Multi-parameter FWI for structural imaging, amplitude fidelity and reservoir properties

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Summary

In the last few years, there has been an increased interest for multi-parameter Full Waveform Inversion (MP-FWI) in the seismic industry. In this paper we will revisit the motivation for this approach and show examples of what MP-FWI can offer compared to traditional FWI. Furthermore, we will discuss the key building blocks that should be considered to ensure true parameter de-coupling and simultaneous inversion.

Introduction

Traditional FWI, inversion for pressure velocities, has been a standard tool in the velocity model building (VMB) sequence in the seismic industry for almost two decades. With better access to increased compute resources and developments of cycle-skipping robust norms (Mao et al., 2020), this approach has been pushed to the full bandwidth of the recorded data, hoping that it would provide attributes that could directly reveal reservoir properties. These high-frequency models have become increasingly popular for structural interpretation, especially when structural derivation of the models is done to produce seismic looking images; FWI Image, FWI derived reflectivity (FDR), Pseudo reflectivity (different names but same meaning). This methodology has further been developed to produce partial stacks, through different data-selections (near, middle and far angles or offset) prior to parallel and independent inversions after the macro model is resolved using the full shot record. For obvious reasons, there has been a debate in the community about the amplitude reliability of this approach. Especially the density/velocity ambiguity with the single parameter inversion (Korsmo et al., 2022).

In contrast, MP-FWI rely on two (or more) models to explain the observed data. The basic principles are that the tomographic kernel in FWI, “banana and rabbit ears”, is utilized to resolve the long wavenumber kinematic effects to ensures correct structural imaging, while the migration isochron is used to provide the reflectivity model inferred through a least-squares reverse-time migration (LS-RTM). If these two model parameters are fully de-coupled, we can: 1) avoid density effects being mapped incorrectly as velocity boundaries, 2) allow the background model to be resolved without the dominance of the strong migration/impedance kernel and 3) directly compute “relative” attributes that are linked to reservoir properties; impedance and density. “Relative” means that they will have a resolution limited and dictated by the seismic experiment. Absolute attributes would require incorporation of well log information.

This method can be extended to provide angle dependent reflectivity gathers without the requirement of doing approximate angle selections in the data-domain prior to inversion followed by un-constrained parallel inversions for near, middle and far angles.

In this paper, we will explain why and show examples of how our implementation of MP-FWI can facilitate a de-coupled simultaneous inversion for velocities and reflectivity, provide reliable attributes for quantitative interpretation (QI) and can be extended to the prestack domain to give us access to more reservoir attributes (including elastic properties).

Methodology

MP-FWI, as outlined in this paper, started with the reformulation of the wave-equation, parametrized with variable velocity and reflectivity (Whitmore et al., 2020). This work showed that the new parametrization provides identical modeling results to the original velocity-density parametrization and could facilitate simultaneous inversion for velocity and reflectivity without the requirement of building an accurate density model, which is anyway practically impossible early in the VMB sequence. The choice of reflectivity over density in the modeling engine, enabled a robust and effective parameter de-coupling that originally was implemented for RTM (Whitmore and Crawley 2012). Whitmore and Crawley implemented a new imaging condition (IC) for RTM based on inverse scattering theory; Inverse Scattering Imaging Condition (ISIC). Rather than cross-correlating the forward and back-propagated wavefields at every imaging step, they formulated a weighted sum of the time and spatial derivative component of the interactions between the two wavefields. As a result, they could remove the low-frequency noise that occurs when the two wavefields propagate in phase with each other during the imaging process. Ramos-Martinez et al., (2016) applied the same method, with the opposite weights to let FWI emphasize on kinematic updates by suppressing the strong and dominating migration isochron. Reflection inclusive FWI, using conventional cross-correlation IC, can suffer from reflectivity leakage early in the VMB sequence if the background model (low wavenumbers) is not correct. This can lead to velocity boundaries at incorrect locations, that would be difficult to correct later in the sequence. With ISIC we can mitigate this undesired effect and allowed the inversion to resolve the background model with the tomographic components of the FWI kernel.

Finally, vector reflectivity modeling, ISIC and the simultaneous inversion were combined into a single inversion framework, enabling for MP-FWI as outlined in this paper (Yang et al., 2021).

The natural next step was to extend this method to the pre-stack domain and provide angle dependent reflectivity gathers. This was achieved by mapping the reflectivity into angle bins based on the reflectivity vector and the direction of the forward propagated wavefield (Poynting vector), (Chemingui et al. 2023). With this approach we mitigate the approximate angle data-selection and multiple parallel un-constrained inversions done for the angle-sectored FWI Imaging. Figure 1 shows how the two vectors, source wavefield and reflectivity, allows for angle mapping during the inversion.

It is important to recognize that the reflectivity derived from MP-FWI differs significantly from traditional data-domain LS-RTM. Unlike LS-RTM, MP-FWI leverages the entire wavefield, including multiples, and surpasses the single scattering (Born) approximation. This method inherently involves nonlinearity, as the background velocity model is iteratively updated throughout the inversion process.

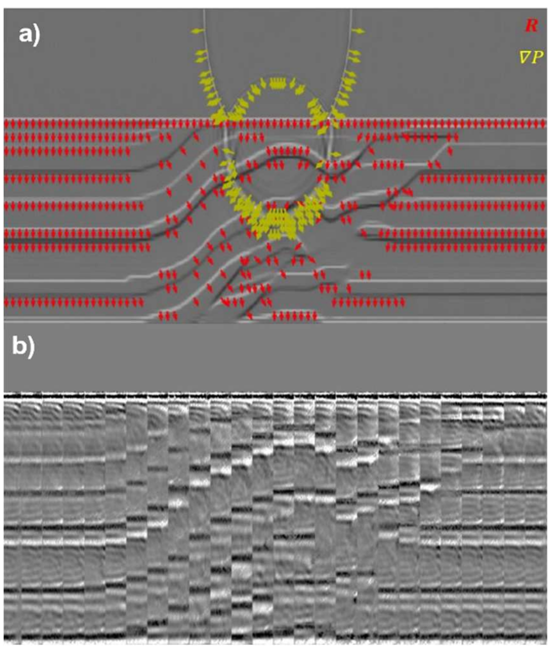

Figure 1: Direction of the forward propagated wavefield and the reflectivity vector a) allows for the angle mapping as illustrated in figure b).

Examples

In first example, we focus on the reflectivity product from MP-FWI. The field dataset was acquired with multi-component streamer data over a complex faulted region in the North Sea. The inversion was done in frequency stages up to 45Hz (f3), allowing for both structural corrections, through the refinements of the velocity model, as well as illumination corrections and de-blurring. Figure 2 shows the first a) and final b) iteration of the 45Hz reflectivity model. As annotated by the black arrows, we can see how the acquisition related footprints in the initial reflectivity gets attenuated with the MP-FWI process. Furthermore, we see an overall improved stack response, resolution/de-blurring and improved imaging of the target structure (yellow ellipse) after MP-FWI.

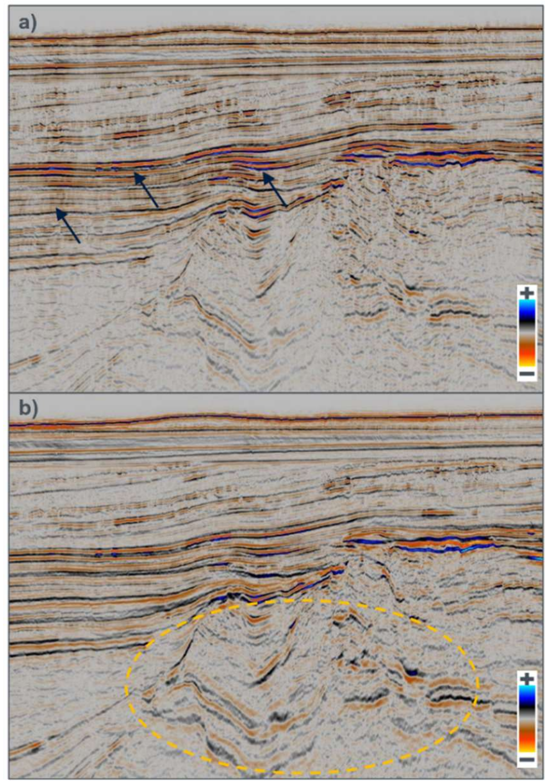

Figure 2: Initial reflectivity a) and final reflectivity b) at 45Hz with MP-FWI. Notice how the acquisition related illumination artifacts (black arrows) have been corrected in the final MP-FWI reflectivity and provides a better balanced and de-blurred stack response, improving the target reflectors (yellow ellipse).

The next example is from the Central Graben in the North Sea, where a shallow gas anomaly is present over a deeper salt dome which has been migrated and pushed through the Chalk layer. The acquisition type is multi-component streamer data. Figure 3a and 3c shows the vintage velocity model and the corresponding Kirchhoff PSDM image, while the MP-FWI results are shown in figure 3b and 3d. As annotated with the white ellipse in figure 3b, the velocities from MP-FWI resolves the shallow low-velocity anomaly and corrects the structural sag related to the gas-contact as annotated with the first yellow arrow in figure 3d. Furthermore, we see significant velocity updates and imaging improvements in the deeper section, especially for the salt overhang and the pre-salt reflectors (yellow arrows) with MP-FWI. It is important to emphasize that these results were purely data-driven with MP-FWI, except for one single pass of salt interpretation to condition the deepest model mid-way throughout the inversion.

In the final example, we show how MP-FWI can estimate reservoir properties directly from the inversion. The inversion was done over a heavily faulted region of the Norwegian Sea, where the aim was primarily to correct for a fault shadow zone, evident as amplitude dimming/artifacts on the vintage data near a large regional fault (Pankov et al., 2023).

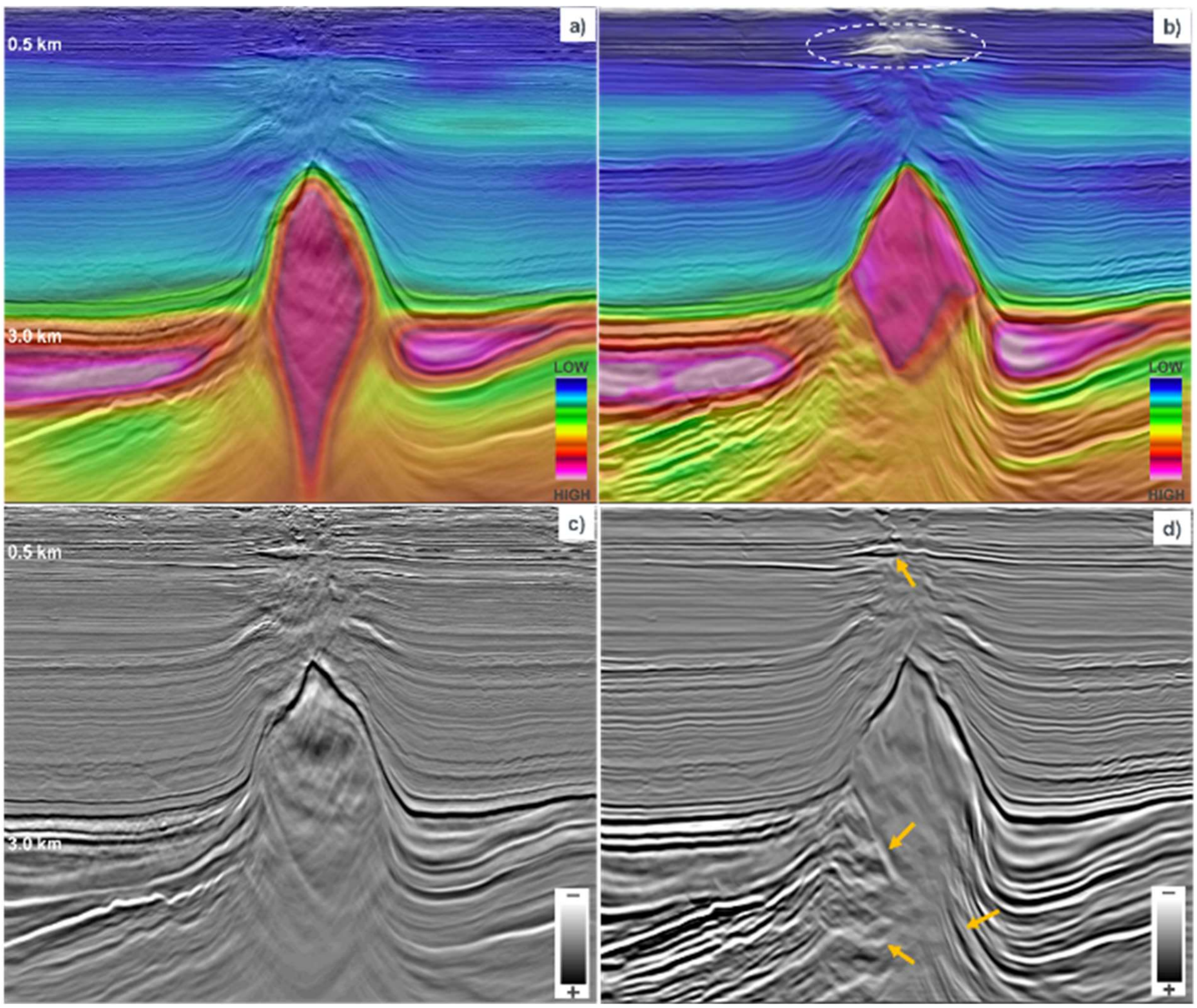

Figure 3: Vintage velocity model a) and the corresponding Kirchhoff PSDM image c). MP-FWI velocity model b) and the corresponding MP-FWI reflectivity d). Notice how the background velocity model from MP-FWI resolves the shallow gas-anomaly as well as the deeper structure. The reflectivity volume shows imaging improvements from the shallow section (flattening the gas-contact, first arrow), as well as imaging the deeper salt-flanks and pre-salt reflectors (the two deeper yellow arrows).

Figure 4a shows the final MP-FWI reflectivity, 4b shows the velocity perturbations and the 4c shows the relative density volume computed directly from the inversion. The final reflectivity volume in figure 4a show no evidence of amplitude dimming near the regional fault (yellow dotted line), indicating that MP-FWI have address any residual illumination artifacts that could lead to false amplitudes near the fault system. The background velocity update in figure 4b cause structural corrections of the reflectivity by utilizing the tomographic components of the FWI kernel. The relative density volume in figure 4c was directly computed post-inversion from the two de-coupled velocity-reflectivity parameters by integrating the reflectivity and diving it with the inverted velocity model. The relative density volume correlates nicely to the measured response at the well and maps the two low-density sand layers in the 3D volume (black arrows).

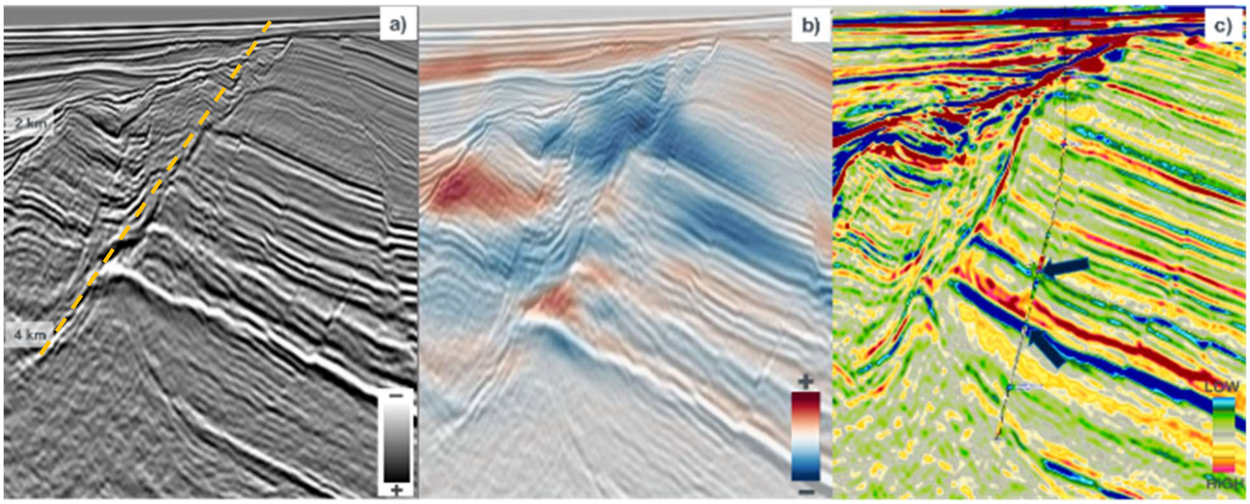

Figure 4: MP-FWI reflectivity a) background velocity perturbation from MP-FWI b) and relative density from MP-FWI c). The MP-FWI reflectivity show no sign of amplitude dimming near the regional fault (yellow dotted line), the velocity updates ensure structural corrections by using the tomographic part of the FWI kernel and the 3D density volume maps out two low-density layers (black arrows) that are seen in the measured response at the well.

Conclusions

MP-FWI offers an alternative approach to conventional FWI and FWI Imaging. The key elements in our implementation are the vector reflectivity formulation of the wave-equation and the Invers Scattering Imaging Condition, enabling simulations inversion for FWI and LS-RTM. The two parameters represent different scales of the earth response, where the FWI model controls the structural imaging by using the tomographic kernel in FWI and the LS-RTM de-blurs and corrects for illumination artifacts by using the migration kernel. Our method makes no assumptions about the density model and avoid density effects being mapped incorrectly as velocity variations. With different field data examples, we have demonstrated how MP-FWI can significantly improve imaging in complex geology compared to conventional methods. Furthermore, we have shown how these two inverted parameters can directly provide a valuable reservoir property, like relative density. Finally, we have described how this method can be extended to the pre-stack domain without making approximate angle-selections prior to inversion.

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