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## Full Waveform Inversion of Simultaneous Long-Offset Data

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### Summary

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The standard workflow for velocity model building (VMB) in complex regimes is an interpretive process that requires time-consuming manual intervention, and remains an error-prone process that can produce suboptimal results. Here we discuss an application of Full Waveform Inversion (FWI) to automate the refinement of legacy velocity models generated by conventional workflows. We demonstrate our solution on a full-azimuth (FAZ) survey acquired in the Gulf of Mexico using dual-sensor streamers and blended sources in the form of simultaneous long-offsets (SLO). The dual-sensor acquisition provides low-frequency data while the SLO configuration enables the recording of long offsets in excess of 16 km. The long offsets and low frequencies were key to using both refractions and reflections to update the deeper parts of the velocity model. Our solution directly inverts the simultaneous data as acquired in the field. We also employed an FWI velocity gradient that eliminates the migration isochrones, removing the reflectivity imprint from the model updates. The FWI application to the field survey successfully refined the geometry of the salt bodies including the base salt and the intra-salt enclosures. It also improved the RTM image particularly the salt flanks and the subsalt reflectors.

## Introduction

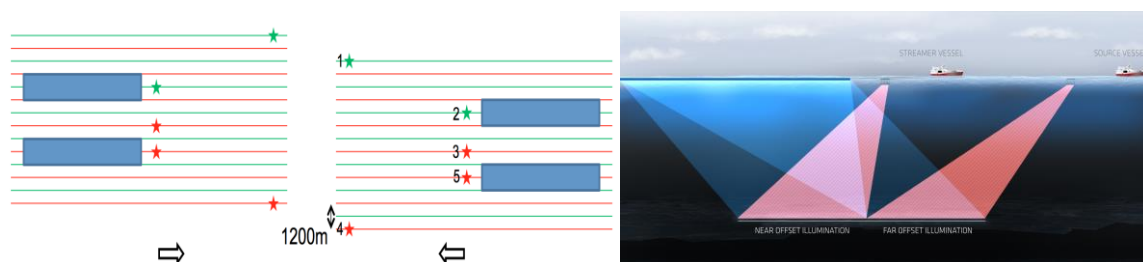
Full waveform inversion (FWI) is the tool of choice for building high-resolution velocity models. It involves nonlinear minimization of the misfit between the recorded and modeled seismic data, while iteratively updating the subsurface model. The success of FWI depends on the seamless recovery of the short- and long-wavelength features missing in the starting velocity model.

Most FWI applications have targeted shallow water environments where the recorded refracted and diving waves enable the inversion to resolve the small-scale geologic features up to the deepest turning point (e.g. Sirgue et al., 2009; Zhou et al., 2015). Recently, there have been successful FWI applications in deep-water scenarios where refracted and diving waves are often missing due to limited cable length in towed-streamer acquisitions. Consequently, there has been a growing demand for acquiring better data for FWI, e.g., longer offsets from ocean bottom seismic (Shen et al., 2017) and lower frequencies with a high signal-to-noise ratio (Dellinger et al., 2016). Alternatively, FWI developments have focused on better inversion solutions that can reduce the data requirements and produce deep model updates. These efforts have targeted combinations of modified gradients, robust norms for measuring the data misfit, and *a priori* model constraints to enable utilization of all wave modes in the data (reflections, refractions, and diving waves).

Here, we combine an acquisition strategy that employs simultaneous shooting to record long offset data with a robust FWI solution that inverts both reflections and transmitted arrivals. Our inversion simulates the blended data as acquired in the field, therefore no separation of the simultaneous sources is performed during data preparation.

## Acquisition of long-offset and low-frequency data

The survey was designed to acquire high-fold, long offset, and full-azimuth (FAZ) data in the Central and Western planning areas in the Gulf of Mexico (Long et al., 2014). Two streamer vessels were used, each towing ten 8 km dual-sensor streamers. The acquisition employed three additional source vessels in SLO configuration (Figure 1). The two far sources (1 and 4) fired simultaneously, with a random delay from the near sources (2 and 5) providing offsets in excess of 16 km. The near source vessel (3) fired independently from the others. The sailing configuration was antiparallel, and the acquisition template was repeated in three different azimuths 0, 60, and 120 degrees, ensuring full azimuth coverage of the deep targets. The dual-sensor streamers were towed at 20 m to obtain a good signal-to-noise ratio at low frequencies. As a result, the data contained wide azimuths, long offsets, and low frequencies, all beneficial for FWI. The water depth for the test area varied from 1200 m to 1400 m.

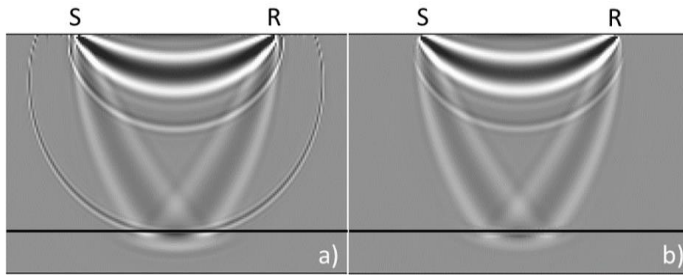


**Figure 1:** Five-vessel configuration (left) employed for simultaneous long-offset shooting (right).

## FWI on blended data

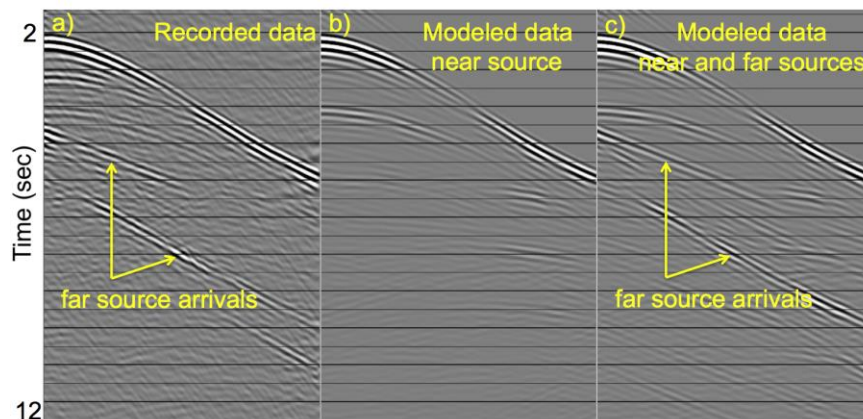
Our inversion algorithm uses time-domain wave propagation and a normalized form of the Born scattering kernel to compute the FWI gradient (Tarantola, 1984). We solve the two-way anisotropic wave equation using the pseudo analytic (PA) method (Ramos-Martinez et al., 2011). We use a variable-density implementation for better matching of the relative amplitudes, particularly from the water-bottom reflections and high-contrast interfaces. We implemented a robust velocity gradient derived

from Inverse Scattering theory and impedance-velocity parameterization of FWI (Ramos-Martinez et al., 2016). This eliminates the migration isochrones that dominate conventional cross-correlation FWI gradients (Figure 2).



**Figure 2:** Sensitivity kernels for a source-receiver pair in a model with a  $V(z)$  layer over a half-space. (a) Conventional cross-correlation FWI gradient. (b) FWI velocity gradient for long wavelength model updates. It eliminates the migration isochrones and removes the reflectivity footprint.

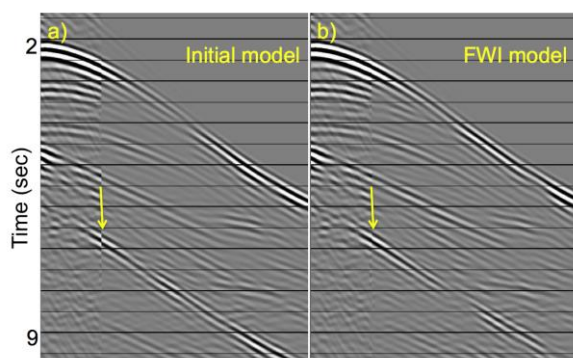
The modeling kernel for the FWI algorithm was adapted to accommodate data from simultaneous shooting. Figure 3a shows a blended shot gather corresponding to sources 1 and 2 (see Figure 1). The horizontal axis extends across the cable (8.1 km) and contains data from the near and far sources with offset varying from 125 m to over 16 km. Figure 3b displays synthetic data from the near source only, while Figure 3c shows data from the blended near and far sources. The difference between panel b and c represents the long offset recordings from the far source.



**Figure 3:** Shot records: (a) field data, (b) modelled data from near source, (c) modelled blended data from simultaneous near and far sources.

### Application to the field data survey

To minimize the likelihood of cycle skipping, we performed a multi-stage FWI starting with data that exhibited coherent signal in the 2-4 Hz frequency band. The initial velocity model was generated using an interpretive VMB workflow including wavelet-shift tomography and salt interpretation following a top-down strategy.

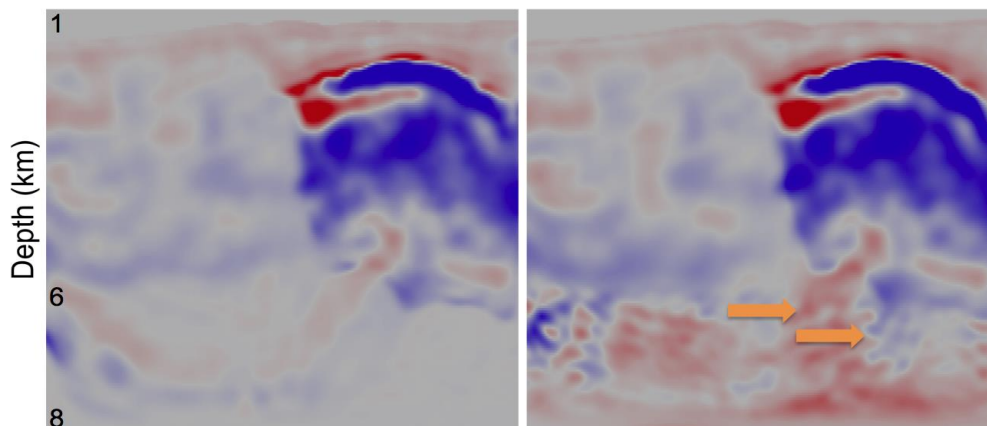


**Figure 4:** Comparison of field data (left of arrow) and modelled data (right of arrow). (a) data modelled with initial model. (b) data modelled with FWI model. Note the improved match after FWI of the far-source events (far offsets) marked by the arrows

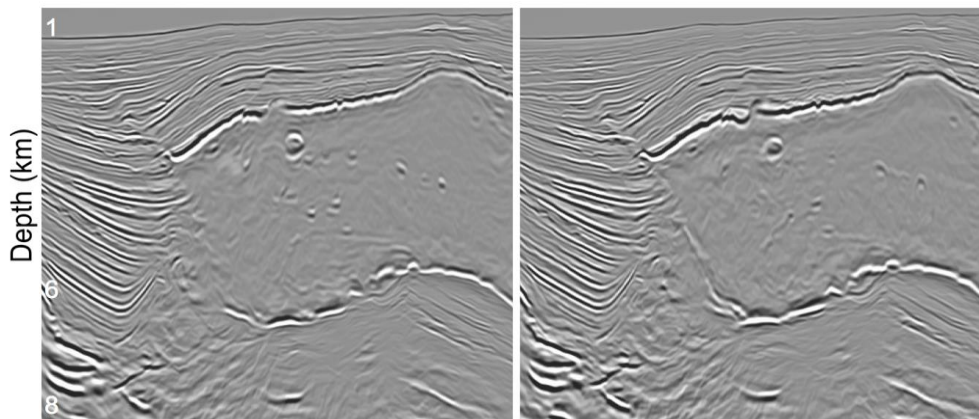
Figure 4 compares the data fitting using the starting model (Figure 4a) and the FWI model (Figure 4b). Figure 4a shows a good match of the near source refractions, with an error smaller than half the period

of the dominant frequency. After FWI the small kinematic mismatches are corrected, as well as the larger errors at later arrivals (marked by arrows pointing to refracted energy from the far source).

Figure 5 shows a comparison of the updates using only refractions (left) and a combination of refractions and reflections (right). Note that the refracted modes produce reliable velocity updates up to 6 km depth. In contrast, our robust FWI velocity gradient is able to use the reflections to update the velocity model beyond the penetration depth of diving gradient waves. Figure 6 shows a comparison of the RTM images from the initial (left) and the FWI (right) velocity models. The FWI velocity model improves the image of the salt boundaries (top, bottom, and flanks) as well as the sediment truncations against the salt. Similarly, the deeper reflectors display improved continuity after FWI. Figure 7 further validates the FWI model improvements. It illustrates the refinement process of the velocity model by FWI. The errors in the salt interpretation (bottom left) are corrected by FWI that removes salt (blue updates) and adds salt (red updates), as needed.



**Figure 5:** FWI updates comparison: using only refractions (left), vs. using combined refractions and reflections (right). Reflections can update the long wavelength components of the velocity model beyond the penetration depth of diving waves (orange arrows).



**Figure 6:** RTM images comparison: initial (left), vs. FWI (right). Note how the FWI model improves the imaging of the salt boundaries and the sediment truncations.

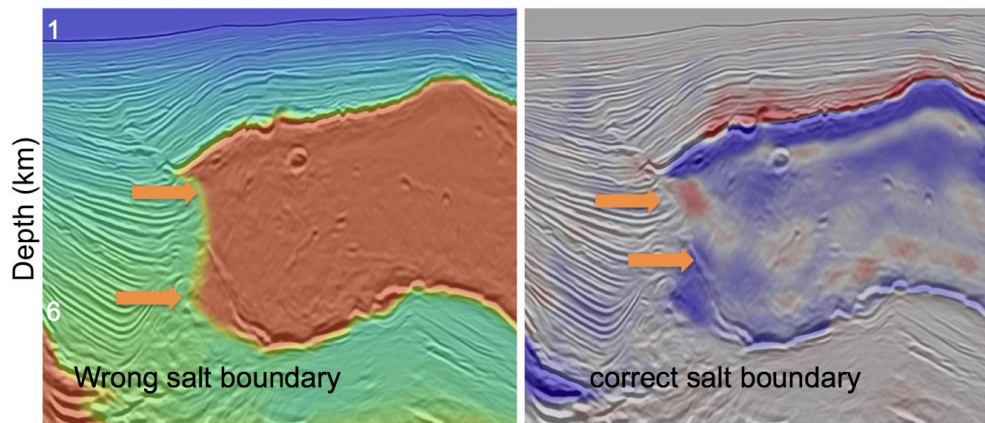
## Conclusions

We discussed an automated workflow for refining velocity models in complex regimes using data from simultaneous long-offset recordings and a robust FWI gradient that incorporates reflection data for deep model updating. Our inversion simulates the blended data as acquired in the field without source separation. Application to a dual-sensor survey from the Gulf of Mexico demonstrated that FWI is able to refine the sediment velocities and repair the geometry of the salt including the intra-salt enclosures. It also improved the RTM image particularly the salt flanks and the subsalt reflectors.



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**Figure 7:** Legacy velocity overlaid on the FWI RTM image (left), and FWI model updates overlaid on the FWI RTM image (right). Note how FWI corrects the salt interpretation by “removing” salt (blue update) and “adding” salt (red update) as needed (areas marked by orange arrows).

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