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Virtual Source Redatuming of Synthetic Land Data Acquired with Shallow Buried Receivers

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SUMMARY

Virtual source redatuming is tested in a synthetic modelling study using shallow (30 m) buried receivers. Both model and acquisition geometry are based on an actual field experiment conducted over an onshore field in Saudi Arabia. While redatuming is expected to improve both imaging and repeatability, in this study we concentrate on optimizing the image. The synthetic data is strongly contaminated with both surface and internal multiples. Various pre-processing options are examined that can address these multiples and improve virtual source imaging using the shallow buried sensors. The effects of source aperture and sampling are demonstrated on the final images. An optimal selection of the cross-correlation time gates is made by observing the effects of different ghost arrivals on the resulting stacks. Using analysis of the correlation gathers, we quantify improvements introduced by up-down wavefield separation using land dual sensor technology and justify the selection of a larger trace aperture.

Introduction

Performing 4D land acquisition with surface sensors represents a significant challenge due to poor repeatability. Experimental data from around the world have shown that shallow burial of the sensors can significantly improve data repeatability (Schissele et al, 2009). The use of buried sensors provides an opportunity to do virtual source redatuming to the receiver level and does not require any knowledge of the velocity model. It has been shown that redatuming can simplify the wavefield and eliminate distortions associated with heterogeneity located between the source and receivers (Bakulin and Calvert, 2006). In addition, we expect redatuming to improve survey repeatability and mitigate time dependent (4D) noise effects caused by seasonal variations, small changes in acquisition geometry from survey to survey, as well as differences in shot coupling (Bakulin and Calvert, 2006). Previous work concentrated mainly on a deep redatuming (a few hundred meters to kilometres below the surface). For land applications there is now more interest in evaluating redatuming using shallow buried sensors (a few meters to tens of meters below the ground). In this synthetic study we analyse the shallow redatuming problem using a realistic geologic model and concentrate on optimizing the image for a deep target. Future work will address the repeatability issue.

Synthetic case study: model and acquisition geometry

In this work we consider a horizontally layered synthetic model with a free surface (Figure 1a). The model and acquisition geometry are based on log measurements and a recent field experiment over an onshore field in Saudi Arabia. The model includes an uppermost low-velocity layer comprised of 16 m of sand cover. Vertical geophones are buried below the sand layer at a depth of 30 m. Seismic data was generated using a vertical force, at the surface, simulating a surface vibrator. A dense source spacing of 7.5 m was used in the modelling to simulate the actual existing field acquisition experiment. The model includes many high and low velocity layers which generate significant amounts of internal and surface multiples. This is confirmed by analysis of synthetic VSP data from the same model (Lesnikov and Owusu, 2011).

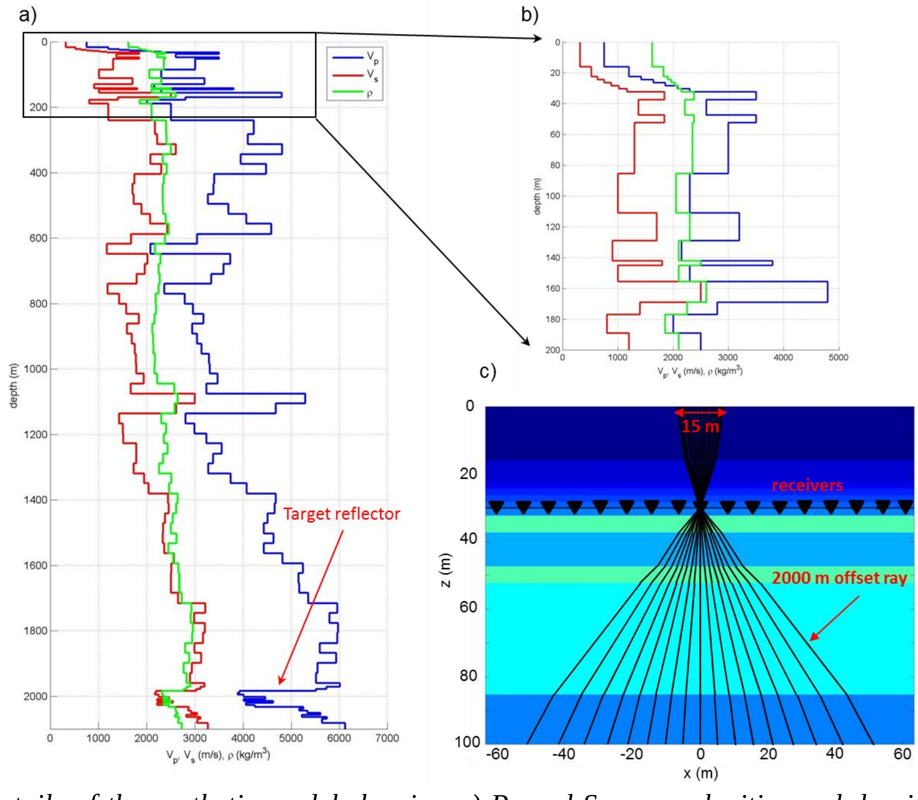

Figure 1 *Details of the synthetic model showing a) P- and S-wave velocities and densities from the surface to the target at 2 km, b) a zoom-in of the near-surface portion and c) ray paths for reflections from the target horizon with offsets of up to 2000 m.*

The virtual source method is a seismic interferometry technique based on estimating the Green's function via cross-correlation of wave fields. This approach, suggested by Bakulin and Calvert (2006), allows one to redatum the sources from the surface to the receiver locations. This method assumes adequate source sampling and therefore avoids the problems of a complex near-surface on the seismic data. Construction of virtual source gathers involves cross-correlation of the wave fields and stacking over an aperture of surface sources. This technique is valid for a generally heterogeneous medium inside the area of integration. However, the assumption is made that the medium outside this integration area is homogeneous (Wapenaar et al., 2010). This implies, in particular, the absence of a free surface. For land applications with abundant free-surface multiples, this poses a serious problem that needs to be addressed.

We test several different approaches to virtual source redatuming and compare these results with data generated from sources at the receiver locations as well as a VSP corridor stack. Our goal is to devise a workflow and parameters that provide an optimum image of a target horizon at a depth of 2 km.

Virtual source redatuming

To generate virtual source data from the initial synthetic shot records we follow a simple workflow. First, the records are subject to FK-filtering to remove linear arrivals such as surface and refracted waves. The filtered data is then used to construct a virtual source gather by cross-correlating and stacking over sources (Bakulin and Calvert, 2006). To produce a stacked image we apply an NMO correction to each virtual source gather and stack. The resulting trace is replicated eight times to show the expected image in 1D. Virtual source theory requires stacking over a closed surface covered with sources. In practice, the stacking is limited to some finite aperture, which includes a stationary phase point. Ray tracing results (Figure 1) show that a surface aperture of only 15 m is enough to cover the range of required offsets for this model, the target depth and the acquisition configuration. Due to rapid increases in velocity with depth in the subsurface (Figure 1b), rays with shooting angles greater than 5^{o} reach critical angle in one of the shallow horizons and do not produce reflections from the target. Ray tracing however is a high-frequency approximation to the wave equation. In actual acquisition relatively low frequencies are used, thus some energy leakage and tunneling through thin high-velocity layers is expected to occur. As a consequence, we consider larger apertures in our testing than those predicted by ray tracing.

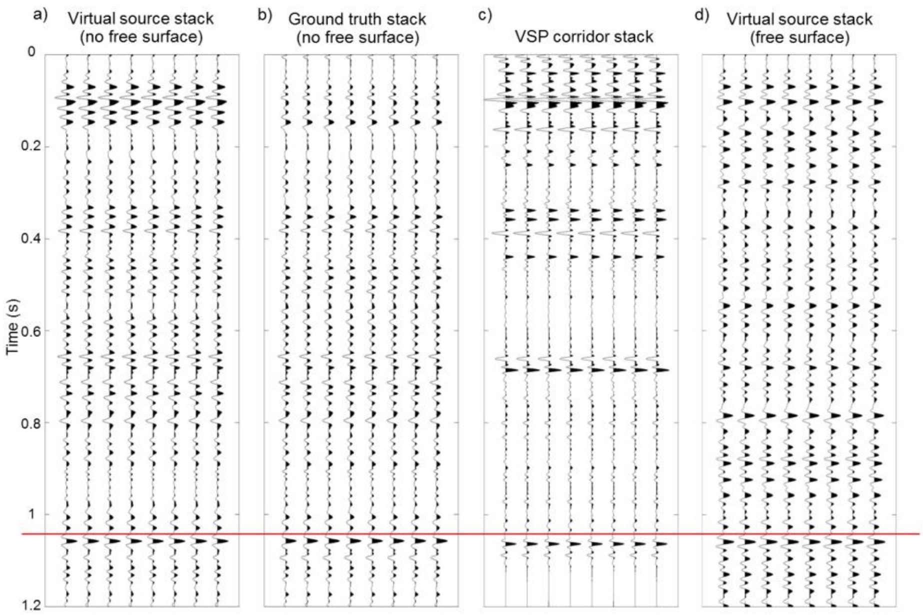

Figure 2 *Stacked sections including a) a virtual source stack for the model without a free surface, b) the ground truth stack for the model without a free surface, c) a VSP corridor stack and d) the virtual source stack for the model with a free surface.*

Figure 2a shows a virtual source stack for the model without a free surface. This stack is compared with a ground truth stack (Figure 2b), obtained using the same NMO correction and stacking. The ground truth response is computed with an actual buried source at 30 m. It assumes a homogeneous half-space above 30 m with the same properties as of the source layer (Mehta et al., 2007). The virtual source stack is very similar to the ground truth. Figure 2c displays a VSP corridor stack that contains only primary reflections. While some arrivals on the ground truth stack match those from the VSP stack, most of them do not because of the presence of internal multiples. The presence of a free surface introduces strong free-surface multiples and as consequence, generates additional spurious events on the virtual source stack (Figure 2d). In all cases however, the target reflection (red line), is still visible. Results from this study suggest that the best image is achieved with an aperture of around 200 m; much larger than the 15 m predicted by ray theory. It was also found that extending the time gate to include several events after the direct wave increases the amplitude of the arrival from the target horizon in the virtual source stack. The best estimates for the time gate (180 ms) and trace aperture (200 m) were used to build the virtual source stack shown in the Figure 2.

Up-down wavefield separation

To address the issue of surface multiples and eliminate spurious events, we applied wavefield decomposition before cross-correlation as suggested by Mehta et al. (2007). In this case, we performed production-type preprocessing of the input data using more sophisticated noise removal followed by wavefield separation. In the actual field experiment, the geophones and hydrophones were buried at the same depth of 30 m. In this study, geophone and hydrophone responses were computed and combined after noise removal to perform wavefield separation. The actual summation was performed using adaptive scaling. The rest of the processing steps, including the virtual source creation, followed the same workflow as before.

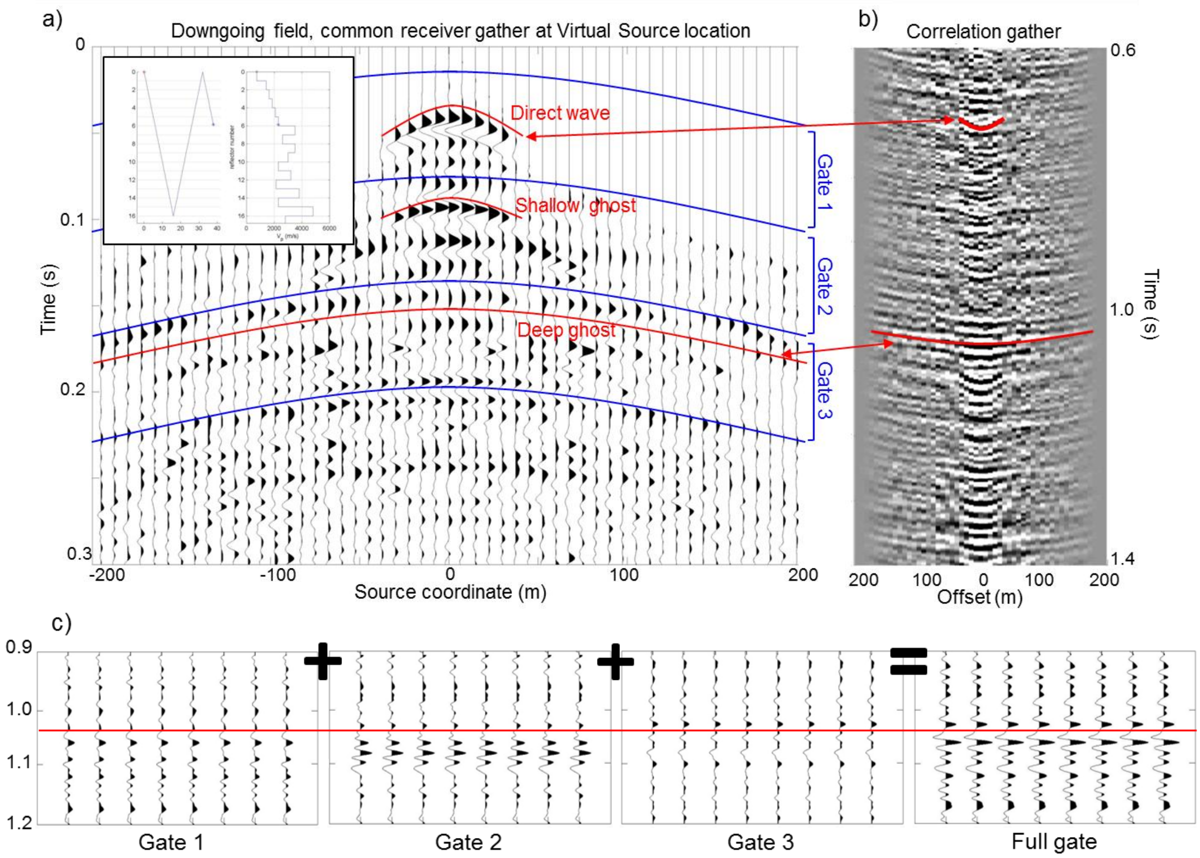

Figure 3 *a) The downgoing wavefield after production-type preprocessing (gain ~ $v_{nmo}(t)\cdot t$ was applied); b) pre-stack correlation before summation for a 200 m offset trace; c) virtual source stack after redatuming using different time gates.*

Figure 3a shows the downgoing wave field after preprocessing. Strong events were identified by ray tracing as source-side ghost arrivals resulting from up-going reflection from shallow horizons prior to reflection from the free surface down to the receivers. While we could have selected a short time gate leaving the direct wave only, we studied the contribution of these later ghost arrivals on the quality of the virtual source gather and stack. For this analysis it is instructive to consider the pre-stack correlation gather (Figure 3b). This gather is built by cross-correlation of the time windowed down-going field, from Figure 3a, with the up-going field before summation. Stacking of this gather yields a virtual source trace for a particular offset. Careful analysis of the correlation gather shows that the direct wave and the shallow ghost events correlate with the up-going field to produce strong steep events dominating the near offsets. In contrast, deeper ghosts produce events which are much weaker and flatter, but spread over a larger range of offsets (Figure 3b). Selection of a larger trace aperture, on the order of 200 m, maximizes the contributions from the deep ghost reflections.

To examine the contribution of different arrivals, the original time gate used for cross-correlation was divided into three distinct gates including the direct arrival, the shallow and deep ghost reflections, and the deep ghost reflections respectively (Figure 3a). While the first gate produces a virtual source stack with the target reflection at the correct time, the amplitude level of this arrival is almost the same as that of neighboring events (Figure 3c). Using the second time gate almost doubles the amplitude of the target event. However, this introduces some artifacts below the target reflection. A virtual source stack obtained using the third time gate has lower amplitude at the target reflection. Nevertheless, the deepest time gate helps to reduce the artifacts introduced by the second gate. The best result is obtained when all three gates are combined into a single 180 ms gate. We determined that direct wave and ghost arrivals from the source side all contribute to the reservoir reflection and improve the signal-to-noise ratio on the final virtual source stack.

Conclusion

This synthetic case study has shown that virtual source redatuming performs well when the sensors are buried at a relatively shallow depth of 30 m. Due to the presence of high and low velocity layers throughout the section, the data contains many internal and free-surface multiplies that create spurious events on the virtual source gather and stack. Increasing the trace aperture and extending the time gate used for correlation enhances the target reflection compared to the background events, though it also increases the amount of spurious events in other parts of the section. Numerical tests suggest that that the best aperture and gate size for the model and acquisition configuration in question are 200 m and 180 ms respectively. Up-down wavefield separation using dual sensor summation further improves the signal-to-noise of the virtual source gather. Noise removal followed by wavefield separation reveals the presence of ghost arrivals from the source side within the extended time gate. It is clear that the correlation of ghost arrivals with the corresponding up-going reflected events makes an essential contribution in enhancing the reservoir reflection. Therefore, if the objective is an optimum image, source-side ghosts should be included in the time gate. It is unclear at this time, if inclusion of the source-side ghost reflections has a positive or negative effect on seismic repeatability using virtual source redatuming.

References

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