Long-offset-aided Full-waveform Inversion

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SUMMARY

When using FWI, the common scheme was to use data sets which have relatively large offsets up to 8 km or more and frequencies as low as 2.8 Hz considering surface seismic acquisition. In terms of the marine environment, Wide Azimuth towed streamer (WAZ) or Ocean Bottom Cable (OBC) data collection provide the above mentioned specifications. Recent advances in acquiring data such as the dual coil system offer significant improvements in characteristics over WAZ and OBC such as better illumination, noise attenuation, lower frequencies, and longer offsets which allow the FWI to more accurately determine the velocity field. The data set that we input to FWI is a result of dual-coil acquisition where the maximum offset is up to 14000 m with full azimuth distribution. Our results demonstrate that FWI can be used for velocity update with the long offsets and low frequencies provided by the dual coil seismic acquisition. In particular, the shallow section of the model can be significantly enhanced by using FWI which can result in an improved overall depth image. Finally, we show the reverse time migration depth image improvements by using the FWI developed velocity field versus that one from the ray-based methodology.
Introduction

Full-waveform inversion (FWI) has become a new tool in recent practice for subsurface velocity model updating. When using FWI, the common scheme was to use data-sets that have relatively large offsets up to 8 km or more and frequencies as low as 2.8 Hz for surface seismic acquisition. In terms of the marine environment, Wide-azimuth towed-streamer (WAZ) or Ocean-bottom cable (OBC) data collection meet the above-mentioned specifications. Recent data acquisition advances such as the dual coil system offer significant improvements in characteristics over WAZ and OBC such as better illumination, noise attenuation, lower frequencies, and longer offsets that allow the FWI to more accurately determine the velocity field. The data set that we input to FWI is a result of dual-coil acquisition where the maximum offset is up to 14000 m with full-azimuth distribution. The shooting is circular with ten towed cables on each recording vessel and two additional gun vessels. To approximate the observed data, the acoustic inversion incorporates anisotropy, in the finite-difference propagators and uses the true source and receiver depth. Our results demonstrate that FWI can be used for velocity update with the long offsets and low frequencies provided by the above-described dual-coil seismic acquisition. In particular, the shallow section of the model can be significantly enhanced by using FWI which can result in an improved overall depth image. One of the difficulties with FWI is the convergence to the local minima that makes the technique very sensitive to the starting velocity model especially when 3D is considered. Furthermore, lower frequencies and longer offsets mitigate the sensitivity of inversion to the initial velocity model by enabling FWI to update the low-wavenumber component of the velocity model. Finally, we show the reverse time migration depth image improvements by using the FWI-developed velocity field versus that from the ray-based methodology. Over the past few years we have been able to execute 3D FWI with the acoustic wave equation on real datasets in marine (Plessix and Perkins; 2009, Sirgue et al.; 2010, Vigh et al.; 2010, 2011) and in land (Plessix, et al., 2010) environments. These results demonstrated that FWI can be used for velocity update if the acquired data have enough of the proper low frequencies and long offsets. In particular, the shallow section of the model can be significantly enhanced by using full-waveform inversion which can result in a more improved overall depth image. One of difficulties with FWI is the convergence to the local minima that makes the technique very sensitive to the starting velocity model especially when 3D is considered. To mitigate the sensitivity of the initial velocity field, low frequencies and long offsets are required (Bunks et al., 1995; Pratt, and Shipp 1999), which enables FWI to update the low-frequency component of the velocity model.

![Figure1 Data collection diagram](image)

GOM dual coil data set

The data set is a result of dual coil acquisition where the maximum offset is up to 14000 m with full-azimuth distribution. The shooting is circular with ten towed cables on each recording vessel. The output size exceeds more than 100 mi² with approximately 64,000
shots covering the area (Figure 2.) using the dual coil layout mentioned above. The gun array, the shot depth, and cable depth allowed observing low frequencies of about 2.5 to 3 Hz on field records. A 50-m X 60-m bin size was selected to run the inversion.

![Figure 2 Shot location map of Green Canyon 512 area of Gulf of Mexico](image)

**Data processing**

Due to the long 14-km offset the dual-coil recorded data are rich in refracted energy (Figure 3.) which is essential to a successful full-waveform inversion; therefore, the data processing was kept at a minimum with de-signature, de-bubble to the input data prior to the FWI. The complex geology created multiples that are observed much later than the valuable refractions and diving waves energy. After spectral analysis of the observed data we concluded that the lowest frequency in the signal was about 3 Hz. The shot gathers were encoded to increase computational speed because the number of shots are large compared to the area covered.

**3D waveform inversion flow and results**

In the inversion, there were two frequency bands used starting with 0-4 Hz and then extended to 0-6 Hz. Starting from a low-frequency range to a higher-frequency range is the multiscale approach that minimizes the risk to converge to local minimum. The inversion was executed in the usual layer stripping manner where the sediment-only FWI was the first step followed by the reinsertion of salt bodies to allow the inversion the opportunity to modify its definition to a small degree. An image gather flatness constraint was implemented that allowed us to freeze certain parts of the model where misfit energy had been minimized. Although the inversion only updates velocity, we utilized our anisotropic propagators using tilted transverse isotropy (TTI) which accommodates velocity, density and the anisotropic parameters $\varepsilon$, $\delta$, dip, and azimuth. The starting velocity was the result of ray-based tomography followed by the sediment-only inversion that had five iterations of FWI. Then the salt was reinserted in the model and salt body FWI iterations were run to enhance the definition of the previously developed top of salt and overhangs with the geological delineation of the minibasins using 12 additional iterations. The velocity slices at 8000 ft depth show significant differences when one compares the FWI velocity field (Figure 5) to the starting model (Figure 4) especially the high resolution and the delineated geology are outstanding between the two. Once completed with these additional iterations, the data were migrated with the final model and QC was performed to check for gather flatness (Figures 6 a and b). Besides the gather kinematics the data misfit was checked across the entire area to ensure the correlations between the predictions and the acquisitions are maximized. Finally, Reverse time migration (RTM) was performed (Figures 7a and 7b) for comparison reasons at well location Knotty Head. Figure 7-b shows significant improvements versus Figure 7-a, which tells us that longer offset acquisition provides better input to derive more accurate velocity fields and using a better velocity field with the longer offset RTM produces a significantly better subsalt image than the short-offset data collection.
Figure 3 Dual-coil shot gathers

Figure 4 Traditional velocity field derived by ray based tomography 8000 feet depth

Figure 5 Waveform inversion velocity filed 8000 feet depth

Figure 6 (a) Gathers with initial velocities. (b) Gathers with the FWI velocities
Conclusions

We showed that waveform inversion using long offsets can be successful in deep-water environments when the refracted energy and diving waves are present in the collected data. We further demonstrated that FWI has its own significant role in the modern velocity model development process when the observed data supports the inversion process especially with long offsets.

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References