Channel modelling using Full Waveform Inversion applied to variable-depth streamer data
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Introduction
Full Waveform Inversion (FWI) aims to estimate high resolution velocity models by minimizing the difference between observed and modelled seismic waveforms. Recent real data examples demonstrate the derivation of high-quality and high-resolution velocity models from FWI that can be used as an interpretative product as well as improving the imaging (e.g. Ratcliffe et. al., 2011). There have also been recent advances in marine broadband acquisition, such as the use of a variable-depth streamer, which enables lower seismic frequencies to be recorded. This acquisition configuration delivers high signal-to-noise (S/N) seismic data over a significantly wider frequency bandwidth than standard streamer acquisition. This is important because good low frequency data plays an important role in the successful application of FWI.

In this paper we discuss the application of FWI to variable-depth streamer data. We show that FWI adapts naturally to this acquisition geometry and hence benefits from the improved low frequencies recorded in this configuration. This is illustrated by an example from the Central North Sea where detailed velocity features associated with shallow channels in the near surface geology are revealed by FWI. Migration with this updated velocity model improves the imaging through the near surface.

Low frequencies for successful FWI
Good low frequency data plays an important role in the practical use of FWI. A key issue is that of avoiding convergence to local minima during the inversion, which is a result of using gradient based algorithms. More sophisticated inversion algorithms exist, which do not suffer from the drawbacks of gradient based techniques, but they are much more expensive and their application is beyond current industrial implementations of FWI.

This local minima problem manifests itself as cycle skipping on the data, with the model converging to the wrong event in the shot record. A common way to overcome this is to combine a good starting velocity model with use of low frequencies in the recorded data, such that the initial modelled field records are not cycle skipped with respect to the real ones. This involves an interaction between the starting model accuracy and lowest usable recorded seismic frequency, and can limit the applicability of FWI. For example, 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 detail to a PreSDM velocity model obtained from a traditional tomographic approach. The initial velocity model would be poor in this situation, for example, a 1D profile, and FWI would only work if the acquired data contained very low seismic frequencies. In general, practical applications of FWI would benefit from the acquisition of better low frequency data.

Variable-depth streamer acquisition and FWI
Variable-depth streamer acquisition is emerging 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 2Hz (Dowle 2006). The variable-depth geometry typically uses cable depths down to 50m, such that the data acquired tends to be less noisy due to the quieter recording environment. 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 these aspects together results in broad bandwidth data, producing 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).

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: the data is modelled directly for the variable-depth recording, with a free-surface in the modelling creating the correct source and receiver ghosts to match the acquisition.

Central North Sea shallow channels
We illustrate the application of FWI to variable-depth streamer data 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 1). The existence of wide braided channel systems can induce subtle long wavelength velocity perturbations, whilst 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. This rapidly varying velocity environment is a very difficult one to model accurately. The pull-ups and push-downs caused by the shallow velocity variations propagate into the deeper section often in a widening cone of influence and can severely affect the quality of the image at target level.

![Figure 1: Time-slice from a near-trace cube showing shallow channel system. The red box indicates the location of the test area shown in subsequent figures (~4×50 km).](image)

Accurately modeling these channel features is problematic. Traditional image gather RMO based tomography typically has too few offsets in the shallow data to successfully recover these shallow velocity variations. 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 only possible for the larger channels, as the majority of these channel systems are masked by multiples and NMO stretch, with many being completely 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 6km long, towed in a variable-depth configuration from 5-50m deep. Cables comprised 480*12.5m groups with a lateral cable separation of 75m giving a nominal acquisition bin size of 6.25m x 18.75m. Inline shot spacing was 18.75m flip flop. The test area comprised 10 sail-lines over a 4km swath of ~50km length (approximately 2800 shots per line).

The FWI was applied using a 3D time-domain approach (Ratcliffe et al., 2011). For input to FWI the raw shot data were band-pass filtered from 4 to 8 Hz; within this band-width the variable-depth streamer data has excellent S/N (Figure 2). An inner and outer mute to highlight the transmitted energy was the only additional pre-processing required on the real data. A modelled source wavelet, filtered to match the seismic wavelet, but with no source or receiver ghosts, was used in combination with a free-surface in the modelling to generate the modelled shot records used in the FWI process.
The starting model consisted of a simple 2 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, down to a depth of 1500m. FWI was run in cascaded passes over different frequency bands, starting at $[0, 5]$ Hz and working up to $[0, 8]$ Hz.

**Results**

Figure 3 shows the starting model and the model estimated using FWI, overlain with the seismic data. The FWI velocity model has very nicely found both the shallow and buried channels: these correlate closely with the observed channels in the seismic section itself.
Figure 4 compares a shallow depth slice of the FWI model with the seismic data – the excellent correspondence between model and the channels extends in a 3D sense.

Figure 4: Shallow depth slice at 350m: (a) FWI velocity model with seismic data on top, and (b) FWI velocity model only. There is excellent correspondence between the channels in the seismic and those in the FWI model.

Figure 5 compares image gathers migrated with the starting model and also with the FWI model. These gathers are not de-ghosted and the variation of the receiver ghost with offset caused by the variable-depth tow is clearly seen. It is pleasing to see that the velocity update from FWI improves the gather flatness. We also note that picking the very shallow events for a traditional tomographic method driven by RMO would be very difficult due to the limited offset available.

Figure 5: Image gathers from: (a) starting, and (b) FWI model. The receiver ghost due to variable-depth acquisition can be clearly seen. Migration with the FWI model nicely flattens the gathers compared to the starting model.
Figure 6 shows the shallow section migrated with the initial model and with the FWI model; post-stack joint deconvolution has been applied to remove the receiver ghost (Soubaras 2010). The distortions caused by the channels are very evident in the image generated using the 1D starting model – these show significant healing when the FWI model is used. These improvements in the shallow section will also clearly improve the deeper data.

![Figure 6: Shallow image after post-stack joint deconvolution for: (a) starting model, and (b) FWI model. The FWI velocity model significantly heals the push-up and pull-downs caused by the shallow channels, as indicated in the red highlighted areas.](image)

**Conclusions**

We have demonstrated the application of Full Waveform Inversion to variable-depth streamer data from the Central North Sea. The FWI process fits neatly with variable-depth acquisition as it can model the wavefield directly at the recording datum, with the free-surface automatically creating the correct ghosts. Moreover, the significant signal in this acquisition system at very low frequencies (<5Hz) is used effectively in the FWI process. This energy drives the update to reveal detailed shallow channels in the near surface geology, which subsequently improves the migrated image.

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**References**


