

Joint 4D Amplitude and Time-Shift Inversion for Enhanced Time-shift Estimation in Snorre Field

Introduction

The conventional workflow for inverting time-shifts and amplitudes to velocity or impedance changes follows a well-established sequence: estimation of time shifts between baseline and monitor surveys, application of these time shifts to align the monitor survey with the baseline, and subsequent computation of aligned 4D amplitudes by subtraction. Time-shift and 4D seismic amplitude attributes can be further inverted to time strain and impedance changes, respectively (MacBeth, et al., 2019). Although nonlinear inversion (NLI) represents one of the most robust methods for time-shift estimation, it remains susceptible to systematic errors that propagate through the inversion chain and compromise interpretational value (Ji, et al., 2021; Duan, et al., 2020). Primary error sources include wavelet interference, particularly problematic in thin-layer or stacked reservoir sequences, uncertainty arising from petro-elastic model (PEM) coupling, and amplitude-kinematic coupling that produces correlated errors hindering the separation of velocity and impedance changes.

Despite extensive documentation of these challenges in the 4D seismic inversion literature, a unified approach addressing them collectively remains elusive. This study builds upon the iterative joint inversion methodology of Williamson (2007) and the workflow of Zhan (2017), introducing modifications tailored to incorporate the coupling coefficient between the amplitude and kinematic. The workflow is tested on a real field dataset from the Snorre field, characterised by stacked thin-bed reservoirs. The chosen section of the reservoir undergoes water-alternating-gas (WAG) injection, and production, presenting a classic monitoring scenario where conventional time-shift estimation methods, limited by nonlinear amplitude responses, tuning artefacts, and side-lobe contamination, require more robust approaches to resolve pressure and fluid movements, particularly in the presence of geomechanically active overburden.

Method

The developed workflow incorporates a PEM-calibrated coefficient and follows an adapted cost function from Williamson (2007), employing the Zhan (2017) iterative alignment scheme based on time shifts derived from proposed velocity changes. The cost function for joint amplitude and time-shift (JAT) inversion is expressed as:

$$E = \|G * \alpha \Delta v/v - D'_{obs}\|_2^2 + \lambda \|S_1 * \Delta v/v\| \quad (1)$$

Where G is linear forward operator, α is well-log calibrated PEM coefficient, $\Delta v/v$ is the velocity changes, D'_{obs} is time-shift aligned 4D seismic amplitude, S_1 denotes the first-order Tikhonov regularization operator for smoothing, and λ represents the regularization weight. Well-log-calibrated PEM values (α) ensure geological consistency, enabling differentiation between overburden and reservoir zones and enhancing the reliability of inverted properties. In the general case, α may be defined as a volume of equivalent dimensions to the seismic cube. Velocity changes derived from the inversion are iteratively converted to time shifts that update the 4D seismic amplitude (D'_{obs}); consequently, both terms in the cost function evolve iteratively.

The JAT workflow was applied to a seismic section from the Snorre field using two distinct approaches, with results displayed in Figure 1. First, JAT inversion was performed on reservoir boundaries only, assuming that NLI-derived time shifts are correct in the overburden. The monitor survey was aligned using these overburden time shifts prior to JAT application. Second, full-seismic-trace inversion was performed with R-factors (values of 5, 10, and 15) assigned to the overburden to integrate geomechanical information. Figure 1 presents estimated time shifts, velocity changes, and impedance

changes. The match between forward-modelled velocity changes (using PEM) and final aligned 4D seismic amplitudes (D'_{obs}), together with the amplitude residual, is also displayed.

Results

The JAT workflow was applied to a seismic section from the Snorre field (Figure 1), where the left flank undergoes WAG injection and the right flank is subject to production. The top row of the figure presents NLI results (first column), JAT results for reservoir-only inversion (second column), and full-trace JAT results using R-factors of 5, 10, and 15 (third to fifth columns, respectively). NLI-derived time shifts exhibit smearing but show reasonable agreement with JAT in the overburden. Within the reservoir, however, significant qualitative and quantitative discrepancies emerge. On the right flank, the hardening signal indicated by NLI is positioned approximately 20 milliseconds later in time than that from JAT, a substantial difference that translates into a significant vertical displacement of the event and carries considerable implications for quantitative interpretation. On the left flank and central portion, NLI suggests hardening while JAT indicates a softening signal.

Comparison of velocity change results, which localise reservoir changes, demonstrates consistency across all JAT scenarios. JAT results for different R-factors are virtually identical within the reservoir, as expected, while overburden events exhibit slightly different magnitudes reflecting the influence of the chosen R-factor values. An analysis reveals several key observations. A hardening signal attributable to compaction on the right side of the section within the overburden is absent from NLI results. Furthermore, NLI suggests hardening in the central reservoir, whereas JAT indicates a softening signal, a finding consistent with the pore-collapse interpretation established by Corte et al. (2025). The softening signal associated with WAG-induced gas injection on the left flank is clearly resolved by JAT; by contrast, NLI places this signal at a different lateral position and exhibits an unrealistic, disconnected gas plume inconsistent with the known injection history. The water injection hardening signal on the left flank is well resolved by JAT at the reservoir base, consistent with the higher density of water, while NLI shows no significant corresponding signal. Finally, NLI exhibits a hardening signal at the top left of the reservoir for which JAT finds no corresponding evidence.

JAT-inverted velocity changes honour both amplitude and time-shift information, ensuring physical consistency between reflectivity changes and time-shift data. Moreover, the PEM coefficient α defines the relationship between velocity and impedance changes, whereas conventional workflows treat these parameters independently. The fourth to sixth columns of Figure 1 display amplitude comparisons between synthetic forward-modelled 4D seismic ($G * \alpha \Delta v/v$), time-shift-aligned 4D seismic amplitudes (D'_{obs}), and the corresponding amplitude residuals. For all JAT approaches, synthetic and observed amplitudes show excellent agreement, with residuals remaining below noise level, indicating no significant unmodelled signal. In contrast, NLI exhibits a poor match between forward-modelled velocity changes ($G * \alpha \Delta v/v$) and time-shift-aligned amplitudes (D'_{obs}), with residuals substantially elevated. The NLI method thus produces spurious time-shift artefacts and non-physical signals within both overburden and underburden, with estimated velocity changes failing to capture meaningful water injection responses and amplitude residuals approaching the magnitude of the observed 4D signal. Following additional testing and rigorous cross-disciplinary validation, these inversion-derived attributes may constitute valuable additions to 4D interpretation workflows.

Conclusions

This study evaluated the effectiveness of a JAT inversion workflow for improving the reliability and physical consistency of 4D seismic interpretation in geomechanically active reservoirs. The proposed joint inversion framework integrates amplitude and time-shift information within an iterative scheme, addressing a limitation of conventional NLI methods, their susceptibility to spurious time-shift artefacts

and non-physical velocity estimates. By explicitly coupling amplitude and time-shift data through the PEM coefficient, the JAT workflow enforces a physically meaningful relationship between velocity and

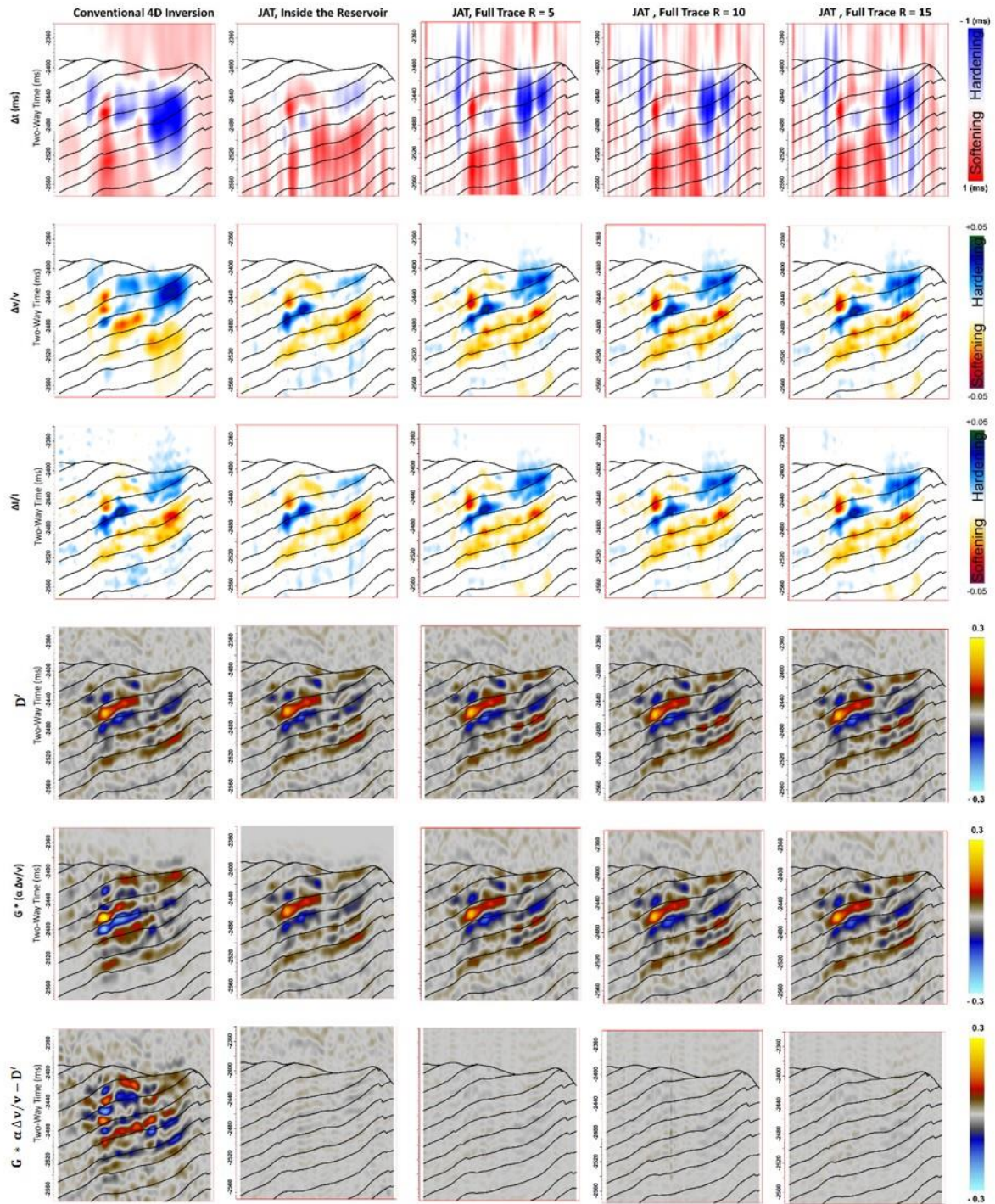


Figure 1. Comparison of Conventional and JAT inversion results for a seismic section from the Snorre field. Columns from left to right: Conventional 4D inversion, JAT applied only within reservoir boundaries, and full-trace JAT with R-factors of 5, 10, and 15, respectively. Rows display (top to bottom) estimated time shifts, velocity changes ($\Delta v/v$), impedance changes ($\Delta I/I$), time-shift-aligned 4D seismic amplitudes (D'_{obs}), synthetic forward-modelled 4D seismic ($G * \alpha \Delta v/v$), and amplitude residuals. JAT consistently resolves physically plausible hardening and softening signals associated with compaction, WAG injection, and production, whereas NLI produces spurious artefacts, unrealistic

gas plume geometries, and elevated residuals. The amplitude match and sub-noise residuals for JAT confirm its accuracy and physical consistency.

reflectivity changes. This coupling ensures that both amplitude and time-shift attributes are jointly honoured during inversion, producing more stable and geologically consistent estimates of reservoir property variations. Application to seismic data from the Snorre field demonstrated that JAT appears to capture localised hardening and softening responses that may be less clearly resolved in conventional workflow, though further validation is required.

In this example, the JAT approach produced amplitude matches and residuals that compare favourably with those from the conventional workflow, suggesting potential benefits for certain applications. The resulting velocity changes and time-shift estimates showed reasonable consistency with expected reservoir physics, including compaction-induced hardening, WAG-related softening, and hardening signals, acknowledging that alternative solutions may also satisfy the observed data. These results suggest potential for reducing spurious signals in the overburden and underburden, which may enhance interpretational confidence in complex, multi-layered, or stacked thin reservoir systems. With appropriate calibration and validation, the JAT workflow can offer complementary insights to existing 4D seismic inversion methods, particularly in settings where conventional time-shift estimation faces known limitations. By integrating amplitude and time-shift domains through a calibrated PEM relationship, this method offers a framework for characterising production- and injection-induced subsurface changes, thereby supporting reservoir monitoring and management decisions.

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