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Emancipating FWI imaging from traveltime tomography in Valhall via optimal transport joint full waveform inversion

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Main objectives In this work, we aim at a robust broadband velocity reconstruction in the Valhall field (North Sea), without relying on the commonly used traveltime-based starting model. We show that, by using a graph space optimal transport objective function, the imprint of cycle skipping is minimised when starting from a linearly increasing one-dimensional velocity model. This is combined with a pseudotime domain joint full waveform inversion of early arrivals and reflected waves, which is key to obtain velocity updates at depths larger than 2 Km within the subsurface target.

New aspects covered A novel velocity model building workflow is presented combining a graph space optimal transport objective function, the joint full waveform inversion of reflections, and refractions and a pseudotime reformulation of velocity inversion. This is applied for the first time to the Valhall field ocean-bottom-cable dataset, showcasing the potential of the proposed workflow in reducing the reliance of FWI imaging on accurate starting models based on traveltime tomography.

Summary (200 words) In the Valhall field ocean-bottom-cable (OBC) dataset, a wide literature have shown that FWI enriches an traveltime-based initial velocity model with geologically meaningful details, improving the imaging of shallow multi-layered low velocity zones and complex deep structures. The quality of traveltime prediction in the starting model makes it possible to use a least-square objective function without cycle skipping. However, building such a starting model requires time-consuming and subjective phase picking and labelling. In this work, we propose a robust velocity-model building workflow starting from a one-dimensional initial guess, which combines: joint diving and reflection FWI (JFWI), to obtain deep velocity updates while constraining the shallow portions of the model; a graph space optimal transport objective function to prevent cycle-skipping; a pseudotime reformulation of the JFWI gradient enforcing velocity-reflectivity consistency. Subject to minimal pre-processing, a satisfactory model reconstruction is achieved despite a very simple starting model, as demonstrated by ground-truth fit and data prediction. JFWI contributes significantly to reconstructing the model at depths larger than 2 Km, while GSOT attenuates the risk of cycle skipping compared to a least-square approach, on the road to a full emancipation of FWI from the use of accurate starting models based on traveltime tomography.

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Introduction

Full waveform inversion (FWI) has been applied over the last two decades with encouraging results on a number of exploration-scale seismic datasets. In the Valhall field ocean-bottom-cable (OBC) dataset, a wide literature shows that FWI enriches an accurate traveltime-based initial P-wave velocity (V_p) model with geologically meaningful details, improving the imaging of shallow multi-layered low velocity zones and complex deep structures (e.g. [Sirgue et al., 2010](#)). The quality of traveltime prediction in the tomographic starting model makes it possible to use a least-square (L^2) waveform objective function with limited or no cycle skipping ([Operto et al., 2015](#)). However, building such a model requires time-consuming and subjective phase picking and labelling prior to waveform inversion. Recently, [Pladys et al. \(2021a\)](#) have applied FWI starting from a one-dimensional model in which V_p and density (ρ) increase linearly with depth, while using weak anisotropy and Quality factor as passive parameters. They demonstrated that, in this case, L^2 norm inversion cycle skips regardless the data-weighting strategy used, while a graph-space optimal transport distance (GSOT, [Métivier et al., 2019](#)) allows FWI to achieve a reasonable model reconstruction. However, despite the long-offsets acquired by the ocean-bottom cables, FWI in Valhall below 1.5 Km depth is mostly driven by relatively narrow-angle reflections ([Prioux et al., 2011](#)), therefore failing to retrieve the model low-wavenumbers regardless the objective function used. Reflection-based FWI has the potential to provide tomographic V_p updates below the depth sampled by diving waves, by exploiting the contribution of deep-reaching wavepaths in a reflective starting model ([Brossier et al., 2015](#)). In this work, we propose a robust velocity-model building workflow starting from a one-dimensional initial guess, which combines the following ingredients: 1) joint diving and reflection FWI, as in [Zhou et al. \(2018\)](#), to obtain deep velocity updates while constraining the shallow portions of the model; 2) a GSOT objective function to ensure robustness against inaccurate starting model, as in [Pladys et al. \(2021a\)](#); 3) a pseudotime ([Plessix, 2013](#)) reformulation of the JFWI gradient ensuring velocity-reflectivity consistency.

Methodology

JFWI jointly inverts early arrivals and reflected waves to obtain tomographic V_p updates both in the shallow subsurface sampled by diving waves and the deeper parts covered by reflection wavepaths. This is combined with a velocity-impedance (V_p - I_p) parametrization enhancing the scale separation between low and high wavenumber components of the model. The objective function of JFWI is a weighted sum of early arrivals and reflections, and its sensitivity kernel contains both the the diving wave kernel of early-wave FWI and the two RWI contributions (rabbit ears, [Brossier et al., 2015](#)). In order to address the dependency of I_p on V_p , and therefore the velocity-depth ambiguity, we consider reformulating JFWI in the pseudotime domain, following [Plessix \(2013\)](#) and [Brossier et al. \(2015\)](#). In this domain, I_p is fixed in pseudotime rather than in depth, and the near-zero offset waveforms are therefore kept in phase, honoring the zero-offset seismic invariant. While the pseudotime approach minimises phase ambiguity at near-zero offsets, a graph-space OT ([Métivier et al., 2019](#)) objective function is used in order to reduce the liability to cycle-skipping at intermediate-to-long offsets. In GSOT, seismic traces are transformed from oscillatory signals into two-dimensional discrete distributions of unit-weight points in the time-amplitude graph-space. Positivity and conservation of mass (weights) between the target (observed) and initial (predicted) distribution are honored in the graph transform. Therefore, Optimal Transport in the graph space retains its convexity with respect to time shifts, as opposed to different OT-based objective functions for seismic waveforms ([Pladys et al., 2021b](#)). The GSOT-JFWI objective function in the pseudotime domain (indicated by the superscript t) reads:

$$\chi(V_p) = GSOT \left(W^e d_{cal} \left[V_p^t, I_{p,0}^t \right], W^e d_{obs} \right) + GSOT \left(W^r d_{cal} \left[V_p^t, I_p^t \right], W^r d_{obs} \right) \quad (1)$$

where: d_{obs} is the observed data and d_{cal} is the data calculated in the current model ([Zhou et al., 2018](#)); W^e and W^r are data weighting matrices selecting early arrivals and reflections respectively; $I_{p,0}^t$ and I_p^t are respectively the smooth and reflective impedance model. Note that, unlike in depth-domain formulations, I_p^t is independent of V_p^t in pseudotime.

Data overview, pre-processing and inversion design

The four-component (4C) ocean-bottom-cable (OBC) dataset was acquired in 2011 in the Valhall field, located in the Norwegian North Sea in a shallow water (70 m) environment. Three velocity vertical seismic profiling (VSP) logs are available to ground-truth the estimated V_p models, one proximal to the target area, the remaining two at the margin of the acquisition area. In our visco-acoustic anisotropic approximation, we use only the hydrophone component of the 4C system following minimal pre-processing. Reciprocity between sources and receivers is applied to reduce the computing cost, as the number of sources of the survey is 25 times larger than the number of receivers. Shots with anomalous root-mean-square (RMS) energy are identified and eliminated, reducing the number of sources from 2048 to 2044. Minimum-phase bandpass frequency filtering is applied to the data, along with Scholte waves muting. Time-domain 3D V_p inversion is performed on the data low-pass filtered below 5.5 Hz, starting from a visco-acoustic anisotropic model made up by a 1D V_p and ρ model linearly increasing with depth, smooth weak anisotropy parameters and constant quality factor in the subsurface. Data simulation in the starting 1D reflection free model is performed to design appropriate diving and reflection widows for JFWI (as per Eq. 1), to which we apply a taper zone of 0.5 seconds to allow for changes in travel-time during inversion minimising leakage of reflected energy in the diving window and vice-versa. For simplicity, a single window function is applied to all the shots. Random source subsampling with batch size equal to 128 is used. An average source wavelet is estimated with the frequency domain method by Pratt (1999). In order to minimise the impact of incorrect subsurface model on the estimated source signature, only the near offset, short time data are used for this task, as in Kamath et al. (2021).

JFWI-based velocity reconstruction

Velocity model building starts with I_p WI of the short offset reflections using an asymptotic preconditioner for near-true amplitude reflectivity reconstruction (Li and Chauris, 2018). One iteration is performed for each 128-shot random batch, for a total of 18 iterations to sample at least once each available shot gather. The asymptotic preconditioner approach makes it possible to obtain a fast and balanced reflectivity image, that is then used to provide JFWI with deep-reaching reflection wavepaths. JFWI is first run on offsets shorter than 5 Km for 18 steepest descent (ST) iterations with linear depth preconditioning, 1 iterations per batch. The offset window is then relaxed to include offsets up to 9 Km, and a second JFWI run is performed, with the same number of ST iterations. In the pseudotime domain, I_p is updated in depth during JFWI simultaneously with V_p , without requiring to re-run I_p WI to ensure consistency between kinematics and reflectivity at short offsets. After the two JFWI runs, V_p -FWI is run for 102 LBFGS iterations with wavefield preconditioning (Kamath et al., 2021) in the same frequency band, to inject higher spatial frequencies in the V_p model and obtain a broadband subsurface reconstruction. At this stage all available offsets are included in the inversion, density is re-set to its initial value and parametrisation is changed to V_p, ρ .

In Fig. 1 we compare results obtained by GSOT JFWI followed by FWI against FWI only starting from the 1D model, with the reference FWI V_p obtained starting from the tomographic initial model. The contribution of JFWI to FWI is apparent at depths larger than 1.5 Km, where the extent and value of the low velocity zone are closer to the reference model than the FWI only results, which are limited by the penetration depth of the diving waves. In Fig. 2, we compare vertical velocity logs with the ground-truth. The comparison suggests that L^2 -FWI is heavily cycle-skipped, as expected in this initial model (Pladys et al., 2021a), providing non-meaningful V_p reconstruction along with poor well-log prediction. GSOT JFWI followed by FWI, on the contrary, predicts the long-wavelengths trend of the logs, also outperforming the GSOT FWI-only results at depths larger than 2 Km thanks to the combined benefits of reflection-based inversion and graph-space optimal transport. A further quality check is performed on a control common shot gather (Fig. 3), demonstrating the improvement in data prediction in the JFWI+FWI model compared to the initial one; while FWI-only data have a similar data fit in diving waves and short two-way time reflections, it shows less accurate prediction of later seismic phases.

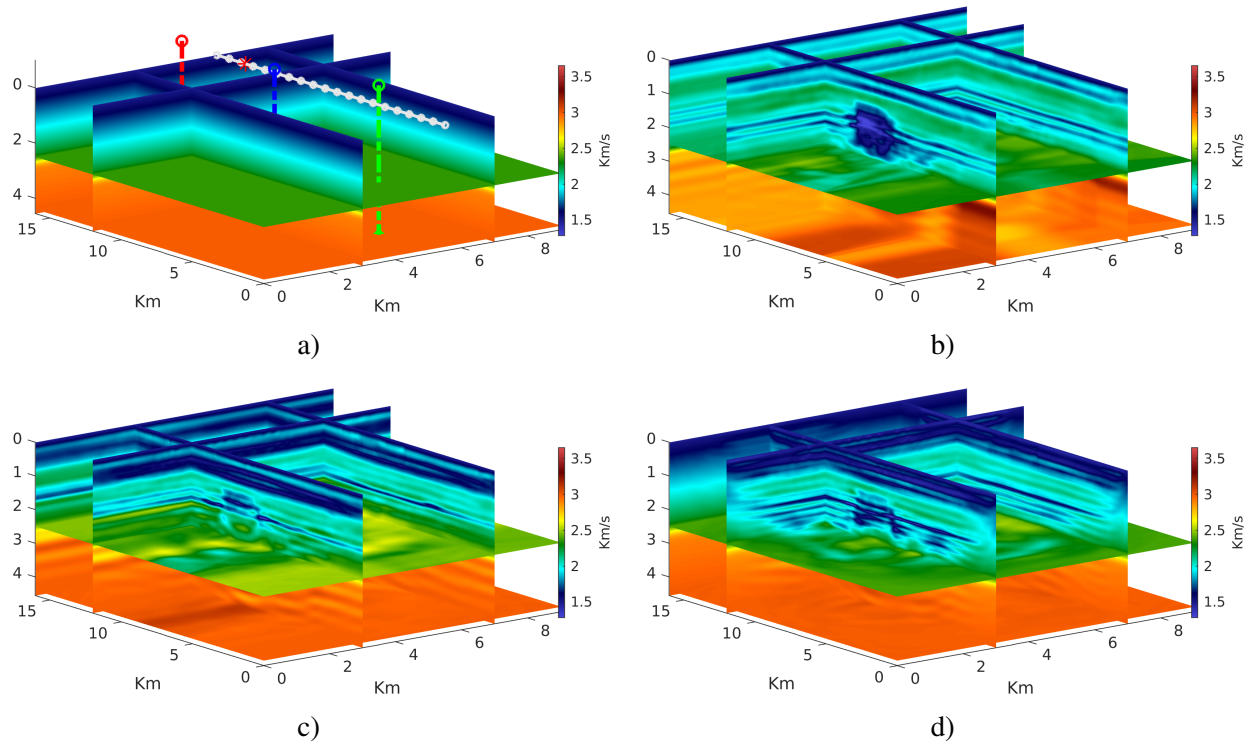


Figure 1 a) Initial V_p , well log positions and control common shot gather location (white receivers line, red shot position); b) GSOT FWI V_p from traveltime-based model; c) GSOT FWI V_p from a); d) GSOT JFWI + GSOT FWI V_p

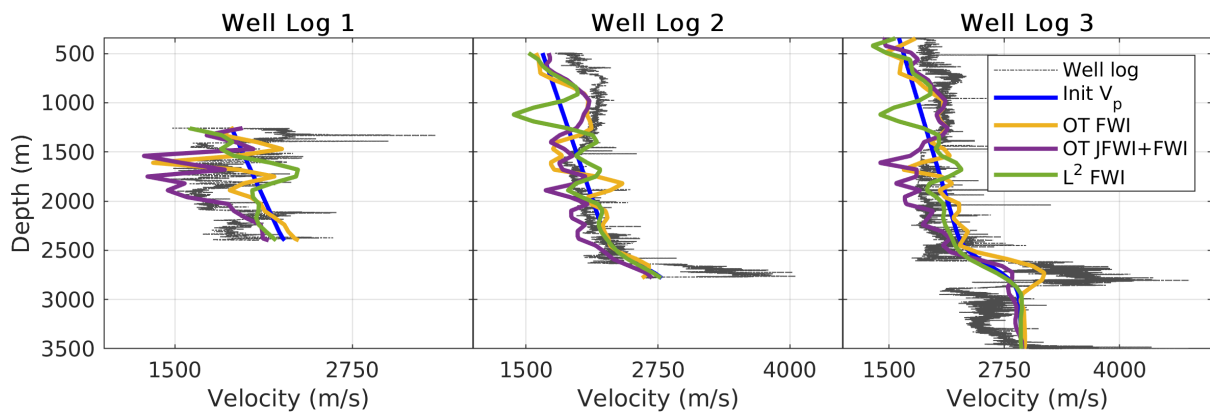


Figure 2 Well log prediction. Approximate logs positions are presented in Fig.1a as vertical lines

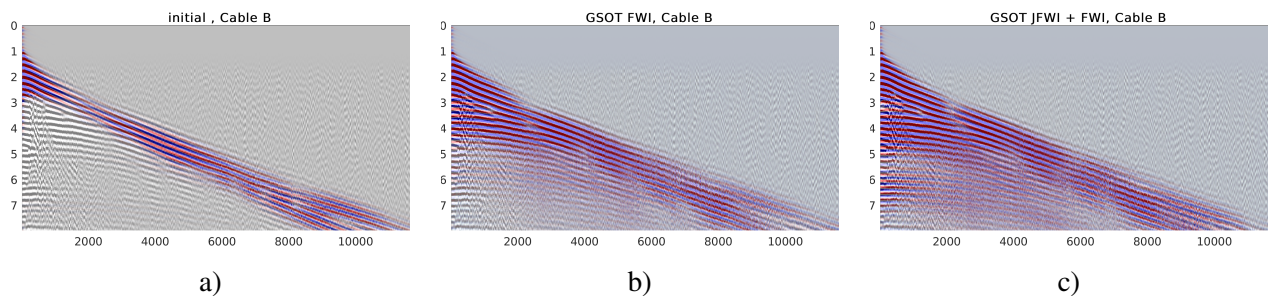


Figure 3 Data fit QC on common shot gather (white line in Fig.1c): a) Initial, b) GSOT FWI and c) GSOT JFWI + GSOT FWI models. Fit improves as black covers red.

Conclusions

In this case study, we have applied graph-space optimal transport joint inversion of diving and reflected waves in the Valhall field, on the road to a full emancipation of FWI from the use of accurate starting models requiring time-consuming and subjective tomographic approaches. After minimal pre-processing and a rather straightforward parameters choice, a satisfactory model reconstruction is achieved despite a very simple starting model, as demonstrated by ground-truth fit and data prediction. While GSOT FWI outperforms L^2 -based FWI thanks to an improved robustness to cycle-skipping, JFWI contributes significantly to reconstructing the model at depths larger than 2 Km. The cost of each JFWI gradient is comparable to the cost of a RWI gradient, and amounts to two times the cost of the FWI one. The computing cost of velocity model building is highly reduced by the choice of the pseudotime domain inversion, which minimises the need for reflectivity updates during V_p inversion, while ensuring $V_p - I_p$ consistency unlike depth-domain approaches.

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