

Time-shift assimilation methods and their impact on pressure-saturation inversion

Introduction

The estimation of reservoir pressure and saturation changes from 4D seismic data faces many challenges commonly addressed by research studies, such as petro-elastic model uncertainty and the ambiguity between the pressure and saturation signals. Côte and MacBeth (2026) provide a study focusing on a less commonly addressed challenge, the vertical ambiguity between genuine 4D anomalies and their sidelobes and the vertical interference between genuine vertically stacked 4D anomalies. They show the benefit of joint time-shift assimilation in helping to resolve those ambiguities.

A central question in the joint inversion of 4D amplitudes and time-shifts is how the synthetic time-shift is modelled within the inversion. On the data side, time-shifts are measured by wiggle-alignment of the monitor to the baseline. Various wiggle-alignment methods can be used, all containing their associated errors and artefacts (MacBeth et al., 2020). Within the 4D inversion, the synthetic time-shifts can be computed in several different ways, which do not necessarily represent the same information as the measured wiggle-alignment time-shifts. Inconsistencies between how the data and synthetic time-shifts are computed can force the algorithm to explain measurement artefacts as genuine property changes.

The objective of this study is to evaluate alternative methods for assimilating time-shift information in pressure-saturation ($\Delta P/\Delta S$) inversion, focusing specifically on how the synthetic time-shift is modelled within the inversion. Four methods are compared on real 4D seismic data from the Catcher field, Central North Sea (Gibson et al., 2020).

Method and Theory

The inversion is a direct, trace-based inversion of the 4D amplitude-difference angle stacks to changes in pressure and saturation. It uses a petro-elastic model calibrated to well-log and core stress-sensitivity data, together with a porosity volume estimated beforehand from a petro-elastic inversion of the baseline seismic. The optimisation is a Levenberg-Marquardt non-linear least-squares scheme. The Catcher reservoir is a thin (10–60 ft) high-porosity, low-shale injectite sandstone, produced by water injection with intermittent reinjection of produced gas. As in Côte et al. (2023), reservoir pressure is held constant because pressure change is minimal in this reservoir, so the inversions shown here update water and gas saturation changes, which keeps the focus on the vertical ambiguities of trace-based inversion.

A key motivation for improving the synthetic time-shift model is that the measured wiggle-alignment time-shifts themselves carry significant uncertainty: their magnitude depends on the parametrisation (e.g. smoothing weights, window lengths). The inversion must therefore account for how the time-shifts are generated rather than treating them as an exact measurement. We test four methods that differ in how the synthetic time-shift is computed and to which measured quantity it is compared (Figure 1).

1. **JAT:** The measured kinematic information is obtained from a joint amplitude-time-shift (JAT) inversion (Raeisdana, 2026) that estimates $\Delta V_p/V_p$ directly by matching the 4D amplitudes, rather than by wiggle alignment. The synthetic $\Delta V_p/V_p$ from the $\Delta P/\Delta S$ inversion is compared directly to this measured $\Delta V_p/V_p$. This removes most wiggle-alignment artefacts and gives a like-for-like comparison in the $\Delta V_p/V_p$ domain.
2. **Theoretical time-shifts:** The synthetic time-shift is computed by vertical integration of the slowness computed from the synthetic $\Delta V_p/V_p$.
3. **NLI 2D:** The NLI (MacBeth et al., 2020) workflow applied to the data is embedded in the synthetic time-shift computation: within the inversion the synthetic monitor is shifted using the synthetic $\Delta V_p/V_p$ and then realigned to the synthetic baseline with NLI, using the same parametrisation as the data. Synthetic and observed time-shifts are then computed identically,

so the artefacts present in the data time-shifts are reproduced in the synthetic time-shifts so the comparison is fair.

4. **Non-warped:** The kinematic information is present in the non-warped monitor and the non-warped 4D differences. So it is possible to retrieve this information by proper modelling of the kinematic effect into the synthetic seismic. This method uses the synthetic $\Delta V_p/V_p$ to shift the synthetic monitor, then compares this directly to the non-warped monitor seismic data. This allows the assimilation of time-shift information without ever computing a time-shift or performing wiggle-alignment. No prior time-shift measurement and no time-shift computation within the inversion are required, making this the fastest workflow.

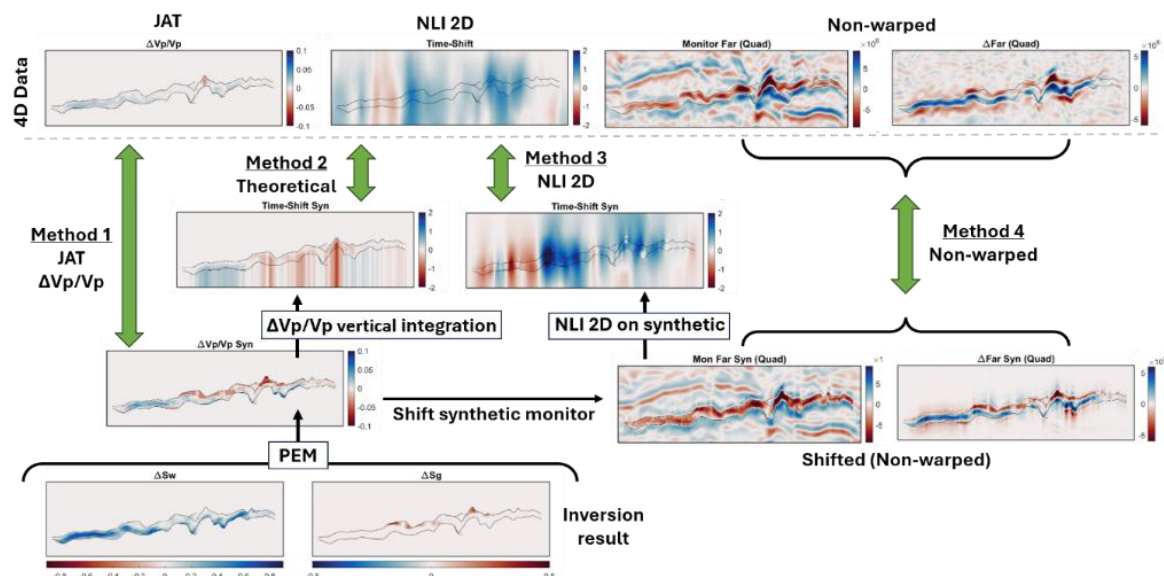


Figure 1 The four time-shift assimilation methods. They differ in how the synthetic time-shift is modelled within the ΔP_{AS} inversion and to which measured quantity it is compared: JAT $\Delta V_p/V_p$ (Method 1), vertically-integrated theoretical time-shift (Method 2), synthetic NLI time-shift (Method 3) and the non-warped monitor and 4D differences (Method 4).

Examples

Figures 2–4 compare the four methods directly. Figure 2 shows that all four methods match the observed 4D amplitudes equally well, leaving weak, noise-like residuals (far-angle stack shown but inversion assimilates near and mid stacks too). The methods differ in how well they reproduce the observed time-shifts (Figure 3) and, consequently, on how well the kinematic information is assimilated. Figure 4 shows the inversion results for all four methods.

The theoretical time-shift method (1) matches the amplitudes but leaves by far the largest time-shift residuals (Figure 3). In the wiggle-alignment time-shifts, the reservoir $\Delta V_p/V_p$ is smeared upward into the overburden. This is not a geomechanical effect as this reservoir goes through very small pressure changes. The time-shifts in the overburden are an artefact of the wiggle-alignment paradigm. The vertical-integration model (Method 1), however, treats the time-shift as a local property and predicts no overburden time-shift. To reconcile the mismatch, the inversion introduces spurious property changes in the overburden – visible in this example as the ΔS_g anomalies above the reservoir in Figure 4 – leaking measurement artefacts into the inversion result. Embedding the NLI computation into the synthetic time-shift (Method 3) reproduces this smearing within the inversion, greatly reducing the time-shift residuals (Figure 3) and removing the spurious overburden anomalies (Figure 4).

The non-warped method matches the non-warped monitor and 4D differences directly, with no time-shift term in the objective function. The synthetic time-shifts shown in Figure 3 are computed only after the inversion by NLI applied on the final inversion synthetic amplitudes, yet they match the

observations well. The kinematic information is present in the non-warped data and is retrieved correctly by modelling the shifting effect of $\Delta V_p/V_p$ within the inversion. The resulting saturation changes (Figure 4) are similar to method 2, but this method is considerably quicker, requires no previous time-shift computation and requires less calibration effort as no time-shift weights are used in the objective function.

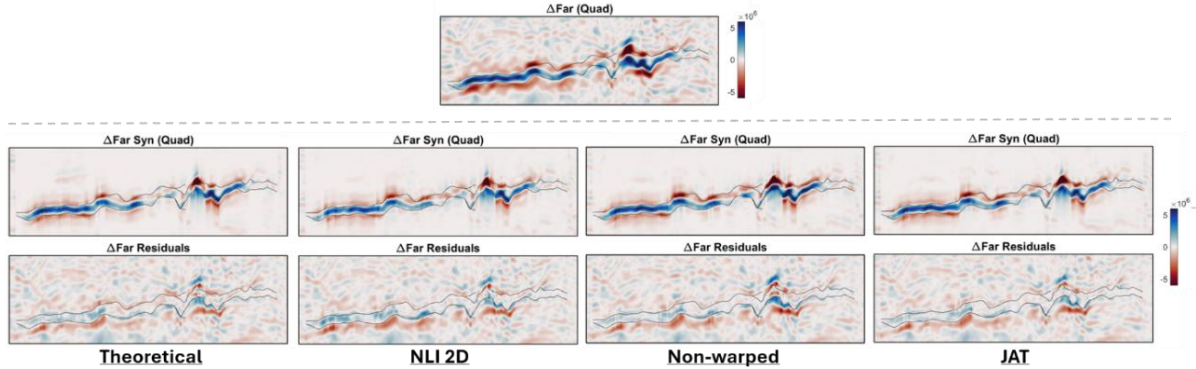


Figure 2 Observed and synthetic 4D amplitudes (far-angle stack) for the four methods (columns), with rows showing the data (top), the synthetic (middle) and the residual (bottom). All four methods match the 4D amplitudes equally well, leaving small, noise-like residuals.

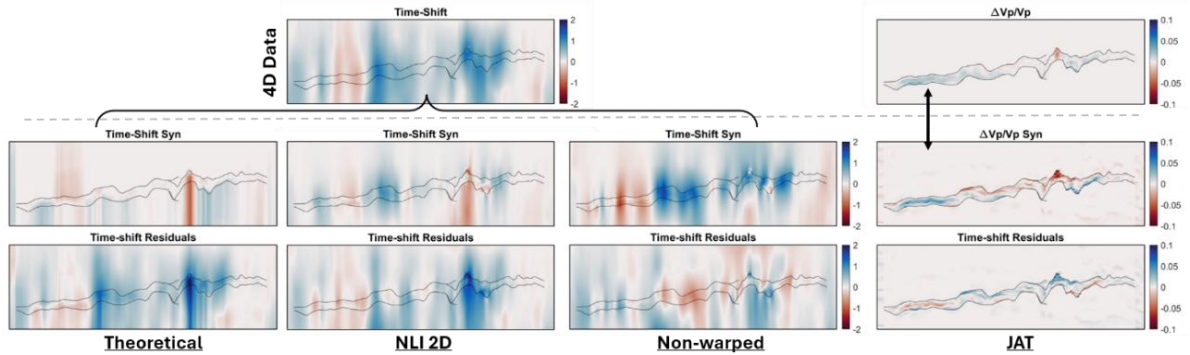


Figure 3 Observed and modelled time-shifts for the four assimilation methods (columns). From top to bottom: the time-shift data, the synthetic time-shift modelled within the inversion, and the residual (data minus synthetic). For the JAT method (right column) the comparison is made in the $\Delta V_p/V_p$ domain rather than as a time-shift. The theoretical method leaves the largest residuals, whereas the NLI 2D, non-warped and JAT methods match the data well.

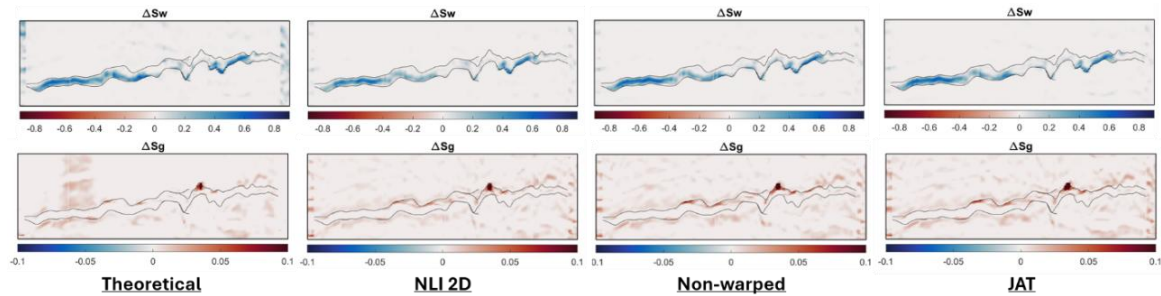


Figure 4 Inverted water- and gas-saturation changes (ΔS_w , top; ΔS_g , bottom) for the four methods (columns). The theoretical method leaks spurious gas-saturation changes into the overburden, whereas the NLI 2D, non-warped and JAT methods produce clean results.

The JAT method uses the JAT $\Delta V_p/V_p$ as the kinematic data and is compared in the $\Delta V_p/V_p$ domain (right column of Figure 3). Because JAT estimates $\Delta V_p/V_p$ by amplitude matching without wiggle alignment, it is largely free of NLI artefacts and gives saturation results very similar to the non-warped

method (Figure 4). This method runs faster within the $\Delta P\Delta S$ inversion, as no shifting or realignment is needed, but it requires a prior, time-consuming JAT inversion process. JAT inversion also considers a linear PEM, which is a simplistic approximation. Method 3 incorporates the JAT time-shift computation workflow and extends it to a non-linear petro-elastic model.

Conclusions

We compared four methods for assimilating time-shift information in 4D $\Delta P\Delta S$ inversion, differing in how the synthetic time-shift is modelled (Table 1). All four match the 4D amplitudes equally well, but they differ in their time-shift match and in the saturation changes they produce. Using theoretical, vertically-integrated time-shifts is not recommended: the inconsistency between methods for computing data and synthetic time-shifts leads to leakage of artefacts into the inversion. The preferred method is the non-warped approach, which incorporates the synthetic modelling of the kinematic effect directly into the $\Delta P\Delta S$ inversion, achieving proper assimilation of the time-shift information at low computational cost and without any explicit time-shift computation. The JAT method gives very similar results and is a good alternative, at the cost of a prior JAT inversion. Modelling the wiggle-alignment time-shifts within the inversion (NLI 2D) also assimilates the kinematic information correctly, but it is the more expensive $\Delta P\Delta S$ workflow and may require additional calibration of weights, NLI parameters and wavelet amplitude.

Methods	Real data time-shift computation ?	Forward shift synthetic monitor ?	Synthetic NLI time-shift computation ?	Consistency in synthetic vs real comparison ?
Theoretical time-shifts	Yes - NLI 2D (time consuming)	No	No	No
NLI	Yes - NLI 2D (time consuming)	Yes (time consuming)	Yes (time consuming)	Yes
JAT	Yes - JAT (very time consuming)	No	No	Yes
Non-warped monitor	No	Yes (time consuming)	No	Yes

Table 1 - Summary of the four methods and their requirements: whether a measured (real-data) time-shift computation is needed, whether the synthetic monitor is forward-shifted, whether an NLI computation is run within the inversion, and whether the method yields a consistent synthetic-versus-real comparison.

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