3D elastic time-lapse full waveform inversion using multi-component seismic data

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Introduction

- As a result of the increase in computational power the recent years, we now can leave the acoustic assumption behind, and instead use the elastic wave equations to model wave propagation in a medium.
- Multi-parameter elastic full waveform inversion is complicated both from a theoretical and computational point of view.
- Time-lapse seismic data contains information about changes in the subsurface, and has proven to be an effective tool in reservoir imaging and for monitoring of injected CO_2 in the subsurface.
- 3D FWI is computer intensive and still a challenge on large scale models.
- We study a full 3D isotropic time-lapse elastic FWI implementation using multi-component data.

Full waveform inversion

Goal: *Find a parameter model from which it is possible to create synthetic data that is close to some measured data*

Define $\Psi(\mathbf{m})$ as the measure between synthetic and measured data. The least-squares objective functional is given as

$$\Psi(\mathbf{m}) = \frac{1}{2}\sum_{(s,r)\in\mathbf{S}} \left\| \mathbf{u}(\mathbf{m};\mathbf{x},t) - \mathbf{d}(\mathbf{x},t) \right\|^2.$$

FWI is then the problem

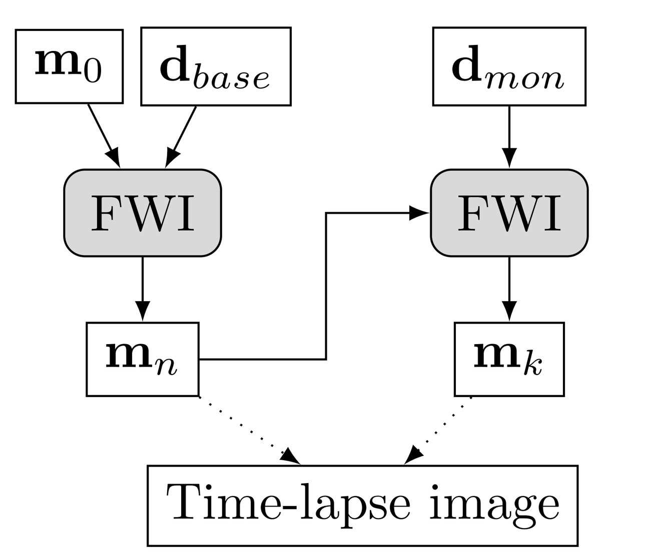
$$\arg\min_{\mathbf{m}} \Psi(\mathbf{m}).$$

Solved using an iterative method

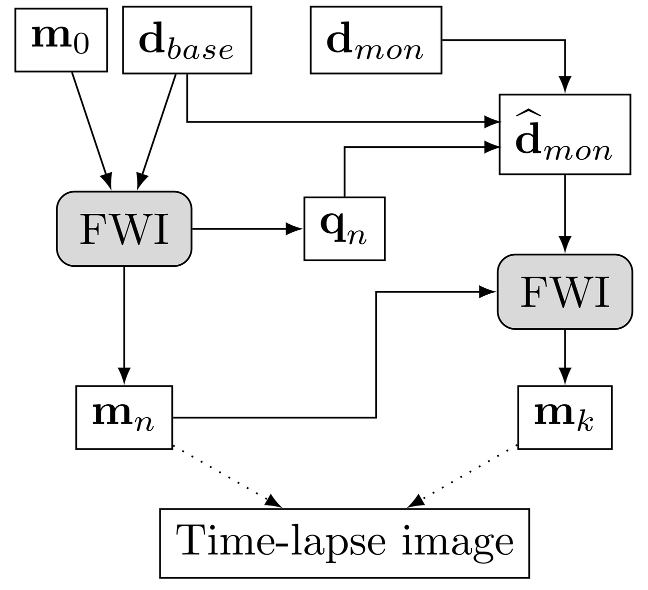
$$\mathbf{m}_{k+1} = \mathbf{m}_k - \alpha_k \mathbf{H}_k^{-1}\mathbf{g}_k,$$

where $\mathbf{m}_k$ is the model at iteration k, $\mathbf{g}_k$ is the gradient of $S(\mathbf{m})$ at iteration k, $\mathbf{H}_k$ is the Hessian of $S(\mathbf{m})$ at iteration k, and α_k is the step length at iteration k.

Time-lapse full waveform inversion



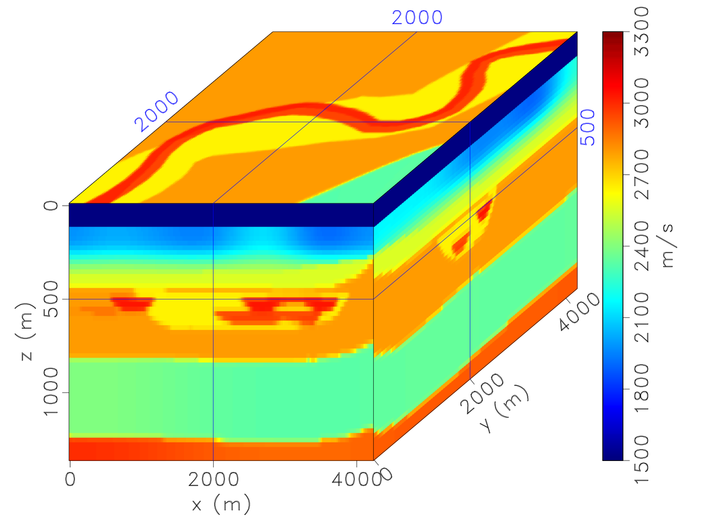
Sequential strategy



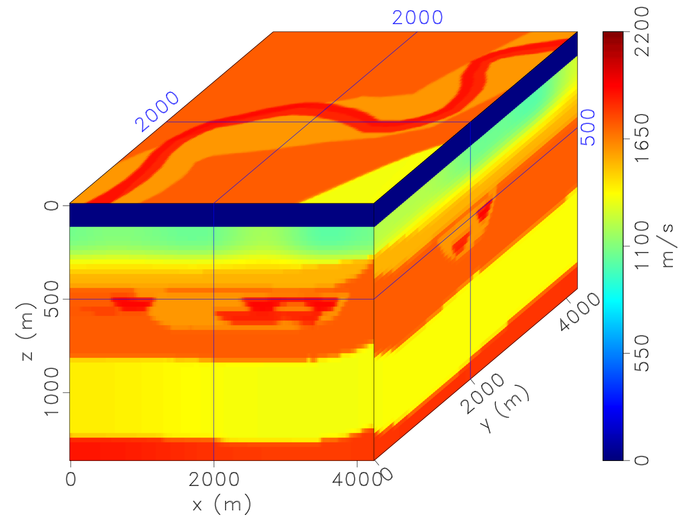
Data-difference strategy

Here, $\widehat{\mathbf{d}} = \mathbf{q}_n + (\mathbf{d}_{mon} - \mathbf{d}_{base})$ is the "new" monitor data set.

Synthetic model



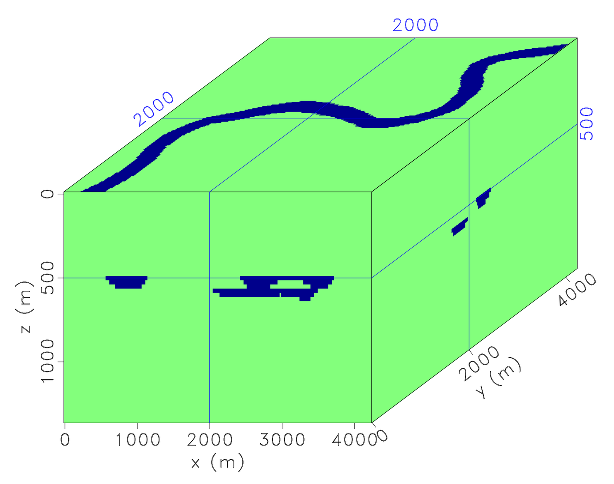
True P-wave velocity



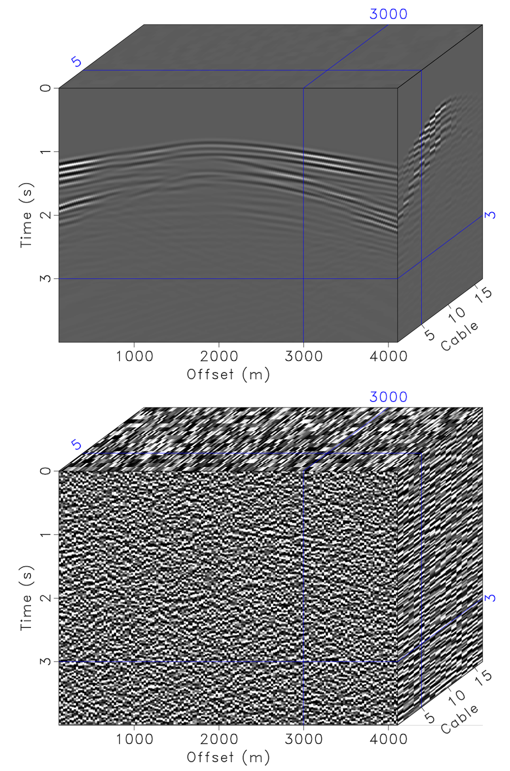
True S-wave velocity

- 16 multi-component cables with a length of 4 km on the sea floor.
- Crossline distance between each cable is 250 m.
- Inline distance between each receiver is 25 m. In total 2560 receivers.
- 441 shots on a square grid, with shot sampling of 125m in both horizontal directions and depth 25 m.
- Source signature is a Ricker wavelet with center frequency 6.0 Hz.

Time-lapse changes



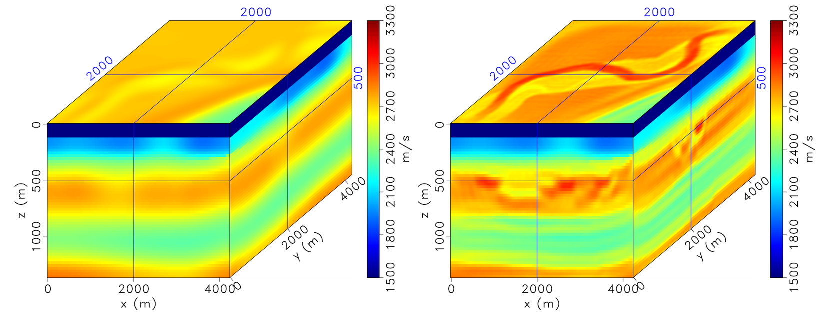
- **1%**: 0 – 30 m/s for V_p and 0 – 20 m/s for V_s.
- **5%**: 0 – 152 m/s for V_p and 0 – 96 m/s for V_s.



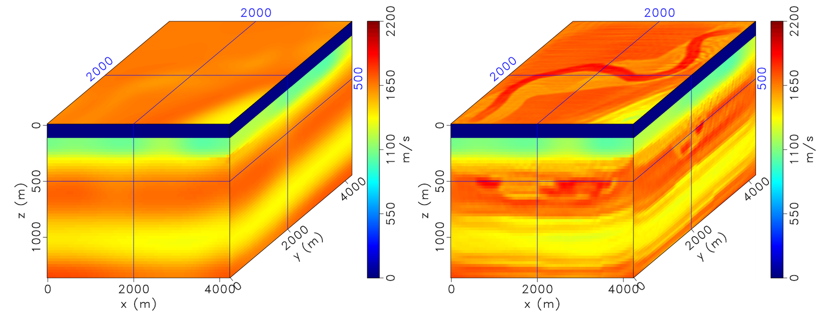
Top: Pressure data-difference without noise

Bottom: Pressure data-difference with noise

Baseline inversion

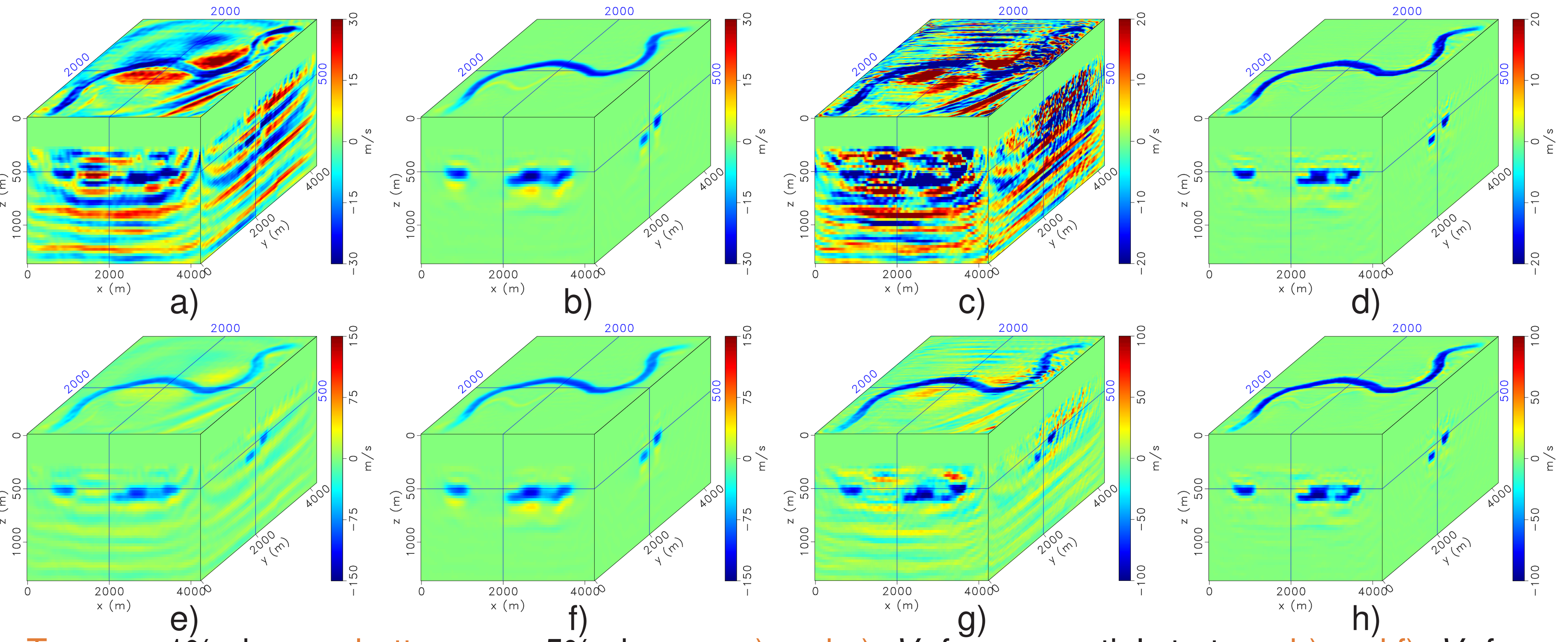


Left: Initial V_p, right: Inverted V_p



Left: Initial V_s, right: Inverted V_s

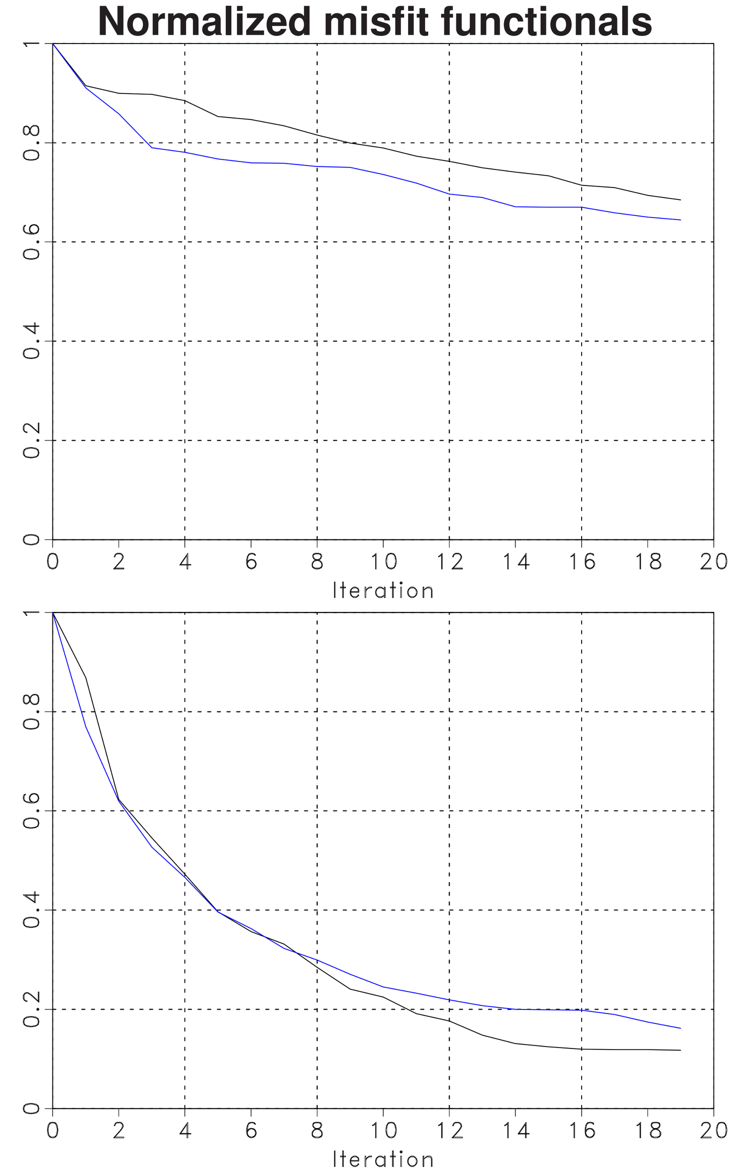
Results: Noise-free data



Top row: 1% change, bottom row: 5% change. a) and e): V_p for sequential strategy, b) and f): V_p for data-difference strategy, c) and g): V_s for sequential strategy, d) and h): V_s for data-difference strategy,

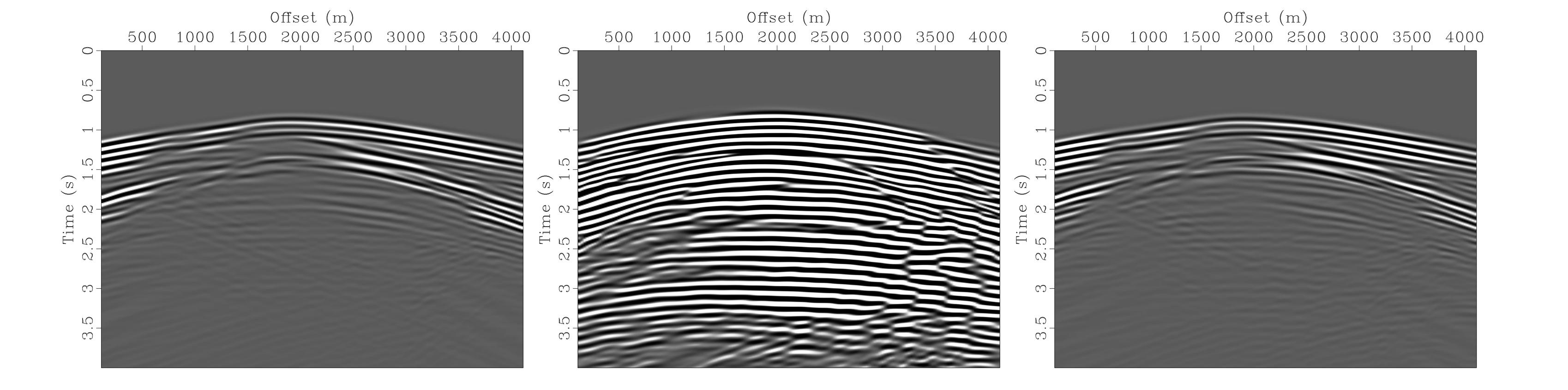
- Inverted simultaneously for V_p and V_s. To achieve good results the weighting of the different data components is important.
- Inverted V_s models are sharper than the corresponding V_p models. This is due to the shorter wave lenghts for the shear waves.
- To obtain good time-lapse images it is important to have a good inverted baseline model. If not, the time-lapse effects may be wrongly placed in space.
- More artifacts in the time-lapse images for for the sequential strategy compared to the data-difference strategy. As a result, small time-lapse changes can be difficult to detect using the former strategy.
- V_s seems to be more sensitive to artifacts than V_p. The V_s model is more like to be cycle-skipped due to the shorter wave lengths, as well as mode conversions in the data.
- Misfit is more reduced for the data-difference strategy than the sequential strategy.
- The data-difference strategy induce strong requirements on the acquisiton geometry and repeatability in general.

Normalized misfit functionals



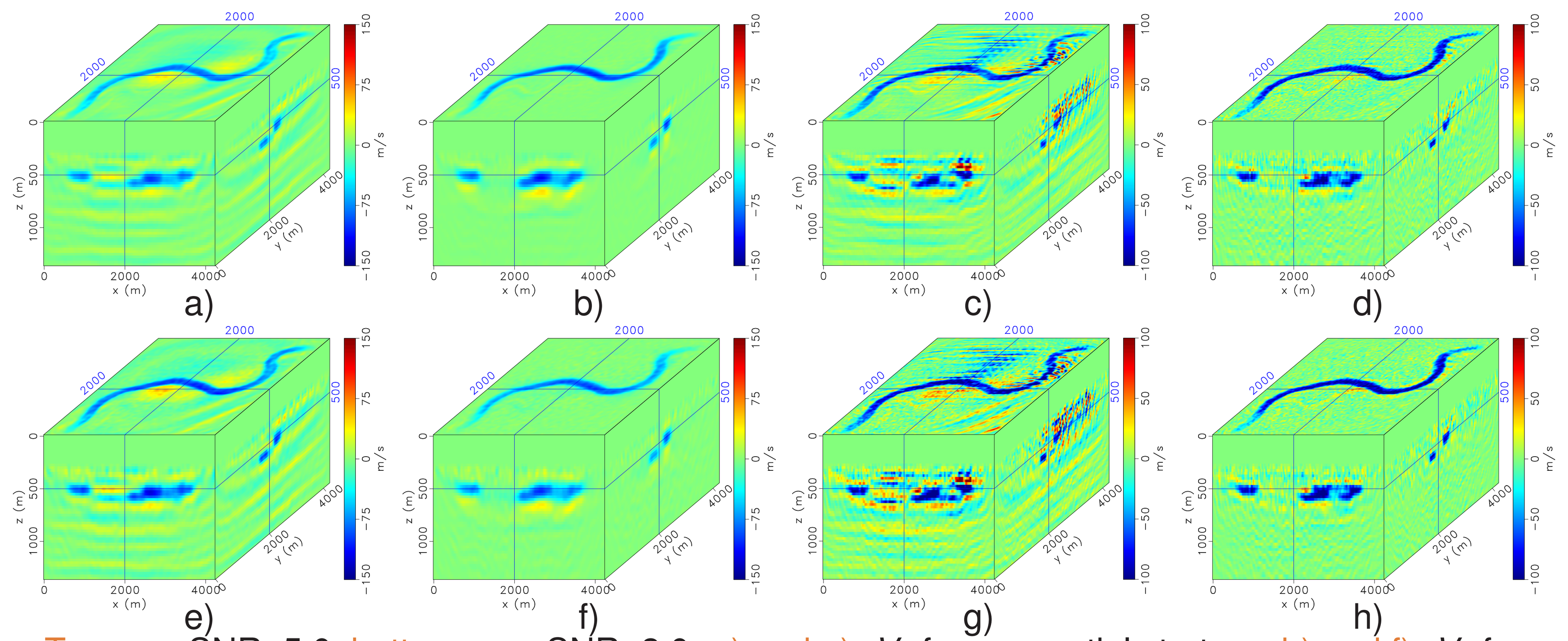
Top: sequential strategy, bottom: data-difference strategy (black: 1% change, blue: 5% change).

Data differences



Left: true data-difference, middle: inverted data-difference for sequential strategy, right: inverted data-difference for data-difference strategy.

Results: Data with noise



Top row: SNR=5.0, bottom row: SNR=2.0. a) and e): V_p for sequential strategy, b) and f): V_p for data-difference strategy, c) and g): V_s for sequential strategy, d) and h): V_s for data-difference strategy,

Summary and remarks

- Inverting for data-differences seems to be the correct way for time-lapse imaging using FWI. However, this induce strong repeatability requirements.
- The two strategies are able to obtain good results when random noise is present in the data.
- Using real data time-lapse imaging using FWI is challenging due to uncertainities in for instance the acqusition geometry, source wavelets and non-repeatable noise.
- It is possible to perform 3D elastic time-lapse FWI within acceptable runtimes.
- Multi-parameter FWI is difficult due to a more complicated inverse problem.

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