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High resolution Full Waveform Inversion: Two Pitfalls and a Remedy

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Summary

In the last decade, Full Waveform Inversion has gained popularity as a very powerful tool to estimate velocity models of the subsurface with unrivalled resolution. Interpreters can now use high-resolution models obtained by FWI directly, in addition to migrated images. However, the FWI velocity models do not necessarily ensure optimal flattening of common image gathers. A fundamental reason for this is that mid to high wavenumbers are brought into the model by the reflection amplitudes, which are only partly explained by changes in velocity. A residual low wavenumber update of the model is then frequently done with the consequence that the positioning of small-scale events in the model may no longer be consistent with the migrated image. In this paper, we first illustrate the above-mentioned pitfalls, and propose an innovative workflow based on FWI-guided tomography. It ensures the optimal focus of the migrated image and it also ensures a better match between the fine-scale velocity structures and the migrated image. The approach is validated on a 2D marine broadband dataset using 32 Hz High-Resolution FWI.

Introduction

Full Waveform Inversion (FWI) allows the construction of detailed velocity models of the subsurface with unrivalled resolution. One must first estimate the low wavenumbers of the velocity, using for example low frequency and transmitted wave-FWI, or tomography. Then, the mid wavenumbers are solved using either high-resolution tomography or FWI using the transmitted waves or even the amplitude of low frequency reflected waves (broadband datasets have useful data starting at 3 Hz or lower). Tomographic approaches cannot recover the high wavenumbers of the velocity (above 6 Hz or so), unlike high resolution (HR) FWI (Qin et al. 2015). Inverting up to 20 Hz is now routinely affordable (Jones et al., 2018), but some published results have gone as high as 40 Hz (Routh et al., 2017), the limit being the computing and memory cost. As mentioned in these works, such HR models are much appreciated for interpretation and are very helpful for reservoir characterization and field development. However, the amplitude of the reflected waves, as a function of the reflection angle, depends not only on the P-wave velocity contrasts but also on other parameters including density and S-wave velocity. Estimating all these coupled parameters using HR FWI suffers crosstalk and is an ill-posed problem. Since the mid wavenumber part of the HR FWI velocity perturbation impacts the kinematics of the reflections, common image gathers (CIGs) flatness may be degraded after HR FWI.
In the upcoming sections, we illustrate this CIG flatness problem on a real broadband dataset. We show that the classical workaround of applying a low wavenumber tomography update is not a good solution as the positioning of small-scale events in the model becomes inconsistent with the migrated image. We then propose a new workflow based on FWI-guided tomography that does not suffer from these problems.

Pitfalls in high resolution FWI-based model building

Using a 2D broadband (2-70 Hz) marine dataset acquired offshore Australia, we computed the residual move out (RMO) using a low wavenumber model, and after HR FWI. The velocity models and RMO distributions are visible on the first two columns of Figure 1.

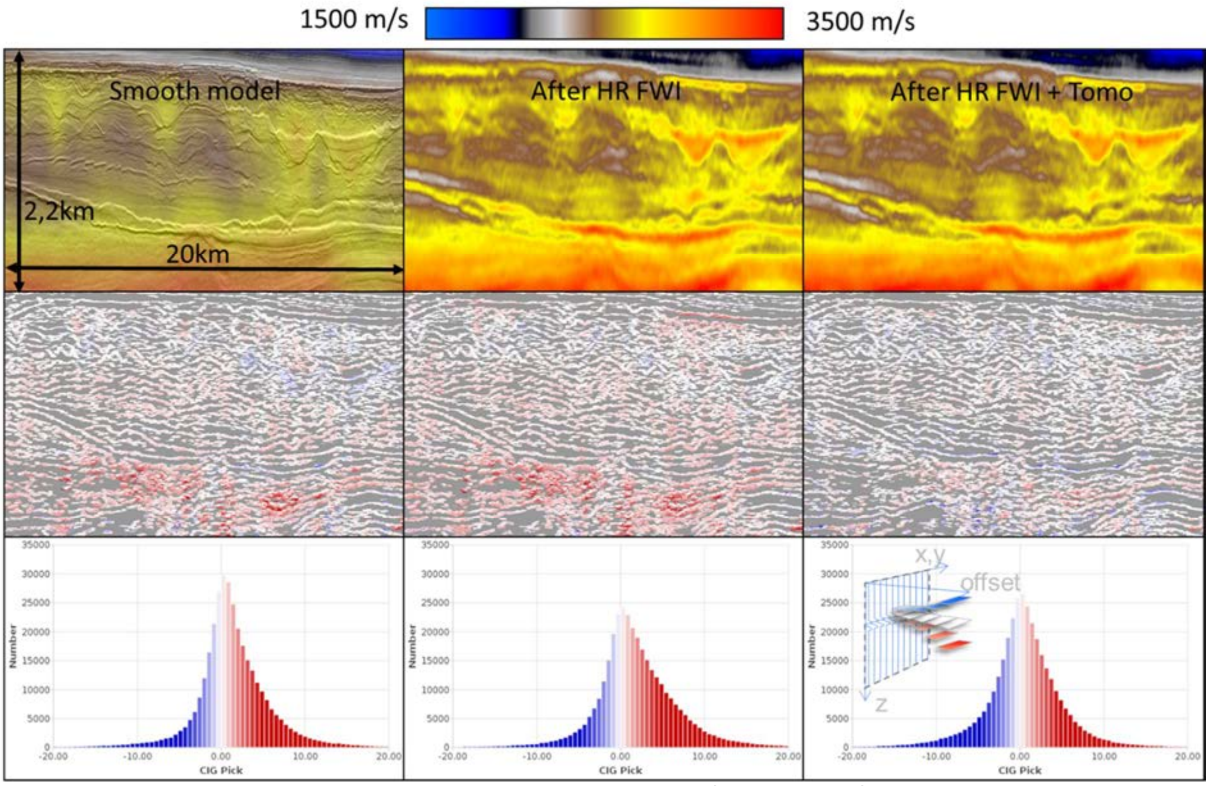

__Figure 1__ Top row: velocity model (overlaid on stack section for the top left picture); central row: RMO picks; bottom row: histogram of RMO. First column: low wavenumber model; second column: after HR FWI; third column: after HR FWI followed by tomography.

The distribution of RMO becomes wider after HR FWI and the mean increases. This could be related to the crosstalk when using single parameter FWI on reflection data. Note that we do not expect much 3D effects on this dataset so that similar conclusions hold on 3D datasets. One commonly used solution is to compute a low wavenumber velocity update after HR FWI, using reflection tomography (Vigh et al., 2016). We call this approach the conventional workflow. We see on Figure 1 (third column) that indeed the mean RMO decreases and the RMO distribution has a smaller standard deviation.

However, this conventional workflow has a flaw: the positioning of small-scale events in the HR velocity model will no longer be consistent with the migrated image generated using the model after tomography. Since only the low wavenumbers of the model are updated, the high wavenumbers become mispositioned. We can quantify this mispositioning by computing local time shifts between the HR velocity perturbation converted to reflectivity and the migrated image (Figure 2). The time shifts increase considerably after a low wavenumber tomography to flatten CIGs as shown in Figure 3. Of course, a simple 1D stretch of the small-scale events in the velocity model may partially solve the positioning problem but it would not guarantee CIG flattening.

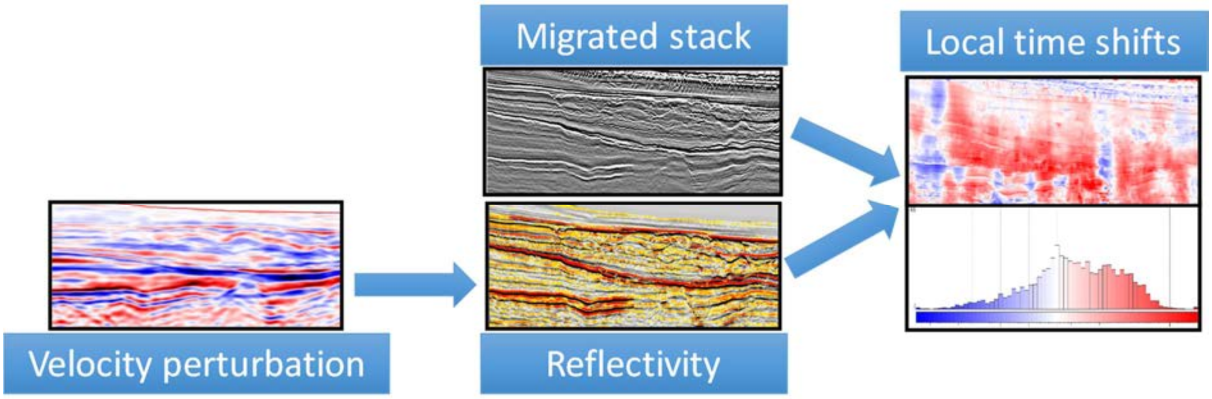

Figure 2 *Workflow to quantify the mispositioning of the velocity model's fine details: velocity perturbation is converted to time and then to reflectivity by taking the vertical derivative, and it is compared to the migrated image (converted to time) to obtain local time shifts.*

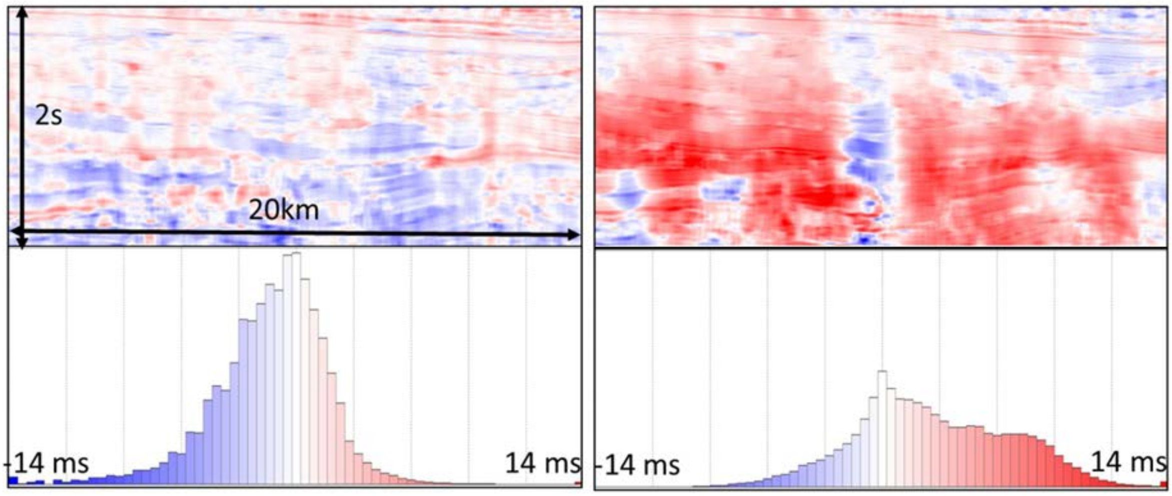

Figure 3 *Local time shifts measuring mispositioning between the velocity perturbation and the migrated image. Left: after HR FWI; Right: after HR FWI but with an extra low wavenumber tomography update to flatten CIGs.*

Allemand and Lambaré (2014, 2015) proposed to use the information coming from HR FWI as a guide for the tomography update, taking advantage of the overlap in the mid wavenumbers of information coming from HR tomography and low frequency reflected energy present in broadband data. This method consists of several steps: first to estimate a background model that contains the low and a part of the mid wavenumbers; then to compute a velocity gradient (called the guide) with HR FWI that contains the high and a part of the mid wavenumbers; finally, to use tomography to estimate a smooth step length volume based on the gather flatness criteria. The final model is the sum of the background model and the product of guide and step length volume. The challenges in this approach are ensuring that:

- the background model and the guide are correctly separated in the wavenumber domain, i.e. there should be no gap and no overlap for the method to be effective.
- the information contained in the guide is compatible with the data used for the tomography, i.e. both should drive the velocity model in the same direction. This means that the HR FWI perturbation has to be correctly positioned.

Proposed workflow

We recently developed a workflow to overcome the above challenges as follows:

1. We estimate a background model that contains the low wavenumber information
2. Then use High Definition (HD) tomography (Sioni et al. 2012) to update mid wavenumbers
3. Followed by HR FWI to obtain mid and high wavenumber perturbation.
4. Define the guide as the sum of HD tomography and HR FWI velocity perturbations
5. Perform guided tomography using the output of step 4 and gather curvatures as input.

The HD tomography step is crucial as it allows the HR FWI perturbation to be consistently positioned, bringing robustness to the workflow.

We apply our workflow on a 2D marine broadband dataset from offshore Australia. During denoising and demultiple stages, particular attention is paid to low frequencies. The HR velocity model from the proposed workflow results in small RMO, while maintaining consistent positioning of the small-scale events (Figure 4, to compare with Figure 1 and 3). Figure 5 highlights these small-scale events in both the resulting velocity model and the migrated image. The HR model (obtained using 32 Hz HR FWI) clearly delineate the well channels and thin layers and can further aid interpretation (Shen et al. 2018).

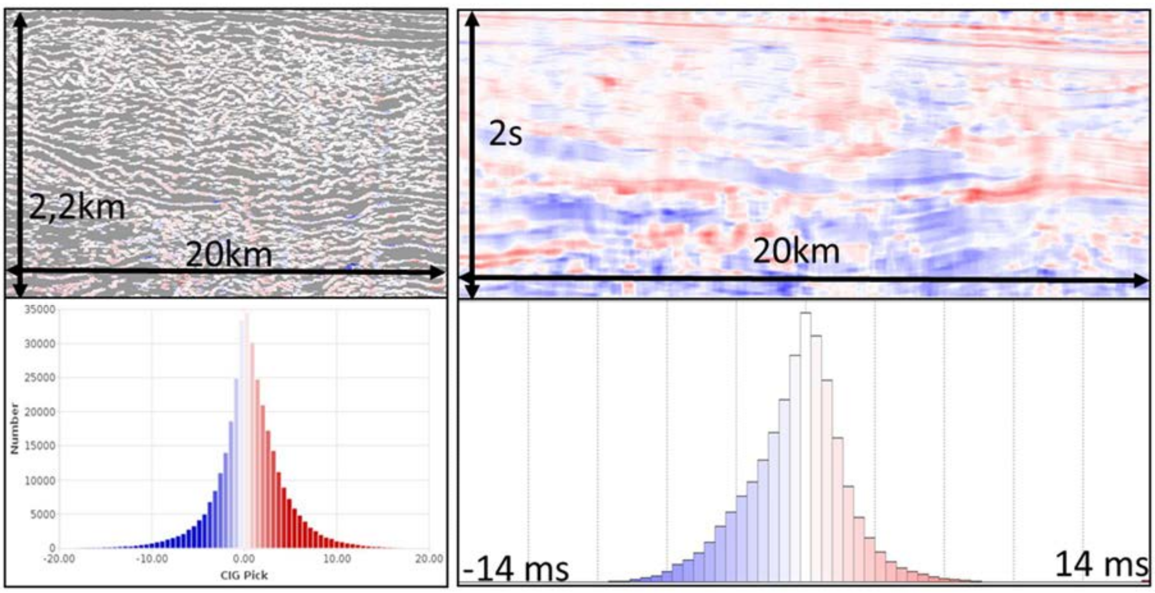

Figure 4 *Distribution of RMO (left) and time shifts between the velocity model and the migrated image (right), calculated in the model obtained using the proposed workflow.*

Conclusion

The construction of HR velocity models with FWI may lead to discrepancies: CIGs may not be optimally flat, and small-scale events positioning may be inconsistent between the velocity model and the migrated image. We proposed an improved workflow that mitigates these issues by taking advantage of the overlap of tomography and FWI in the wavenumber domain for broadband data. We demonstrated our workflow and its effectiveness on a real data example. This should pave the way for better reservoir characterization.

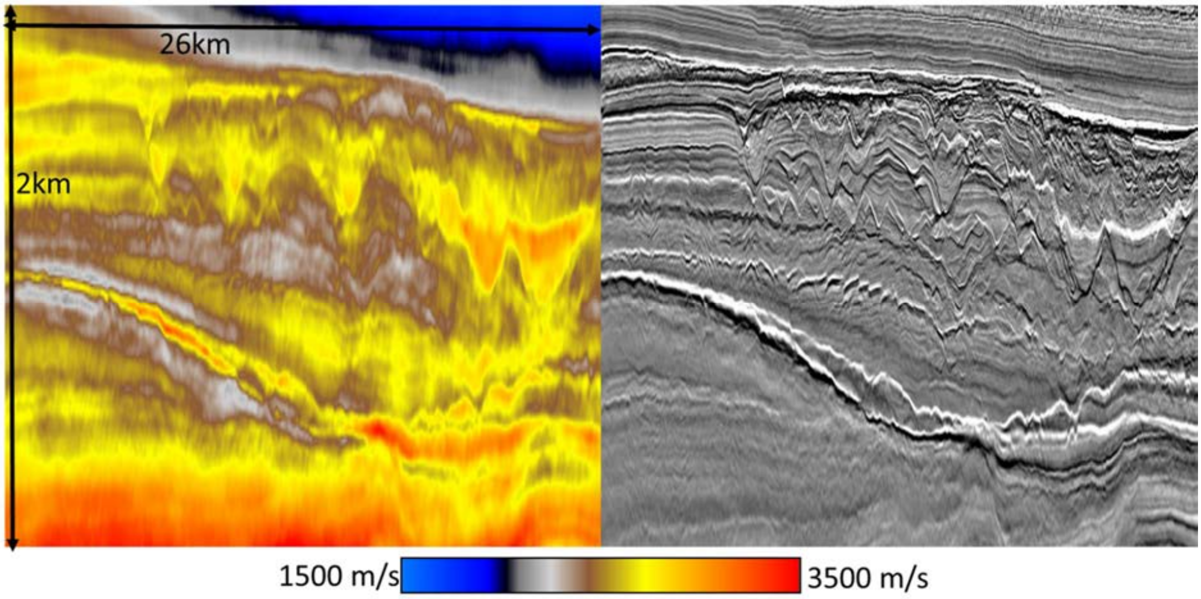

Figure 5 *Left: high resolution velocity model obtained with the proposed workflow, using 32 Hz HR FWI. Right: corresponding migrated image.*

Acknowledgments

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