Using full-waveform inversion in the modern velocity model building flow

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Abstract

The conventional FWI is exposed to cycle skipping especially when the initial model is inadequate and the ultra-low frequencies are not present in the observed data. If the FWI does not have the power to mitigate the cycle skipping then initial velocity must be built by travel-time tomography. This way the model building would comprise of travel-time tomography followed by FWI and finish the flow with travel-time tomography. Our FWI does not require half wavelength convergence criteria this is why we can skip the first travel-time tomography in the flow which shortens the turnaround time on depth imaging projects. This FWI and the new workflow are demonstrated by synthetic and field data examples. This FWI and the new workflow are demonstrated by synthetic and field data examples. Going beyond the conventional FWI's half wavelengths criteria allows us to optimize the velocity model building flow and reduce the turnaround time.

Introduction

One of the pitfalls of the conventional full-waveform inversion (FWI) is it's dependency upon either an accurate starting velocity or the presence of very low frequencies in the observed data. Because the conventional FWI minimizes the least-squares difference between the acquired and the predicted data, it is exposed to cycle-skipped solutions that cause the process to converge to local minima rather than the global minima. The cycle skipping is especially difficult to detect in field data case because the misfit energy reduction can be observed while the iterations are in the local minima. Most of the early efforts from the FWI community began with an initial velocity derived by tomography to mitigate the lack of low frequencies in the observed data by deriving a more accurate initial model.

There have been dedicated efforts to make FWI more robust to overcome this handicap. Earlier Shin et al., (2013) employed the Laplace Fourier domain approach where a Laplace transform is applied to the time-domain shot gathers to build the low wavenumber component of the velocity field. Biondo et al. (2013) extended the velocity model along the time-lag axis to constrain the FWI with tomography while Gao et al. (2014) proposed a new objective function introducing the differential semblance in the data domain. Warner et al., (2014) used Wiener filters between the predicted and the acquired data forcing them to zero-lag delta functions. All of these methods allow us to start the FWI with a simple velocity model and converge towards the global minima. When salt or high velocity anomaly like salt is present in the geology as we can observe in offshore Brazil the cycle skipping is a serious issue to address during the FWI iterations.

Method used to mitigate cycle skipping

The conventional FWI algorithm is based on iteratively updating the model by minimizing the least- squares (LS) misfit function, as shown in Equation (1), which measures the difference-based objective function using the acquired data and the simulated data:

$$\min_{m\in M} J := \frac{1}{2}\sum_{s=1}^{Ns}\left\| F[m](x_r,t) - d_0(x_r,t;s)\right\|^2 \quad (1)$$

where J denotes the misfit function, m represents the models, d_0 defines the observed data, and F[m] is the forward map, which simulates predicted data.

To avoid or mitigate the cycle skipping of the conventional FWI, Jiao at al., (2015) introduced a robust traveltime-shift-based objective function. For a single frequency, the traveltime shift, ΔT, between two signals is proportional to the phase difference $\Delta\varphi$. Therefore, FWI can use the conventional phase-only objective function to back-project the traveltime error into model error. Identifying the correct traveltime shift in the time domain is an easier task than finding the correct unwrapped phase difference. This traveltime shift in the time domain can be computed as local attributes as a function of time shown in equation (2). This local traveltime shift can then be translated into the corresponding unwrapped instantaneous phase error as a local attribute. Such an instantaneous phase error describes the local phase misalignment. Thus, FWI can directly minimize the traveltime shift objective function as shown in Equation (2), and use the instantaneous phase gradient formulation to back-project the local traveltime shift into model error.

$$\min_{m \in M} J_T := \frac{1}{2}\sum_{s=1}^{Ns}\left\|\Delta T\right\|^2 = \frac{1}{2}\sum_{s=1}^{Ns}\left\| \ \Delta T(\Delta\phi) \ \right\|^2 \quad (2)$$

Synthetic data example

To demonstrate the difference between the conventional FWI least squares and the previously introduced time shift or displacement-based objective function we used the SEG Advanced Modelling Program Phase I (SEAM) model where salt is present that can trigger cycle skipping easily with the LS objective function. The initial velocity is created with a significant slowdown in the supra salt region (Figure 1a). In the vertical overlay (Figure 1d), the blue line is the initial model while the green line is the true velocity profile and their difference can create a mismatch for the salt event beyond the half wavelength convergence criteria, which cannot be recovered by the conventional FWI (Figure 1b). After overcoming the cycle skipping with the new objective function (Figure 1c) with the long wavelength error of the model input to FWI, one may well see the possibility of starting the field data FWIs with a simple starting model rather than building the starting model with travel-time tomography. The vertical overlay (Figure 1d) confirms that the Adjustive FWI (red line) reconstructed the true (green line) velocity satisfactorily and the reverse time-migrated (RTM) image improved (Figure 1f) versus the conventional FWI-produced image (Figure 1c).

Field data investigation and results

Based upon the encouraging results obtained from the synthetic data example, we embarked on a field data exercise to demonstrate that FWI can be executed at an early stage before traveltime tomography. The data set chosen from the Gulf of Mexico (GoM) acquired with 14.3-km maximum offset in conjunction with full azimuthal distribution. The observed data are rich in low frequencies but the high noise level present on the low side of the spectra might pose some difficulties for the LS objective function or require significant noise reduction in the data prior to beginning the process. When the new objective function is employed, the starting frequency can be increased to obtain a better signal-to-noise ratio for the time displacement attribute analysis without converging to the local minima. The selected test area is roughly 750 km2 with approximately 260,000 long offset shots. The first test was to compare the FWI performance with the new objective function versus the traveltime tomography beginning with the same simple legacy velocity model shown in Figure 2a (depth slice) and Figure 2d (vertical section). After executing traveltime tomography (Figure 2b) and FWI (Figure 2c) from the same starting velocity, the updates are very similar although the FWI has higher resolution (Figure 2e vs. Figure 2f) due to fact that frequencies up to 6 Hz were used for the inversion. After analysing the updates, one can draw the conclusion that the updates are very similar, which implies that there is an early role for FWI in the velocity model-building flow, even in complex geological settings. Therefore, FWI can be applied early in frontier areas where little velocity information is available. The details can be introduced early and the velocity model-building flow should be completed with traveltime tomography for the deeper section of the velocity model.

Discussion

The value of FWI can be extracted if it is applied early in the velocity model-building flow prior to the preconditioning steps of the traditional traveltime tomography flow. If we can obntain the shallow details added to the velocity model early without demultiple and signal processing but with only noise attanutation, then the processing flow cycle can be significantly shortened. In Figure 3, we color coded the updating power of FWI and traveltime tomography, therefore we can conclude that they complement each other. FWI has higher power in resolving the shallow section while traveltime tomography's power is in the deeper portion of the model. If we apply FWI and tomography in the most efficent order by using FWI first followed by traveltime tomography, then we can eliminate one set of traveltime tomgraphy from the beginning of the sequence as seen in the flow comparison shown in Figure 3. If FWI is not used in the beginning, then the initial model built by traveltime tomography will have flat gathers in the deep section while the shallow section might have some error due to the small-scale anomalies which is picked up by FWI; however, after inserting the small-scale anomalies, the deep portion becomes incorrect so additional traveltime tomograhy is needed to repair the moveout errors in the deep section again. A more efficient workflow would be to correct the shallow section first and then work on the deep section to place the kinematics in order. Although this method of building velocity models requires a more robust FWI as we described previously to avoid the cycle skipping, our recomandation is to use FWI without initial traveltime tomography as shown in Figure 3 to maximize the resolving power of both techniques.

Conclusions

Enabling FWI to go beyond the half-wavelength convergence criteria allows for using FWI in the beginning of the velocity model-building flow, and the initial velocity does not need to be very accurate. If FWI is employed early in the model-building sequence with a simple initial velocity, the turnaround time can be reduced as model-building can begin, prior to surface demultiple techniques which are required for producing quality image domain gathers for the deeper traveltime tomography techniques. While it is running, FWI can demonstrate its power using the surface related multiples in the modelling as well as in the observed data. The velocity model-building flow can be made more efficient in cycle time and optimized by flattening image domain gathers initially in the shallow part with FWI. Then, traveltime tomography can be applied for the deeper part of the image gathers using the resolving power of each process at the right place of the flow. This demonstrated improved flow is relevant in the offshore Bazil environment too.

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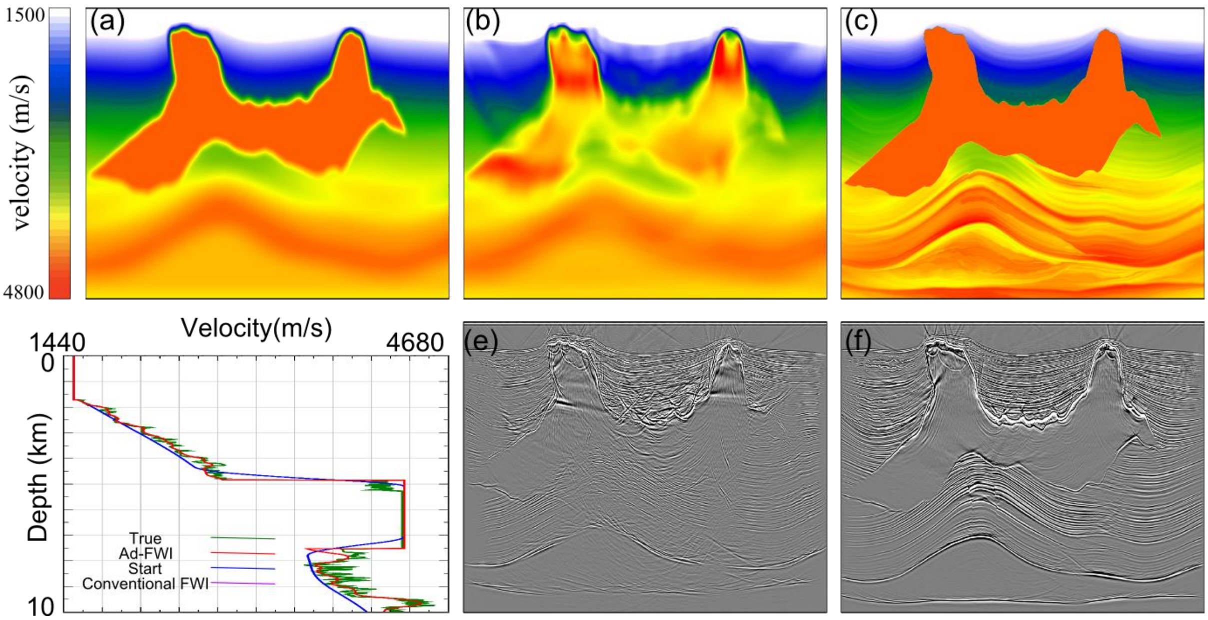

Figure 1. *(a) Initial velocity model (b) FWI with LS objective function (c) FWI with the adjustive option (d) Pseudowell display of different results (e) RTM image of LS FWI (f) RTM image of adjustive FWI*

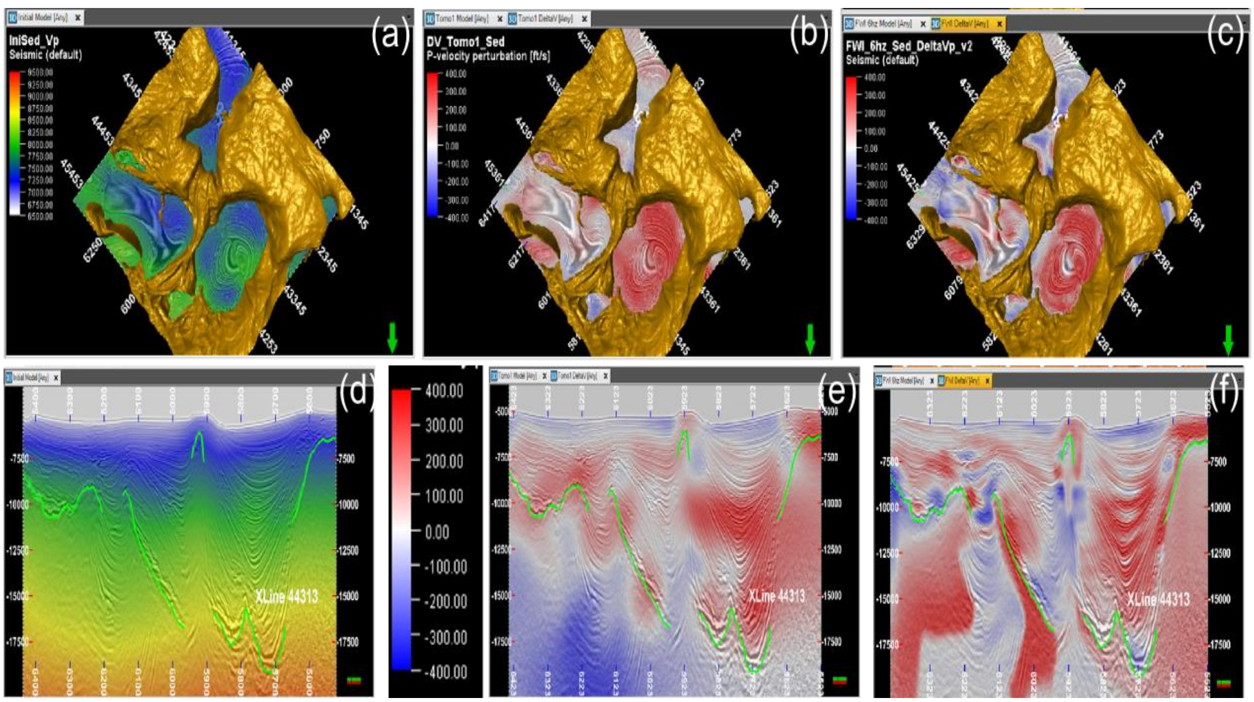

Figure 2. *(a) Initial velocity depth slice (b) tomography update in depth slice mode (c) FWI update in depth slice mode (d) Initial velocity with top of salt interpretation (e) tomography update with top of salt interpretation (f) adjustive FWI update with top of salt interpretation*

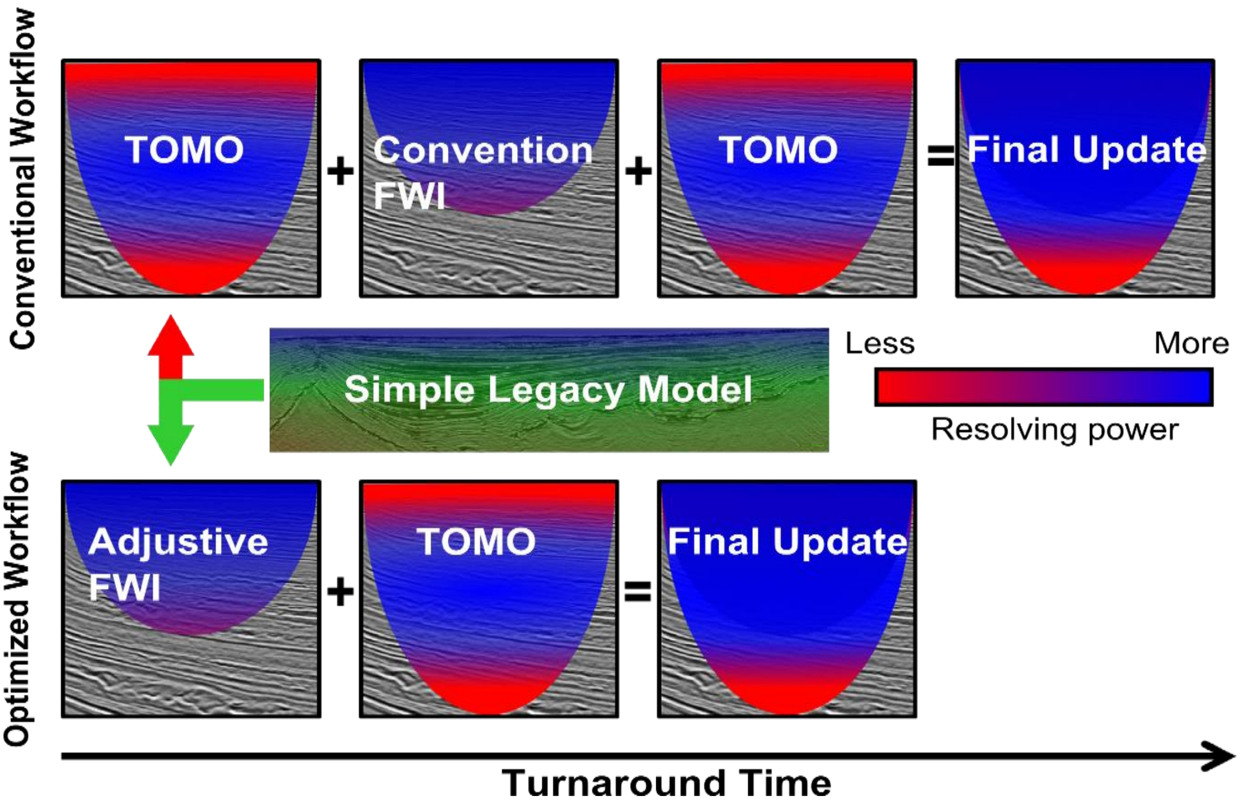

Figure 3. *Conventional FWI place in the flow versus the optimized workflow for velocity model building*