Full-waveform inversion of variable-depth streamer data: An application to shallow channel modeling in the North Sea


Industry implementations of full-waveform inversion (FWI) are driven by the lower frequencies in the seismic data. This is in conflict with conventional acquisition scenarios where the free-surface ghost attenuates these desired low frequencies. In this article, we discuss the application of FWI to variable-depth streamer data and show that FWI adapts naturally to this acquisition geometry, hence benefitting from the improved low frequencies recorded in this configuration. We illustrate this with an example from the central North Sea, where detailed velocity features associated with the shallow channels in the near-surface geology are revealed by FWI. Migration with this updated velocity model improves the imaging through the near surface.

Introduction
In recent years, FWI has again become a topic of great interest in the oil and gas industry. This has been fuelled by advances in computing power that now allow real-world 3D data sets to be analyzed on a realistic timescale. It aims to estimate high-resolution velocity models by minimizing the difference between observed and modeled seismic waveforms. After the seminal publication of Sirgue et al. (2009), showing the potential of FWI on a real 3D data set, there are now many examples demonstrating the derivation of high-quality and high-resolution velocity models from FWI. These velocity models can be used as an interpretative product in themselves, as well as the more obvious benefit of improving the imaging through complex geological and structural environments.

At the same time, there have been advances in marine broadband acquisition, such as the use of a variable-depth streamer, which enables lower seismic frequencies to be recorded. Low seismic frequencies with good signal-to-noise (S/N) ratio play a key role in the FWI process. Here we combine these two topics and apply FWI to variable-depth streamer data to give a data-driven solution to a shallow-channel problem in the central North Sea.

Low frequencies for successful FWI
Good low-frequency data play an important role in the practical use of FWI. A key issue in the successful application of FWI is that of avoiding convergence to local minima during the nonlinear inversion process as a result of using gradient-based algorithms. More sophisticated inversion methods that find global minima, such as simulated annealing or evolutionary algorithms, exist in the scientific literature. While these do not suffer from the drawbacks of gradient-based techniques, they are significantly more expensive and their application is beyond current industrial implementations of FWI.

The local minima problem is connected to cycle skipping on the data, with the modeled data being associated to the wrong event in the shot record. A common way to overcome this is to combine a good starting velocity model with the use of low frequencies, such that the initial modeled field records are not cycle-skipped with respect to the real ones. This involves an interaction between the starting model accuracy and S/N of the lowest recorded frequency. Unfortunately, this can limit the applicability of FWI. In fact, we would like to use FWI to aid the building of the velocity model in the early stages of the processing flow, rather than just adding final details to a prestack depth migration velocity model obtained from a traditional tomographic approach. The initial velocity model at this early stage is likely to be of poor quality; for example, just a 1D profile, and FWI would work only if the acquired data contained very low frequencies. In general, applications of FWI benefit from the acquisition of better low-frequency data (Plessix et al., 2010).

Variable-depth streamer acquisition and FWI
Variable-depth streamer acquisition has emerged as an effective technique for providing wide-bandwidth seismic data (Soubaras and Dowle, 2010). This technology combines elements of improved equipment, acquisition, and processing to deliver broadband data. The use of solid streamers, to reduce recording noise, with new-generation electronics, allows the recording of signal at the very low-frequency range, down to 2 Hz (Dowle 2006). Variable-depth geometry typically uses cable depths to 50 m, such that the data acquired tend to be less noisy because of the quieter recording environment at depth. The variation in the receiver depth introduces receiver ghost diversity over different offsets, which enables the receiver ghost to be fully removed by using a joint-deconvolution method (Soubaras 2010). Combining all of these aspects together provides broad bandwidth data that produce sharper wavelets for better resolution of important features such as thin beds and stratigraphic traps. The improved low frequencies provide better penetration for deep targets, as well as better stability for seismic inversion (Soubaras and Lafet, 2011).

The improved low-frequency recording with good S/N has obvious benefits in the use of FWI. Application of FWI to variable-depth streamer data is straightforward; because the wavefield can be extracted at any point in the model volume, the data can be modeled directly for the variable-depth recording datum. Including a free surface in the modeling creates the correct source and receiver ghosts to match the acquisition. Figure 1 demonstrates the data quality obtained with the variable-depth streamer acquisition by showing a series of low-frequency, narrow band-pass filters applied to a raw shot record. We clearly see that the variable-depth streamer data has excellent S/N down to 3–4 Hz and, perhaps, even usable signal below this frequency.
Full waveform inversion

in one, or more, deeper marker horizons. Where structural interpretation of these channels is possible, an attempt can be made to constrain the 1D update within these channel systems. However, this is often possible only for the larger channels, as the majority of these channel systems are masked by multiples and NMO stretch, with many being completely

North Sea shallow channels

The application of FWI to variable-depth streamer data is illustrated using an example from the central North Sea. Like much of this area, the shallow section is affected by the presence of recent glacial channels and in-filled canyon systems that can have a profound effect on velocities. Figure 2 shows an example of these on a depth-stretched prestack time migration image at a depth of 320 m. The existence of wide, braided channel systems can induce subtle long-wavelength velocity perturbations, while the more deeply incised canyons induce pronounced short-wavelength perturbations. Differing types of channel fill and levels of gas content across the area, and also within individual channels, cause significant lateral velocity variations. These are seen in the seismic as pull-up and push-down effects, often in close proximity. The distortions caused by the shallow velocity variations propagate into the deeper section, often in a widening cone of influence, and can severely affect image quality at target level.

The rapidly varying velocity environment of these channel features is difficult to model accurately. Traditional image-gather RMO-based tomography typically has too few offsets in the shallow data to successfully recover these shallow velocity variations—the picking becomes too difficult because of the limited offset available at this depth. Grid-based tomography can partially resolve these channels but usually corrects for the depth delay by smearing the velocity perturbation throughout the whole Tertiary section. More modern high-resolution tomographic inversion engines have more success, but usually the lack of offset information is insurmountable.

A common solution is to apply a 1D velocity correction based on the distortion these velocity anomalies cause in one, or more, deeper marker horizons. Where structural interpretation of these channels is possible, an attempt can be made to constrain the 1D update within these channel systems. However, this is often possible only for the larger channels, as the majority of these channel systems are masked by multiples and NMO stretch, with many being completely

Figure 1. Example input shot gather and narrow band-pass filter panels from 1 to 10 Hz. Variable-depth streamer data have good signal down to 3 Hz with little contamination from acquisition noise.

Figure 2. A depth slice at 320 m from a depth-stretched prestack time migration image showing an example of the shallow channel systems in the central North Sea. The holes in the image correspond to the locations of infrastructure in this area.
invisible to the seismic. Consequently, the 1D update is frequently applied within a thin dummy layer of constant thickness below the water bottom. Such approaches are driven by a structural interpretation rather than by the data. FWI offers a way to build accurate shallow velocity models that are truly data-driven.

**Application of FWI**

The acquisition here used 10 cables, each 6 km long, towed in a variable-depth configuration from 5–50 m deep. Cables comprised $480 \times 12.5$-m groups with a lateral cable separation of 75 m giving a nominal acquisition bin size of $6.25 \times 18.75$ m. Inline shot spacing was 18.75 m flip-flop, with a nominal 300-m sail-line spacing. FWI was applied using a 3D time-domain approach (see Ratcliffe et. al., 2011, and the references therein). For input to FWI, the raw shot data were band-pass filtered from 4 to 8 Hz; within this bandwidth the variable-depth streamer data has excellent S/N, as shown in Figure 1. An inner and outer mute to highlight the transmitted energy was the only additional preprocessing required on the real data. A modeled source wavelet, filtered to match the seismic data, but with no source or receiver ghost, was used in combination with a free-surface in the modeling to generate the shot records used in the FWI process.

The starting model consisted of a simple two-layer model with a constant velocity water layer and a 1D function in the Tertiary. The second layer also included constant anisotropic parameters. Both velocity and anisotropic functions were taken from vintage models in neighboring areas. The FWI update of the velocity was computed in the shallow section containing the channel features, to a depth of 1500 m. FWI was run in cascaded passes over different frequency bands, starting at $[0, 5]$ Hz and working up to $[0, 8]$ Hz in 1-Hz increments. We ran initial FWI tests over an area comprising 10 sail-lines of a 4-km swath of ~50 km length (approximately 2800 shots per line) and used this to optimize the FWI parameters described above (Jupp et al. 2012). After these tests proved successful, we ran production on a neighboring region, which was part of the same acquisition, with a total area of ~800 km$^2$, with a full fold update of ~630 km$^2$. The total number of shots used in the inversion was ~116,000.

**Figure 3.** Velocity overlay of the same depth slice in Figure 2 with the final FWI velocity field. There is an excellent agreement between the structures in the seismic and those found in the velocity model by the FWI process.

**Figure 4.** Example inline section of the seismic depth volume with an overlay of the starting model used in the FWI. This model is a simple 1D function, extrapolated using conformable horizons throughout the survey area. It is clear there is no evidence of the channels in this starting velocity model.

**Figure 5.** An overlay of the final FWI velocity model for the same inline as Figure 4. This confirms that the correlation between seismic and velocity exists in depth as well as spatially.
As we explained earlier, an important quality control (QC) of the starting point for FWI is that the real shot records are not cycle-skipped with respect to the synthetic gathers computed using the starting velocity model. The only modification in the starting model in moving from the test area to the production area was to extrapolate the 1D velocity model using conformable horizons, a sensible yet necessary procedure. The crossline sampling of the shots is driven by the sail-line interval. The acquisition cost implications dictate this is usually greater than we would like in a perfect world. Consequently, a clear sail-line acquisition footprint is present in the FWI velocity model. We have a number of tools that can remove such stripes without damaging the underlying signal. These tools are applied to the data we show here and give us our final FWI velocity model.

Figure 3 shows the seismic data from Figure 2 overlaid by the final FWI velocity model. Recall this slice is 320 m deep and we use it here simply for QC purposes. The structures in the FWI velocity model correlate closely with the observed channels in the seismic section itself. This excellent correspondence between the model and the channels exists in a full 3D sense over the whole production volume. Figure 4 shows an inline section extracted from this seismic volume, overlaid with the starting velocity model. It is clear this model has no lateral structure, other than the conformable horizon mapping, and no information on the channel systems. Figure 5 shows the same inline section with the final FWI velocity model overlaid. The FWI velocity model has nicely found both the shallow and buried channels, confirming the correlation between seismic and velocity model in depth as well as spatially.

Figure 6 shows the shallow section migrated with the initial model; pre-imaging deghosting has been applied to remove the receiver ghost in this QC migration. The distortions caused by the channels are evident in the image generated using the simple starting model. Figure 7 shows the same data after migration with the FWI velocity model—this shows significant healing of the pull-up and push-down distortions. Additionally, we see a S/N improvement on the stack section, caused by flatter image gathers with the FWI velocity model prior to stack. The improvements in the shallow section will improve the deeper data as well.

Conclusions

We have demonstrated the application of full-waveform inversion to variable-depth streamer data. The FWI process fits neatly with variable-depth acquisition because it can model the wavefield directly at the recording datum, with the freesurface in the modeling engine automatically creating the correct ghosts. Moreover, the significant signal in this acquisition system at low frequencies (<4 Hz) is used effectively in the FWI process. This allows us to start the FWI from a 1D conformable velocity model, generated using vintage data from the general survey area. Given the limited preprocessing needed for FWI, this allows us to use FWI at the start of the processing sequence, rather than at the end of the processing after a full tomography exercise, which is typically seen in published FWI studies.

The data example shown here contains a real and difficult geophysical challenge, namely the shallow channels in the North Sea and the imaging problems they cause. Reflection
tomography struggles with this problem because of the limited offset available at the shallow depths. 1D channel update schemes exist but require structural interpretation and have their limitations—FWI offers a truly data-driven solution. The FWI velocity update reveals detailed shallow channels in the near-surface geology over a production-sized area. This velocity model is shown to subsequently improve the migrated image and correct the image distortions caused by these channels.

Author’s note: Morgane Lombardi now works for Shell Global Solutions International.

References

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