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Comparison of time-lapse full waveform inversion strategies and nullspace shuttling: Sensitivity to reservoir monitoring scenarios

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Summary

Time-lapse full waveform inversion is a powerful approach for detecting subtle subsurface changes, but it is highly sensitive to non-repeatable acquisition, noise, and differences in inversion convergence. Conventional time-lapse strategies attempt to mitigate these issues, but they can introduce non-subsurface related time-lapse artifacts, especially when baseline and monitor surveys differ in source density. Nullspace shuttling reframes the problem by searching within the FWI nullspace for model adjustments that preserve the data misfit while minimizing the time-lapse difference. Using synthetic examples, we compare conventional time-lapse full waveform inversion strategies against time-lapse nullspace shuttling for several synthetic field-based reservoir monitoring scenarios to assess the applicability of these approaches and their sensitivity to time-lapse reservoir changes. Results show that while advanced time-lapse full waveform inversion methods reduce artifacts relative to simple approaches, nullspace shuttling most effectively isolates the true time-lapse anomaly, providing clearer recovery of anomalies and demonstrating robustness to sparse acquisition geometries. These findings highlight nullspace shuttling as a promising, computationally efficient alternative to multi-pass time-lapse full waveform inversion.

Introduction

Time-lapse seismic monitoring is an effective tool for characterizing time-variant subsurface changes. It is a standard method for geophysical surveillance of hydrocarbon reservoirs and enhanced oil recovery (Greaves and Fulp, 1987; Wang et al., 1998; Lumley, 2001). Conventional time-lapse FWI (TL-FWI) strategies can be broadly grouped into three classes: parallel-based, sequential-based, and simultaneous inversion (Mardan et al, 2023). Parallel- and sequential-based approaches can also be further defined as simple (i.e., single pass FWI) or advanced (i.e., multi-pass FWI). The objective of any TL-FWI is to estimate the true changes in subsurface parameters using models obtained from inversion. The challenges of FWI, notably noise and processing artifacts that contaminate the signal, are also present in TL-FWI. In addition, the non-repeatability between baseline and monitoring surveys introduces noise, which impedes the identification of weak (i.e., low magnitude) time-lapse changes (Zhou and Lumley, 2020; Fu and Innanen, 2023). TL-FWI strategies have evolved to mitigate noise related to non-repeatability and processing artifacts.

Time-lapse targeted nullspace shuttling, (Keating and Innanen, 2024; Pike et al., 2024), is a post-FWI optimization process in which equally viable parameter models that meet the same FWI data misfit are explored via a secondary optimization. It is an alternative approach to conventional parallel or sequential based TL-FWI to isolate reservoir related time-lapse changes in the

subsurface and has shown promise in its ability to reduce time-lapse artifacts and noise (Keating and Innanen, 2024).

Here we compare several parallel and sequential based TL-FWI strategies with time-lapse nullspace shuttling for multiple synthetic models. Workflow diagrams for the TL-FWI and nullspace shuttling approaches evaluated are shown in Figure 1.

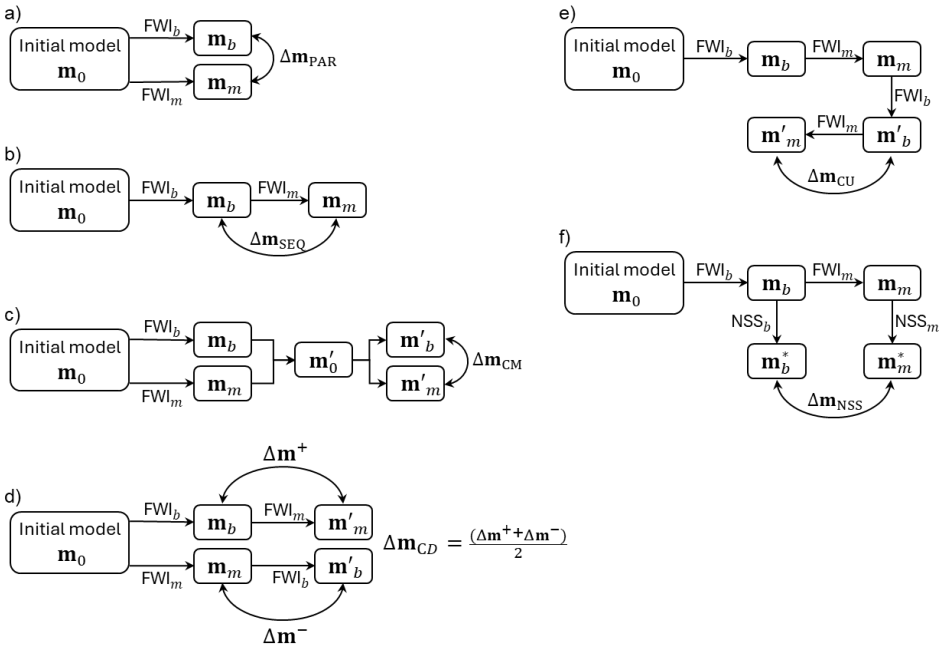


Figure 1. Workflow diagrams of common TL-FWI approaches. An initial model $\boldsymbol{m}_0$ is used to obtain baseline and monitor FWI models $\boldsymbol{m}_b$ and $\boldsymbol{m}_m$. Secondary models, required in advanced time-lapse strategies, are denoted by $\boldsymbol{m}'$, nullspace shuttled models are denoted by $\boldsymbol{m}^*$. Time-lapse differences are using a) parallel $\Delta\boldsymbol{m}_{PAR}$, b) sequential $\Delta\boldsymbol{m}_{SEQ}$, c) common model $\Delta\boldsymbol{m}_{CM}$, d) central-difference $\Delta\boldsymbol{m}_{CD}$, e) cross-updating $\Delta\boldsymbol{m}_{CU}$, and f) nullspace shuttling $\Delta\boldsymbol{m}_{NSS}$ strategies are constructed using baseline and monitor FWI models. Adapted from Mardan et al. (2023).

Bulk elastic properties of a reservoir will be affected by changes in fluid type, saturation, and pore pressure. The associated change in Vp may vary significantly depending on reservoir conditions, which may impact the ability to detect time-lapse reservoir changes using FWI. For example, Macquet et al. (2019) found that changes in Vp ranged from -7.5% to -32.5% in the Basal Belly River Formation, depending on whether only pore pressure, or pore pressure and fluid saturation varied due to CO_2 injection. Here we also assess the sensitivity of nullspace shuttling approaches when the velocity change is small (i.e., only due to changes in pore pressure) and large (i.e., due to changes in both pore pressure and fluid saturation) using velocity values obtained through geophysical and reservoir modeling.

Examples

We use numerical examples, using VSP acquisition geometries, to compare multiple acoustic TL-FWI and nullspace shuttling approaches for multiple reservoir scenarios and assess their sensitivity to time-lapse magnitude and size. We compare three advanced TL-FWI approaches with nullspace shuttling for repeated and non-repeated monitor geometries.

The time-lapse differences and nullspace shuttled differences for repeated baseline and monitor geometries are shown in Figure 2. The time-lapse anomaly can be clearly identified, regardless of approach, however the nullspace shuttled example demonstrates a significant reduction in noise. The time-lapse differences and nullspace shuttled differences for non-repeated baseline and monitor geometries are shown in Figure 3. In this example the effectiveness of time-lapse nullspace shuttling versus conventional TL-FWI methods is better demonstrated.

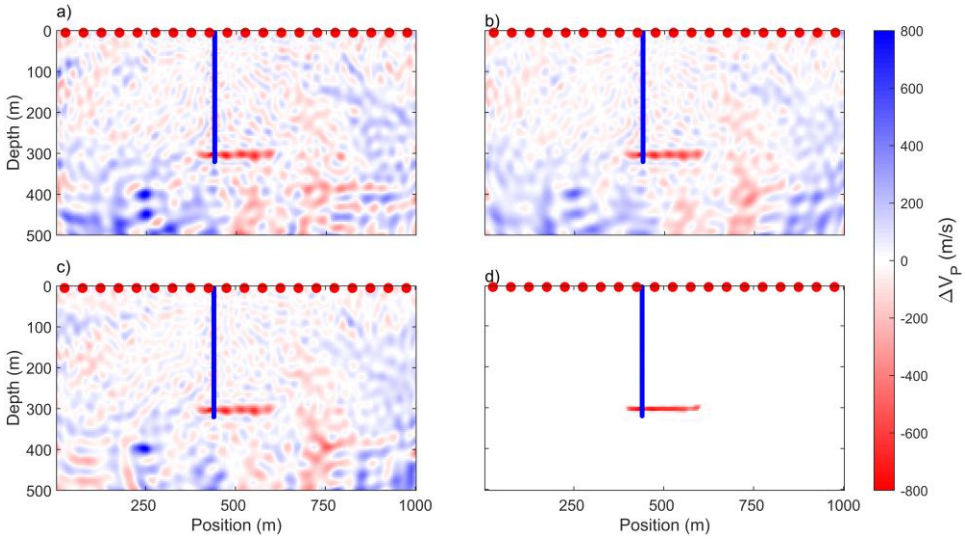


Figure 2. Time-lapse difference models for a repeated baseline and monitor acquisition geometry using a) common-model TL-FWI, b) central-difference TL-FWI, c) cross-updating TL-FWI, and d) time-lapse nullspace shuttling.

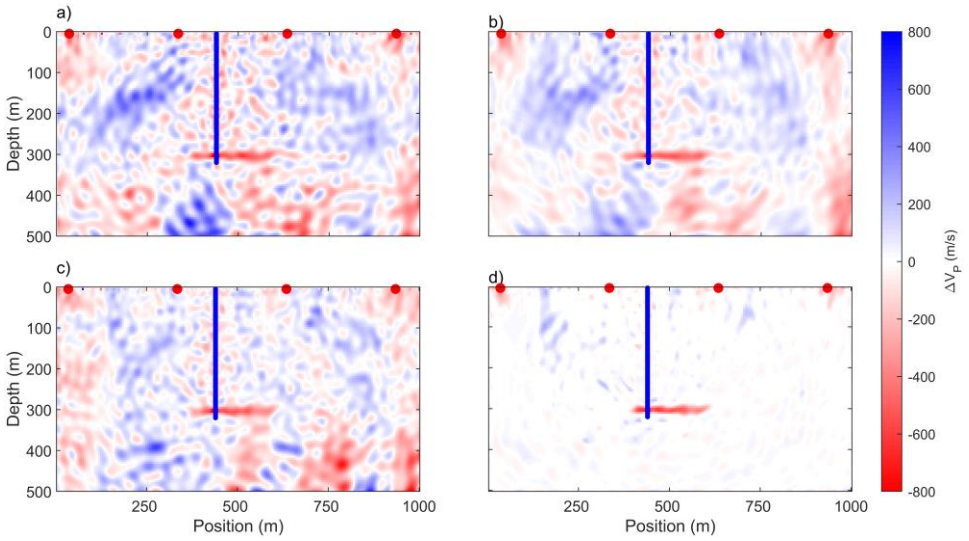


Figure 3. Time-lapse difference models for a dense baseline and sparse monitor acquisition geometry using a) common-model TL-FWI, b) central-difference TL-FWI, c) cross-updating TL-FWI, and d) time-lapse nullspace shuttling.

To test the sensitivity of TL-FWI and nullspace shuttling to time-lapse magnitude we consider scenarios with large (-32.5%) and small (-7.5%) changes in Vp. The time-lapse nullspace shuttled results for these velocity contrasts using repeated and non-repeated monitoring geometries are shown in Figure 4. The sensitivity limits of time-lapse nullspace shuttling are clearly demonstrated in this example. The boundaries of the time-lapse anomaly cannot be distinguished from the background noise when the velocity contrast is low, and the monitor acquisition geometry is sparse.

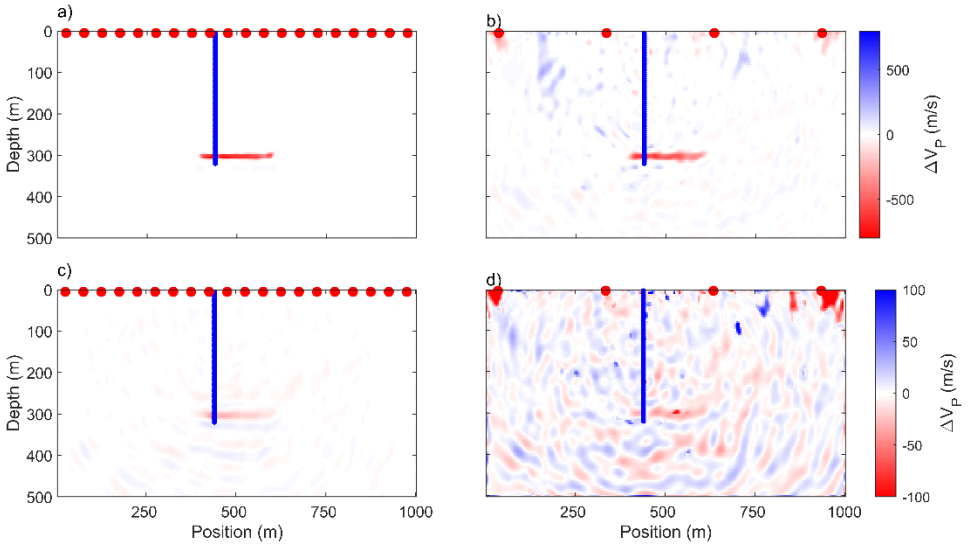


Figure 4. Time-lapse nullspace shuttled differences for a -32.5% velocity change with a) repeated baseline and monitor acquisition geometries and b) dense baseline and sparse monitor geometries. Time-lapse nullspace shuttled

differences for a -7.5% velocity change with c) repeated baseline and monitor acquisition geometries and d) dense baseline and sparse monitor geometries.

Conclusions

Time-lapse nullspace shuttling is an effective tool to isolate reservoir related time-lapse changes in comparison to conventional time-lapse full waveform inversion strategies. It is less susceptible to non-repeatability in acquisition geometries and more effectively reduces time-lapse noise. It is effective in isolating genuine time-lapse perturbations when the associated velocity changes are of sufficiently large magnitude regardless of whether repeated or sparse acquisition geometries are employed. Conversely, when the velocity change is small, reliably distinguishing the true time-lapse signal from background noise becomes increasingly difficult. This challenge is further exacerbated by increased acquisition sparsity.

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