VIRTUAL CHECKSHOT RECONSTRUCTION FROM SEISMIC-WHILE-DRILLING DATA

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Summary

Seismic interferometric redatuming can help reconstruct virtual downhole sources, especially with challenging data quality caused by complex near surface. We applied the interferometric transformation to the seismic-while-drilling dataset recorded with single sensors and suffering from a low signal-to-noise ratio. Using the virtual source method, we created a compressional downhole virtual source. We performed a stationary phase analysis of the data to determine the surface points that yield significant contributions. After interferometric summation over the apertures containing the stationary points, we obtained a less noisy and more robust verticalized virtual P-wave gather than the original non-redatumed gather. The downhole virtual gathers were picked to reconstruct reliable P-wave average velocity profiles.

Virtual checkshot reconstruction from seismic-while-drilling data

Introduction

The Seismic-while-drilling (SWD) technology utilizes drillbit's vibrations to retrieve subsurface information (Rector and Marion, 1991; Miranda et al., 1996; Poletto and Miranda, 2004). A limited number of surface sensors are often deployed in the field to record SWD data and obtain reverse vertical-seismic-profiling (rVSP) datasets. Processing SWD data is quite challenging due to the weak drillbit's signal, which is often obscured by overwhelming noise. This noise is primarily of surface origins near the well, such as shale shakers, engines, and generators at the well site.

Recently, Almuhaidib et al. (2018) and Bakulin et al. (2020) presented and analysed the data acquired by the Drilling Camera (DrillCAM) system that aims to record SWD signal by using a larger number of wireless geophones. The SWD data is deconvolved (Poletto and Miranda, 2004) using a high-quality downhole pilot representing the drillbit signature. The reconstructed data suffer from a low signal-to-noise ratio (SNR) typical for single-sensor records in a desert environment with complex near-surface geology, especially near the wellhead. The reconstructed compressional wave (*P*-wave) checkshot profile is obtained from a receiver gather at about 475 m away from the wellhead. A high-pass filter is typically necessary for SWD data (Poletto and Miranda, 2004) to suppress various surface noises. Lack of low frequencies may lead to a "jittery" first break (FB) picks on the rVSP records.

To alleviate these problems, the virtual source method (VSM) is applied to create redatumed gathers (Bakulin and Calvert, 2006), in which the virtual sources are placed at downhole drillbit locations, and the receivers are placed at deeper drillbit positions. This is achieved by a data-driven cross-correlation interferometric transformation of recorded SWD traces acting as wavefield extrapolators (Wapenaar and Fokkema, 2006; Schuster, 2009).

This study applies the VSM to create both compressional (*P*-wave) virtual sources to reconstruct robust checkshot profiles using noisy SWD data. We redatum each recorded trace by surface receivers and focus it on a subsurface drillbit position as a virtual source. We then complete the interferometric transformation by summing the redatumed virtual source records to enhance the virtual shot's SNR. The resultant gathers have a single-well-profile (SWP) geometry, in which the virtual shot and receivers are placed inside the well providing vertical zero-offset checkshot profiles.

Method

The DrillCAM onshore SWD trial's acquisition geometry consists of 2,500 receivers centred on the well, as shown in Figure 1 (left). A specialized processing workflow was applied to the data to enhance the signal level and extract the reverse VSP profiles from the SWD records (Bakulin et al., 2020).

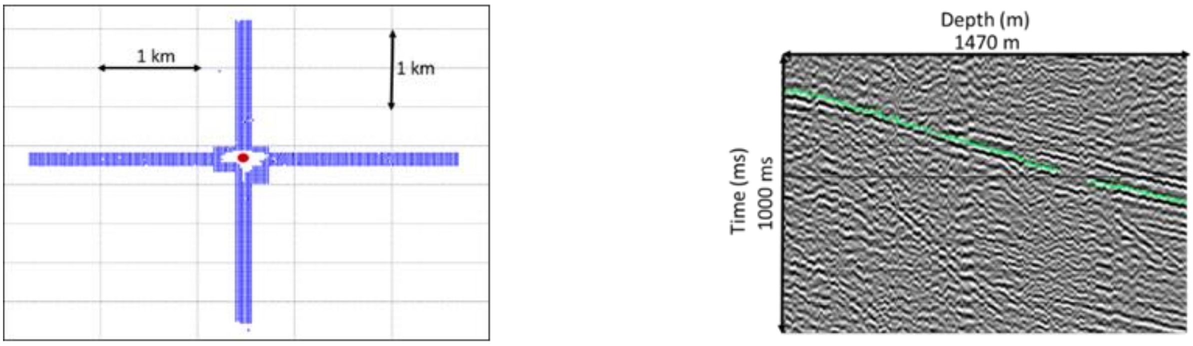

Figure 1 *Acquisition geometry: the layout of wireless receivers (blue dots) and the red dot denote the wellhead (left). The processed and picked rVSP gather from an offset of about 475 m away from the well (right). The green dots denote first breaks picks that experience some jitter.*

It includes deconvolution using the pilot signal, stacking over one drillstring length (i.e., ~10 m depth intervals), supergrouping (Bakulin et al., 2018) of seven adjacent receiver lines, linear noise removal, and high-pass filtering. After deconvolving with the downhole pilot as the drillbit estimate and supergrouping of the north-south striking lines, we extracted a north-south walkaway rVSP line for the interferometric redatuming. In the initial analysis, Bakulin et al. (2020) reconstructed a checkshot profile obtained from a reverse VSP gather, where the receiver location was at an offset of about 475 m away from the well, as shown in Figure 1 (right). This receiver was manually picked as a location that is less affected by rig noise. After the verticalization process required to correct for a finite offset, SWD checkshot gather exhibits highly "jittery" FB picks that may lead to the reconstruction of an oscillatory interval velocity model.

Interferometric stacking allows destructive and constructive interference to play their role and deliver an accurate response from a stationary point expected near the wellhead. Interferometric summation improves the signal-to-noise ratio of the weak drillbit signal, mitigates the FB picks' jitteriness, and reconstructs reliable *P*-wave velocity profiles. To apply the interferometric redatuming, we invoke the reciprocity principle and consider the SWD to have a conventional VSP acquisition geometry. The sources are placed at the surface, and the receivers occupy the downhole drillbit locations. The sources are redatumed using the interferometric transformation to downhole drillbit positions. Mathematically, the virtual downhole source can be computed in the frequency domain as follows (Bakulin and Calvert, 2006; 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 downhole receiver location *B* due to a virtual downhole source at *A*. $G(B|s,\omega)$ is the recorded seismic trace recorded at receiver *B* due to a source at *s*. $G(A|s,\omega)^*$ is the complex conjugate of the recorded trace recorded at downhole location *A* due to a source at *s*. The summation is modified to select the surface sources in the reciprocal VSP domain that has significant contributions based on stationary phase analysis of cross-correlograms (Schuster, 2009).

The traces $G(B|s,\omega)$ and $G(A|s,\omega)$ contain the enhanced downgoing *P*-waves as input to create a downhole virtual *P*-wave source. A schematic ray diagram in Figure 2 shows how the *P*-wave virtual downhole sources are constructed by correlating these two traces. The dashed ray denotes the complex conjugate, and correlating the traces yields the subtraction of the traveltimes associated with the common raypaths.

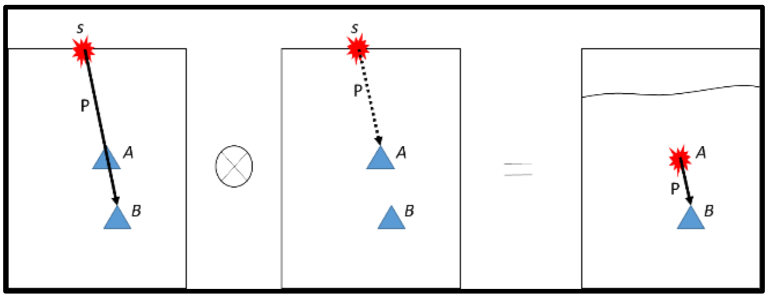

Figure 2 *Interferometric redatuming: correlating two traces with downgoing longitudinal energy to create a virtual P-wave downhole source.*

Field SWD example

The processed 2D SWD acquisition geometry is reconstructed by the supergrouping of the seven lines striking in the same direction. This 2D line consists of 165 single-sensor receivers on the surface and 208 subsurface drillbit source locations extending from a depth of ~10 m to ~1867 m. By invoking source-receiver reciprocity, we consider the sources on the surfaces and the downhole sources as receivers. In the reciprocal geometry, the 165 shots are centred on the well and have a spacing of about 25 m, whereas the downhole receiver spacing is about 10 m.

We initially enhanced the *P*-wave direct and multiple arrivals using FK-filtering. We then applied the interferometric redatuming of the surface sources to create a downhole virtual source at a depth of about 1120 m, which primarily emits P-wave energy. The stationary phase analysis is performed on the cross-correlograms shown in Figure 3 for a particular downhole source-receiver pair. It shows that the main contribution is coming from the particular surface sources spanned by the blue box.

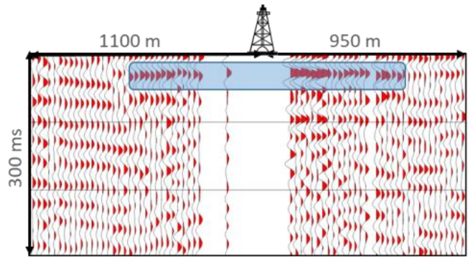

Figure 3 *Stationary phase analysis: cross-correlograms for a particular downhole source-receiver pair showing the significant stationary contributions for the virtual P-wave source inside the blue box.*

We plotted a virtual source gathers after stacking over the stationary surface points in Figure 4 (left) reconstructed at a downhole position. The blue dots in Figure 4 (middle) denote first-break picks that were used to reconstruct the velocity profiles shown in Figure 4 (right). Note that the first break picks are less "jittery" than the verticalized and picks on the raw gather denoted by the brown dots.

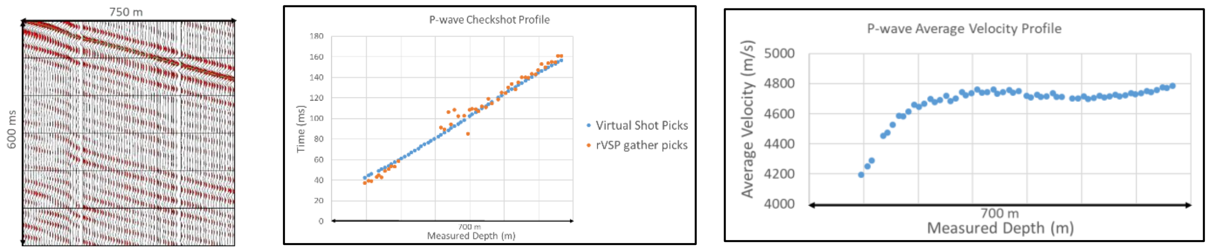

Figure 4 *P-wave virtual source: A redatumed gather at a depth of about 1120 m (left), the checkshot time-depth profile from first-break picks of the virtual gather and raw verticalized gather (middle), and the average P-wave velocities calculated using the FB picks (right).*

Virtual source gathers have a higher signal-to-noise ratio and less jitter. The redatumed virtual shots are not affected by the complex near surface because they were constructed using a data-driven interferometric redatuming, where recorded traces acted as natural wavefield propagators (Bakulin and Calvert, 2006). An additional advantage of the redatumed virtual gather is the natural verticalization of the checkshot profile. The redatuming operations transform the rVSP acquisition into an SWP acquisition geometry, where the virtual sources and receivers are placed in the vertical wellbore. Note that the exact knowledge of stationary point is not required – it only needs to be captured in the surface summation aperture. As a result, a more robust zero-offset profile is reconstructed compared to the profile retrieved from the original SWD geometry (Figure 1 [left]), where the receiver is placed at around 475 m away from the well.

To validate the result, we plotted in Figure 5 the checkshot profiles from two offset wells located within 5 km away from the SWD well. We applied a bulk shift to the checkshot profiles of these offset wells to the same virtual shot depths using an average velocity. Note the remarkable match of the traveltime picks of the offset wells and the SWD virtual source. We calculated the average velocity using the three time-depth curves of this 500-meter interval, and the estimated velocity of this formation is about 4750 m/s.

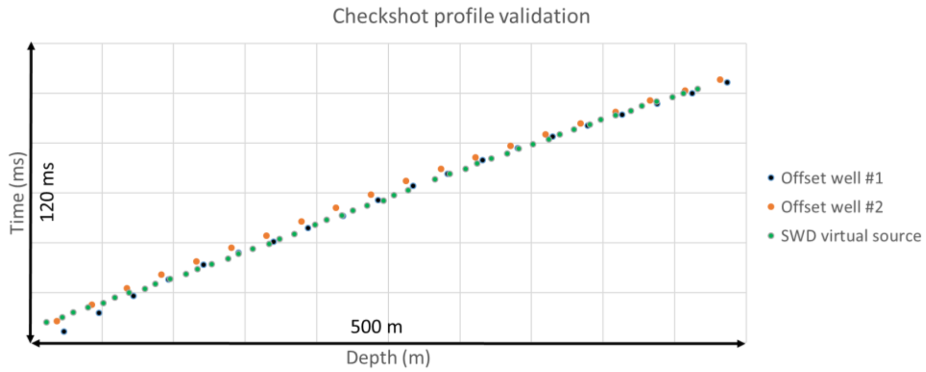

Figure 5 *Checkshot profile validation: the time-depth curves using two offset wells remarkably match the time-depth curve using the redatumed virtual checkshot profile.*

Conclusions

We demonstrated how interferometric redatuming could effectively create a clean and robust virtual *P*-wave virtual downhole source. The redatuming was applied to recently acquired SWD data acquired in a desert environment with a low signal-to-noise ratio. The results show that the virtual gather yields robust time-depth checkshot profiles that helped retrieve reliable *P*-waves average velocity profiles. The interferometric summation based on stationary-phase analysis was essential to enhance the signal-to-noise ratio and reduce the jittering effect of FB picks present in the original reverse VSP gather. The reconstructed time-depth curve is validated using two offset wells that yield similar checkshot profiles and formation average velocity.

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