Phase only reflection full-waveform inversion for high resolution model update

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Summary

Conventional L2-norm reflection full-waveform inversion (RFWI) often suffers from unmatched amplitude between input data and synthetic data for real applications. We propose a phase-only reflection full-waveform inversion (PRFWI) for a high-resolution velocity-model update. To avoid amplitude problems in RFWI, we choose an object function of local crosscorrelation between recorded data and synthetic data with envelope normalization. PRFWI uses the phase-only information to resolve the far-angle traveltime mismatches, which can provide a robust velocity-model update. The application on Crean 3D dataset in Europe shows its capability to resolve local velocity errors.

Introduction

Full waveform inversion (FWI) is a data-domain approach which can be used for high-resolution velocity-model updating. Diving-wave FWI is very robust for a shallow model update (Mao et al., 2016). However, diving waves from the deep part of the subsurface cannot be recorded due to the limitations of acquisition. So, we have to use reflection energy for the deep model update through FWI. A wavepath kernel (Xu et al., 2012; Sun et al., 2017; Wang et al., 2018) can be extracted from a reflection FWI gradient for a low-resolution background update. With a closer starting model, we can perform RFWI for a high-resolution local update.

Conventional RFWI minimizes the L2 norm of data residual between the recorded seismic data and modelled synthetic data, which works well for synthetic data. However, it's quite challenging for real-data applications. The elastic effects with attenuation are present in real seismic data, which cannot be fully simulated by modelling. The true relation between density and velocity can hardly be obtained. The amplitude information is not reliable for inversion. So, people are trying to use the traveltime information for inversion (Warner et al., 2016; Luo, Y., et al., 2016; Jiao et al., 2015).

Phase information carries the kinematic information which is more reliable for inversion. However, phase can be very sensitive to noise and phase unwrapping is not easy, which makes quite difficult for a pure phase-only inversion. Some attempts have been made in frequency domain FWI with unwrapped phase (Choi and Alkhalifah, 2013, 2015). There are some other efforts on the phase-only FWI (Luo, J., et al., 2016; Maharramov et al., 2017). The method proposed by Luo, J., et al., (2016) uses the exponential of instantaneous phase to avoid the phase-wrapping problem, which is much easier for implementation.

Here we propose a phase-only reflection FWI for a model update. We use an object function of the local crosscorrelation between real data and synthetic data with envelope normalization, which can achieve the phase-only inversion for the reflection events. In each iteration, we first migrate the input data and use the migration kernel (Tang et al., 2013) to generate a reflectivity/pseudodensity. Then we perform modelling with reflectivity/pseudodensity to generate synthetic data which contains reflection events. We only invert the far-angle data mismatches. We demonstrate the validity of this method with a real data study in Europe.

Theory and method

The conventional L2 norm FWI objective function can be defined as L2 norm of the residual between the recorded data $d(t)$ and synthetic data $u(t)$ as follows:

$$E = \int [d(t) - u(t)]^2 dt. \qquad (1)$$

With this objective function, the amplitude information will be involved in the inversion, which is not reliable. We define $d_n(t) = d(t)/D(t)$, where $D(t) = \sqrt{d(t)^2 + (H\{d(t)\})^2}$ is the envelope of $d(t)$ and $H\{\cdot\}$ denotes the Hilbert transform. The normalized data $d_n(t)$ only contains phase information. Here we propose the local crosscorrelation-based object function (Zhang et al., 2015) as follow, which measures the phase correlation in the local windows

$$E_c = -\int \frac{d_n(t)u_n(t)}{\sqrt{\int d_n(t)^2 dt}\sqrt{\int u_n(t)^2 dt}} dt. \qquad (2)$$

With this objective function, the adjoint source can be calculated as

$$\frac{1}{\sqrt{\int u_n(t)^2 dt}} \left(c(t)\overline{u_n(t)} - \overline{d_n(t)}\right). \qquad (3)$$

Where $c(t) = \frac{\int d_n(t)u_n(t)dt}{\sqrt{\int d_n(t)^2 dt}\sqrt{\int u_n(t)^2 dt}}$ is the correlation weighting coefficient, $\overline{u_n(t)} = \frac{u_n(t)}{\sqrt{\int u_n(t)^2 dt}}$ and $\overline{d_n(t)} = \frac{d_n(t)}{\sqrt{\int d_n(t)^2 dt}}$ .The integral is calculated in local windows and the window length is decided by the frequency band during inversion.

For a real data application, it's very difficult to simulate a synthetic data which fully matched the amplitude on input data. It's also hard to deal with velocity/density trade off issue. We often see that strong amplitude leads to big update in L2 norm FWI application, which is not always correct. With this new approach, the amplitude problem is minimized and the correlation weighting coefficient $c(t)$ can be used to ensure that the unmatched amplitude of the data will not be brought into the adjoint source, which can give us more robust inversion results.

To use the objective function above for phase-only or traveltime-only inversion for RFWI, we first need to have reflection events modelled in the synthetic. Either Born modelling or pseudodensity modelling can be used for this approach. If there are some velocity errors in the model, the near angle/offset traveltime of reflection events are matched between input and synthetic due to migration/demigration effect and there will be some traveltime difference in far angle/offset. The traveltime difference can be resolved by PRFWI.

The actual workflow contains three steps for each iteration as follows:

Step 1. Migrate input data and use the generate reflectivity /pseudodensity with the migration kernel.

Step 2. Modelling with reflectivity/pseudodensity and calculate the adjoint source with equation (3), back propagate the adjoint source and get velocity update gradient.

Step 3. Do extra forward modelling to calculate step length for the model update

The next iteration will start from step 1 to migrate the input data with the updated velocity and generate a new reflectivity/pseudodensity. Compared to conventional RFWI, PRFWI requires an extra migration. But this step is crucial to use the phase-only or traveltime-only information.

Results

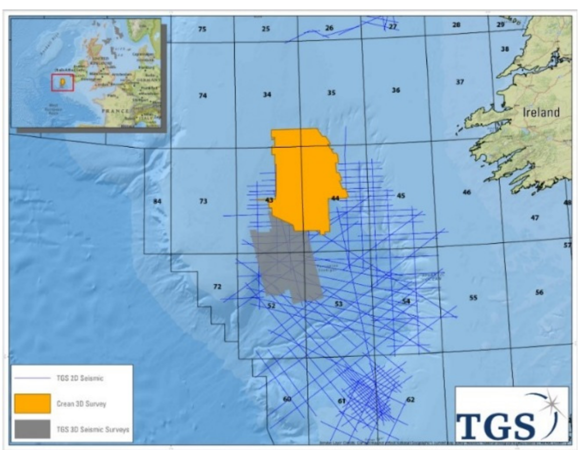

Figure 1: survey area

We applied this PRFWI to a 3D dataset on the Irish Atlantic Margin (shown in Figure 1). The Crean 3D is a survey of more than 5,400 km^2 located in the South Porcupine Basin between the Porcupine High and the Irish Mainland Platform, with a narrow azimuth streamer acquisition (NAZ) acquired in 2017. The streamer cable length is 8100 m, so the recorded diving wave can only reach to roughly 2500 m in depth. We use image-guided (IG) tomography (Hilburn et al., 2014) to build the initial model. Diving-wave FWI is applied for shallow-velocity updating. We discuss the full model-building flow in another case study paper.

Here we focus on the application of PRFWI for a high-resolution model update with reflection energy. In this study, we choose pseudodensity modelling because it is cost effective. The input data is a deghosted and demultipled dataset. Figure 2(a) shows the input shot gather after low-pass filtering (up to 15 Hz). Figure 2(b) is the modelled synthetic without pseudodensity. After IG tomography and diving-wave FWI, some details have already been put in the model, so some weak reflection events which are generated by the velocity contrast can be observed. However, we still see the strong reflection events do not match the input. Figure 2(c) shows the synthetic with pseudodensity which shows a better match to the input. There are some traveltime differences observed in middle-to-far offset (marked by the red curved lines), which can be used for PRFWI.

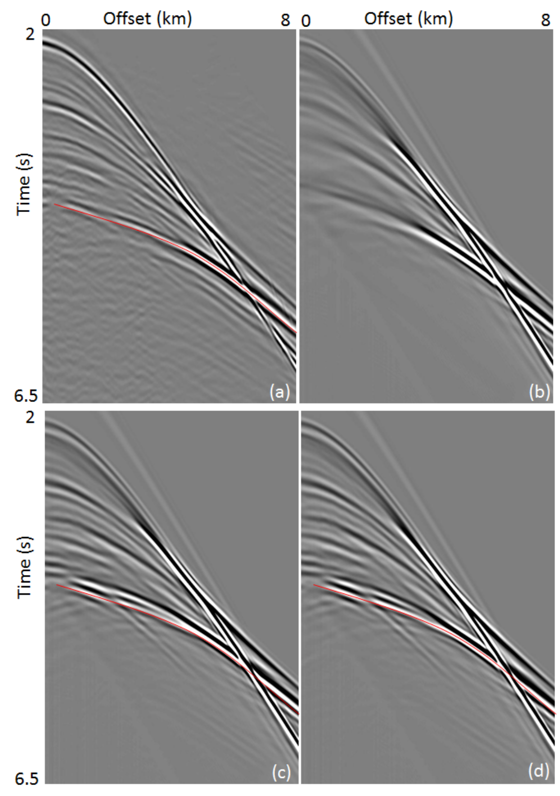

Figure 2: (a) input shot gather up to 15 Hz (b) initial synthetic without pseudodensity (c)initial synthetic with pseudodensity (d) FWI synthetic with pseudodensity

Figure 3 gives the comparison of the velocity update from conventional RFWI and PRFWI. Note that the range of conventional RFWI is ± 400 m/s and PRFWI is ± 100 m/s. From common-image gather QC, we notice that the model is overcorrected with conventional FWI, which degrades the gather flatness. This is because a strong impedance contrast has been added into the velocity model update, which is incorrect. This is a very common problem in conventional RFWI. To overcome this problem, we propose to use PRFWI for a phase-only or traveltime-only update.

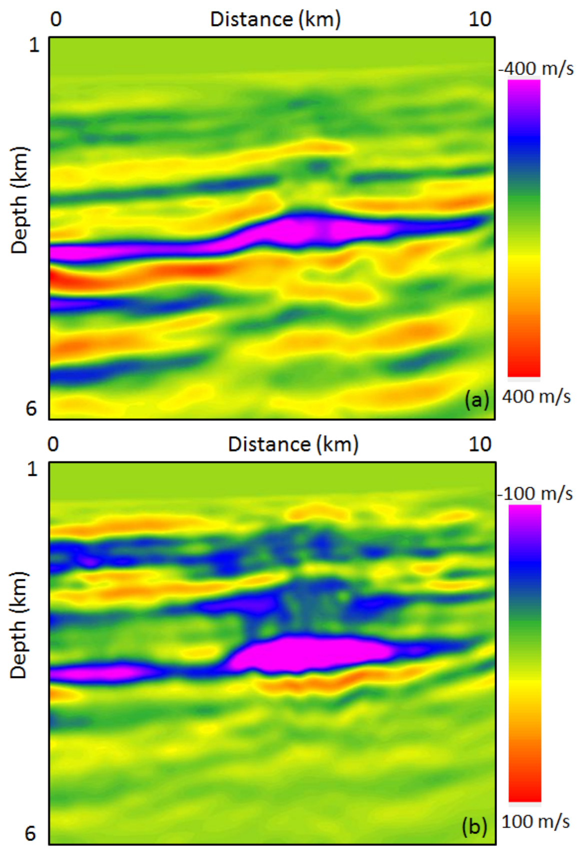

Figure 3: Velocity update from (a) conventional RFWI (b) PRFWI.

The range of the PRFWI update is much more reasonable and provides a high-resolution update. It fixed a far-offset traveltime mismatch which is shown in Figure 2. The red curved lines in the same position in Figure 2 show matched traveltime between input Figure 2(a) and FWI synthetic Figure2(d). Figure 4 is the comparison of migration images with an initial model and a final model. From the image, we can see that image sags are resolved in the center area which contains a low-velocity zone. Some coherent events show up on Figure 5 of the gather comparison around the low-velocity zone which indicate a better model is derived.

Discussions

We develop this method for a small wavenumber, local model update, which means we need a good starting model. If there's still cycle-skip issue with the starting model, we can combine the method with dynamic warping (Mao et al., 2016). Dynamic warping can be used to fix the large traveltime shift in the far offset. On the other hand, it requires enough offset/angle to resolve the kinematic errors. Beyond a certain depth, we cannot get any update due to limited reflection angles in the deeper part. It is similar to reflection tomography, which requires far-offset curvature to invert velocity errors.

Conclusions

We present a practical methodology for high-resolution model building with phase-only reflection full waveform inversion. We often see over updates from conventional RFWI by involving amplitude information for velocity update. Our method is based on reflectivity/pseudodensity modeling, which can better match the synthetics to the input data on the reflection events. Only the far-angle traveltime difference is used in the inversion. The amplitude effects are minimized by envelope normalization and the local crosscorrelation objective function makes the phase-only inversion more robust. We demonstrate the validity with a real-data application in Europe. PRFWI gives us a reasonable high-resolution update compared to the conventional RFWI result and uplifts the subsurface imaging.

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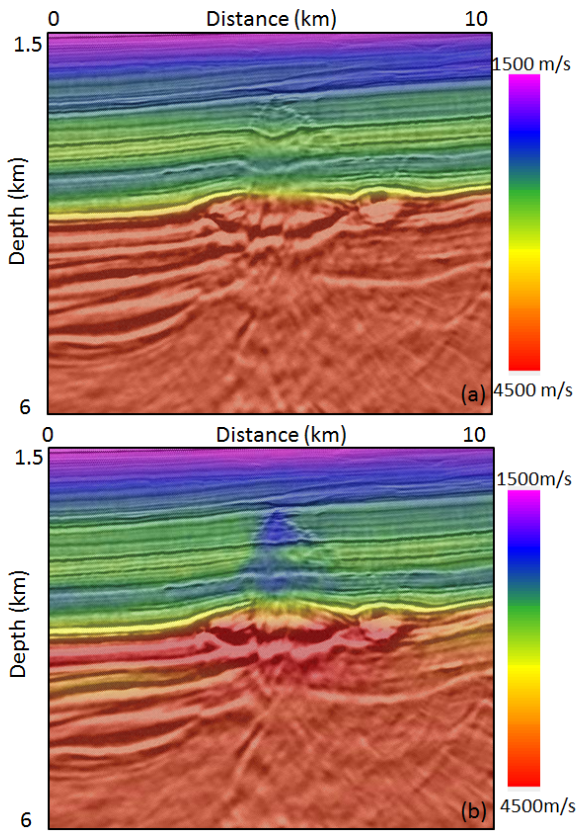

Figure 4: Migration image (a) initial model (b) final model.

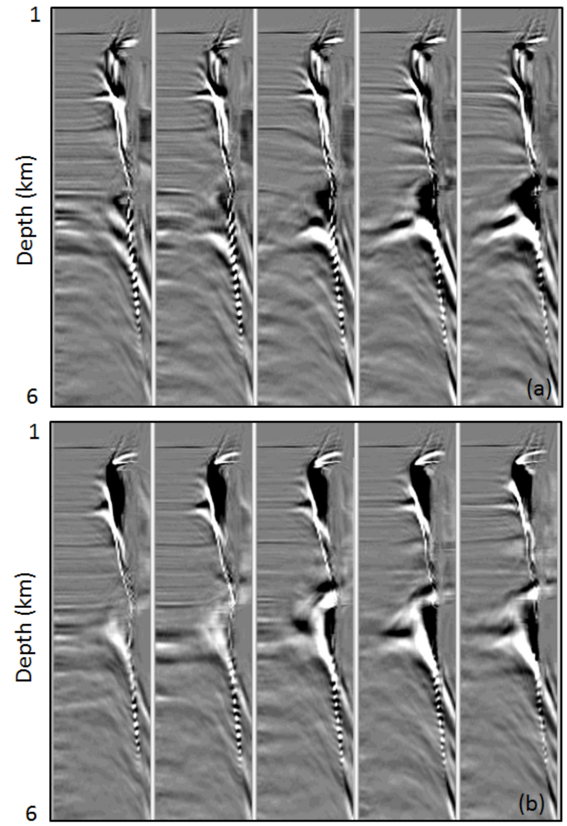

Figure 5: Migration common image gather (a) initial model (b) final model.

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