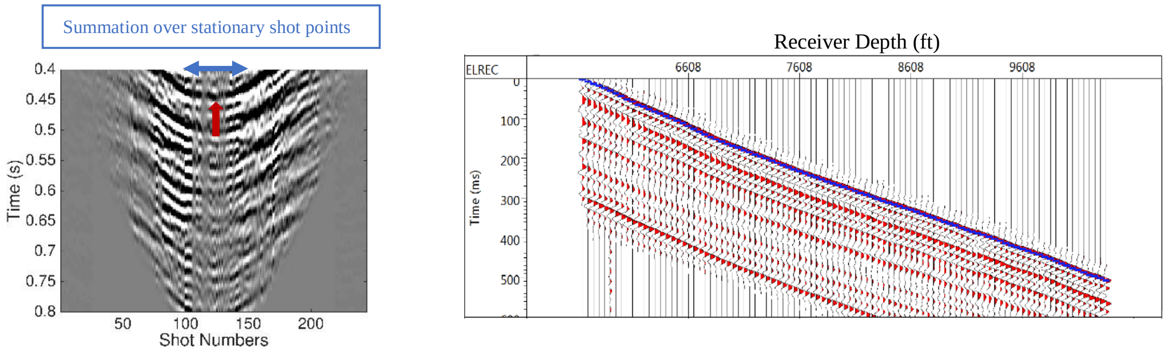

Figure 5 *Same as Figure 4 but obtained using summation over a smaller aperture of shots guided by stationary phase analysis using the cross-correlogram for $G(B_{last}|A_{topmost})$ (left). The blue arrow marks the shots that yield stationary contributions. The red arrow marks the shear-wave first arrival times. The virtual checkshot constructed summing over the stationary points shows less artefacts (right).*

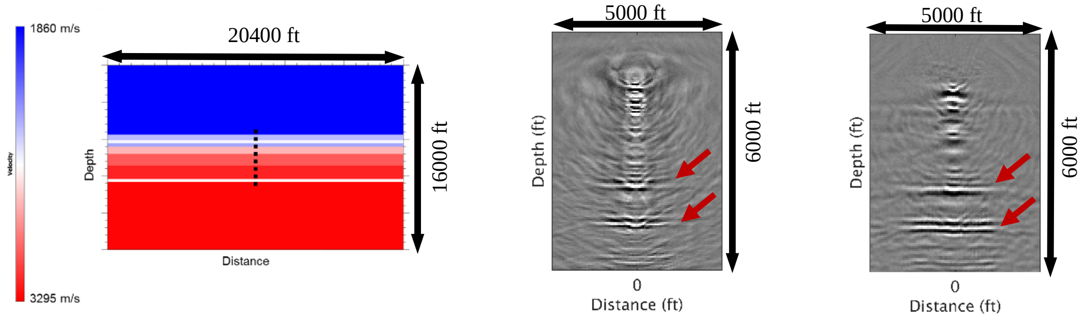

Figure 6 *The field data example: the reconstructed shear-wave formation velocities from virtual checkshot (left). The VSP migrated image of the PS waves (middle) ties well with the VSP migrated image of PP upgoing reflections (right). Two target reflectors, marked by the red arrows, are focused at the same subsurface positions confirming the accuracy of the obtained S-wave model.*

Conclusions

We demonstrate how the virtual shear source checkshot can deliver accurate shear-wave formation velocities for land VSP in a desert environment. A virtual checkshot is obtained by the interferometric redatuming of physical sources along the surface acquired using conventional walkaway VSP geometry. Modified interferometric datuming extracts the stationary contributions by summing the redatumed traces over the shots, which yields physical contributions in the cross-correlograms. As a result, the redatumed data suffers less from non-physical artefacts that alter the shear-wave first breaks in the virtual shot gather. The obtained shear-wave velocity profile was subsequently used for migrating upgoing mode-converted PS VSP reflections and was used to focus target reflectors to their true subsurface positions tying with the conventional VSP migrated image from PP reflections.

References

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