Multi-parameter FWI - fundamentals and applications

J. Brittan[1], Ø. Korsmo[2], N. Chemingui[3], S. Crawley[3]

[1] TGS; [2] TGS; [3] TGS

Summary

In the last few 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

Over the last couple of 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 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.

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. The method uses the Inverse Scattering Imaging Condition (ISIC) to emphasize kinematic updates in FWI. 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. 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.

Example

The example given 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 1a shows the vintage velocity model overlaid on the Kirchhoff PSDM image, with zoomed inline and depth slices in Figures 1c and 1e. The MP-FWI results are shown in Figures 1b, 1d, and 1f. 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 1g and 1h 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 1h highlight improved imaging of salt overhangs and base salt/subsalt events, revealing potential traps below the salt overhang.
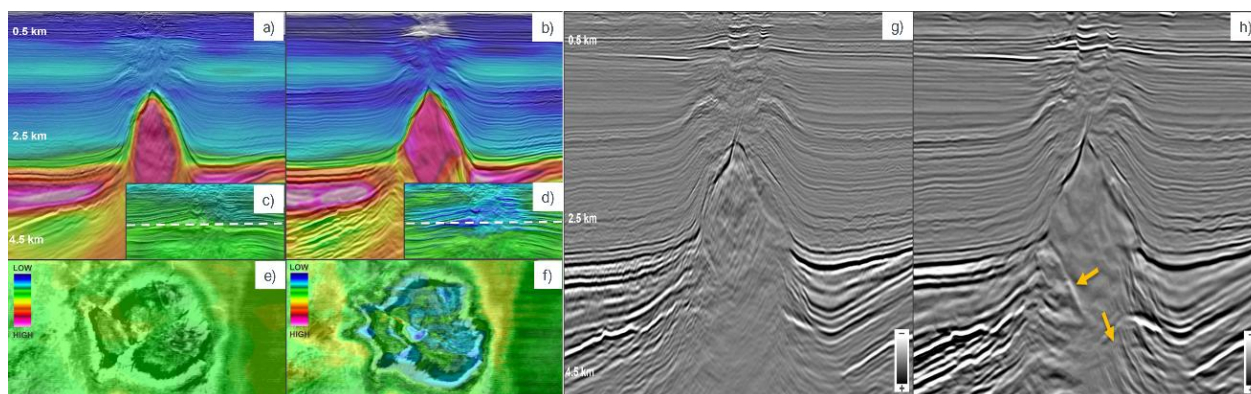

Figure 1 *Vintage velocity model and Kirchhoff PSDM image: full section a), shallow zoom c) and shallow depth slice e). The corresponding MP-FWI velocity results in b), d) and f), where the shallow velocity anomaly has been resolved, leading to the structural corrections of the potential gas-contact. 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.*

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.

Acknowledgements (Optional)

References

Chemingui, N., Y. Yang, J. Ramos-Martinez, G. Huang, D. Whitmore, S. Crawley, E. Klochikhina, and S. Arasanipalai. 2023. "Simultaneous inversion of velocity and angle-dependent reflectivity." SEG Technical Program Expanded Abstracts. Society of Exploration Geophysicists. 625-629.

Whitmore, N. D., J. Ramos-Martinez, Y. Yang, and A. A. Valenciano. 2020. "Seismic modeling with vector reflectivity." SEG Technical Program Expanded Abstracts. Society of Exploration Geophysicists. 2709-2713

Yang, Y., J. Ramos-Martinez, N. D. Whitmore, G. Huang, and N. Chemingui. 2021. "Simultaneous inversion of velocity and reflectivity." *SEG Technical Program Expanded Abstracts.* Society of Exploration Geophysicists. 577-581.