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Revisiting the motivation and the fundamentals of multiparameter FWI

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Abstract

In recent years, there has been an increased interest for multi-parameter Full Waveform Inversion (MP-FWI) within the seismic industry. This paper revisits the motivation for this approach and presents examples demonstrating the benefits of MP-FWI compared to traditional FWI. Furthermore, we discuss the key components necessary to ensure accurate parameter de-coupling for the simultaneous inversion.

Introduction

For nearly two decades, Full Waveform Inversion (FWI) has been essential in the velocity model building (VMB) sequence in the seismic industry. Recent advancements in computational power and cycle-skipping robust norms (Mao et al., 2020) have extended FWI to the full bandwidth of recorded data, aiming to utilize velocities for reservoir characterization. High-frequency models from this process are used for structural interpretation, especially when transformed into seismic-like images, such as FWI Images / FWI-derived reflectivity (FDR). This technique has evolved to generate partial stacks through data selection (near, middle, and far angles or offsets) followed by parallel and independent inversions after resolving the macro model. Despite these advancements, the amplitude-fidelity of this approach is debated, particularly due to the density/velocity ambiguity in single-parameter inversion (Korsmo et al., 2022).

In contrast, MP-FWI uses multiple models to interpret observed data, employing different kernels to update parameters from the same data residuals. Long-wavelength kinematic effects control structural imaging in the velocity model, while dynamic effects are assigned to the reflectivity model through least-squares reverse-time migration (LS-RTM). Decoupling these parameters prevents density effects from being misinterpreted as velocity boundaries, which allows the background model to be resolved without interference from the migration/impedance kernel and directly computes "relative" attributes related to reservoir properties, such as impedance and density. This approach can also produce angle-dependent reflectivity gathers without approximate angle selections prior to inversion.

This paper explains our implementation of MP-FWI and demonstrates how it enables decoupled simultaneous inversion for velocities and reflectivity. We present examples highlighting reliable attributes for quantitative interpretation (QI) and discuss extending this method to the pre-stack domain for additional reservoir attributes, including elastic properties.

Methodology

Our approach to MP-FWI starts with reformulating the variable-density acoustic wave equation using velocity and vector-reflectivity parameters (Whitmore et al., 2020). This new formulation produces the same seismograms as the traditional velocity-density parameterization and uses migrated images as proxies for the density model, facilitating simultaneous inversion of velocity and reflectivity without needing boundaries in the velocity model or a speculative density model. Whitmore and Crawley (2012) introduced the Inverse Scattering Imaging Condition (ISIC) to eliminate low-frequency noise during RTM. Ramos-Martinez et al. (2016) adapted ISIC to emphasize kinematic updates in FWI, and Yang et al. (2021) combined reflectivity modeling with ISIC for simultaneous inversion.

MP-FWI avoids early reflectivity leakage into the velocity model, removes the need for a speculative density model, and enables decoupled inversion where velocities control structural imaging and reflectivity is estimated with nonlinear LS-RTM. The method extends to the pre-stack domain to form angle-dependent reflectivity gathers by mapping reflectivity into angle bins based on the reflectivity vector and the Poynting vector (Chemingui et al., 2023). This approach greatly improves the efficiency without a priori angle data selection and multiple parallel unconstrained inversions. Figure 1a illustrates angle mapping during inversion, and Figure 1b shows angle-dependent reflectivity gathers from a field dataset.

Reflectivity derived from MP-FWI differs significantly from traditional LS-RTM, leveraging the entire wavefield, including multiples, and surpassing the single scattering (Born) approximation. This method is nonlinear, with iterative updates to the background velocity model and high-resolution reflectivity throughout the inversion process.

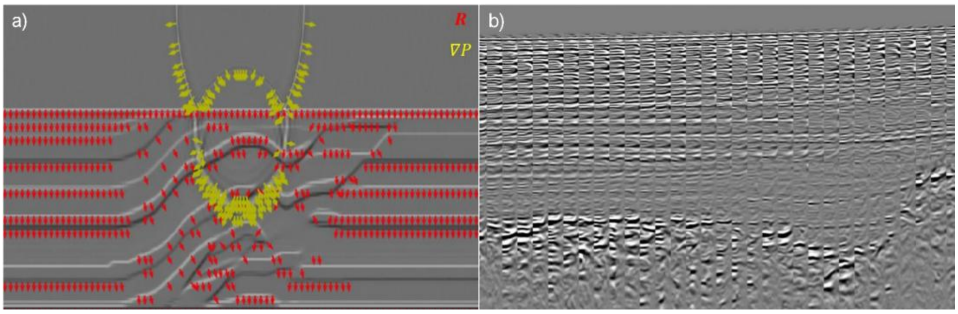

Figure 1: MP-FWI angle mapping based on the source wavefield (yellow arrows) and vector reflectivity (red arrows) a). Field data example with angle dependent reflectivity b).

Examples

In the first example, we analyze the reflectivity output from MP-FWI using multi-component streamer data from a complex faulted region in the North Sea. The inversion was performed in frequency stages up to 45Hz (full power) to enable structural and illumination corrections. Figure 2 shows the initial (a) and final (b) iterations of the 45Hz reflectivity model. The black arrows highlight the attenuation of acquisition related footprints through MP-FWI. Additionally, there is an overall improvement in stack response, resolution/de-blurring, and imaging of the target structure (yellow ellipse) after applying MP-FWI.

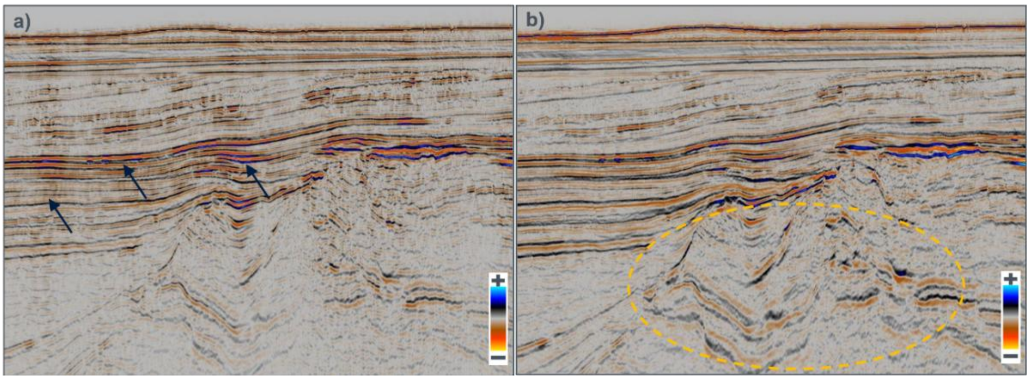

Figure 2: The reflectivity model (LS-RTM) from the initial a) and final b) iteration of MP-FWI at 45Hz. Acquisition related footprints in the initial model (black arrows) have been nicely addressed with MP-FWI and improved the imaging in the target structure (yellow ellipse).

The next example is from the Central Graben in the North Sea, featuring a shallow gas anomaly above a deeper salt dome intruding through the Chalk layer. Data was acquired using a multi-component streamer configuration. Figure 3a shows the vintage velocity model overlaid on the Kirchhoff PSDM image, with zoomed inline and depth slices in Figures 3c and 3e. The MP-FWI results are shown in Figures 3b, 3d, and 3f. The white dashed line in the vintage results indicates a structural sag due to an unresolved slow-velocity anomaly, which the MP-FWI results correct. Notice the enhanced detail in the depth slice with MP-FWI. Figures 3g and 3h compare Kirchhoff PSDM imaging with MP-FWI reflectivity results (LS-RTM), using the final velocity model from the MP-FWI process. The yellow arrows in Figure 3h highlight improved imaging of salt overhangs and base salt/subsalt events, revealing potential traps below the salt overhang.

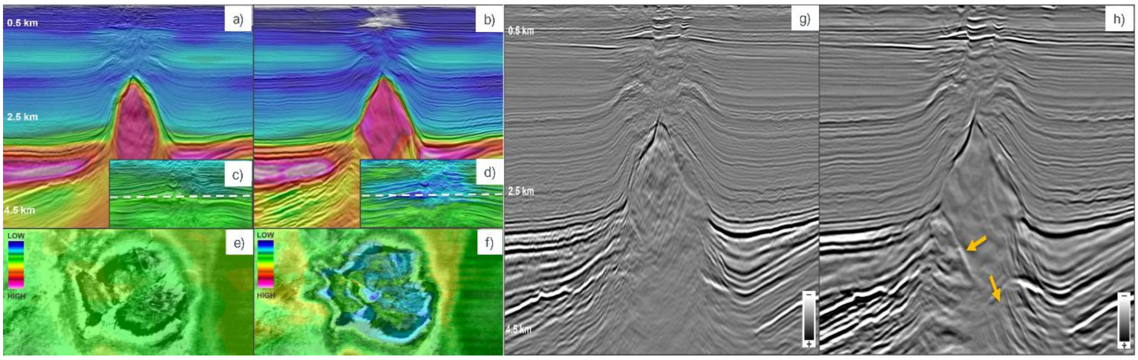

Figure 3: Vintage velocity model and Kirchhoff PSDM image: full section a), shallow zoom c) and shallow depth slice e). The corresponding MP-FWI velocity results in b), d) and f), where the shallow velocity anomaly has been resolved, leading to the structural corrections of the potential gas-contact. Kirchhoff PSDM imaging using the velocity model from the MP-FWI process in g) compared to the reflectivity (LS-RTM) output from MP-FWI in h) demonstrate the power of the inversion-based method.

In the final example, we demonstrate how MP-FWI can directly estimate reservoir properties when velocities and reflectivity have been resolved through a de-coupled inversion. This is achieved by integrating the reflectivity model to form impedance and dividing impedance by velocity to compute the density model.

The inversion was performed over a heavily faulted region of the Norwegian Sea to correct a fault shadow zone, evident as amplitude dimming/artifacts in vintage data near a significant regional fault (Pankov et al., 2023). Figure 4a compares the RTM image of the vintage velocity model versus the MP-FWI reflectivity in Figure 4b, showing healed amplitude dimming near the fault (yellow box). Figure 4c presents the relative density volume derived from MP-FWI versus the measured density response in the well log. Figure 4d highlights the correlation between measured and inverted density attributes, mapping two low-density sand layers observed in the well log.

Conclusions

MP-FWI presents an alternative to conventional FWI and FWI Imaging. The core components of our implementation include the vector reflectivity formulation of the wave equation and the Inverse Scattering Imaging Condition, which enable simultaneous inversion for FWI and LS-RTM. These two parameters capture different scales of the Earth's response: the FWI model governs structural imaging through the tomographic kernel, while LS-RTM addresses de-blurring and illumination corrections via the migration kernel. Our approach does not rely on assumptions about the density model, thereby preventing density effects from being misinterpreted as velocity variations. Through various field data examples, we have demonstrated that MP-FWI can significantly enhance imaging in complex geological settings compared to traditional methods. Additionally, we have shown that these two inverted parameters can directly yield valuable reservoir properties, such as relative density. Finally, we have outlined how this method can be extended to the pre-stack domain without requiring approximate angle selections prior to inversion.

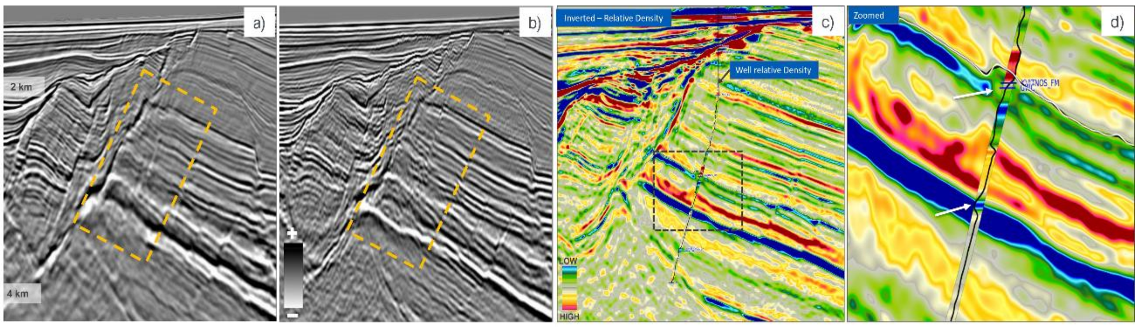

Figure 4: RTM image a) with the vintage model, MP-FWI reflectivity (LS-RTM) b) and relative density, full section and zoomed display, compared to measured well-log density in c) and d). MP-FWI heals the fault shadow zone (yellow ellipse) and detects the two low-density sand layers (white arrows).

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