3D Elastic Time-lapse Full Waveform Inversion

Espen Birger Raknes and Børge Arntsen

Norwegian University of Science and Technology (NTNU)
Department of Petroleum Engineering & Applied Geophysics
E-mail: espen.raknes@ntnu.no

The ROSE meeting
May 6th 2014

Background

- During the last decade full waveform inversion (FWI) has proven to be a promising method for parameter model estimation
- Increase in computational power leads to an increase in problem size and type of wave phenomena included in the modeling
- Using FWI to reveal time-lapse effects directly in the parameter models is a rather new idea

Objectives

- Apply elastic isotropic FWI on multi-component time-lapse data in 3D
- Invert for time-lapse changes in the P- and S-wave velocity models
- Investigate two data-difference based time-lapse FWI approaches

Outline

A Quick Overview of Full Waveform Inversion

Overall Goal

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

Define $S(\mathbf{m})$ as the measure between synthetic and measured data. The FWI is then the problem

$$\arg\min_{\mathbf{m}} S(\mathbf{m})$$

A Quick Overview of Full Waveform Inversion

Overall Goal

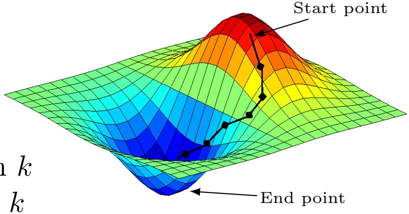
Find a parameter model from which it is possible to create synthetic data that is close to some measured data

Define $S(\mathbf{m})$ as the measure between synthetic and measured data. The FWI is then the problem

$$\arg\min_{\mathbf{m}} S(\mathbf{m})$$

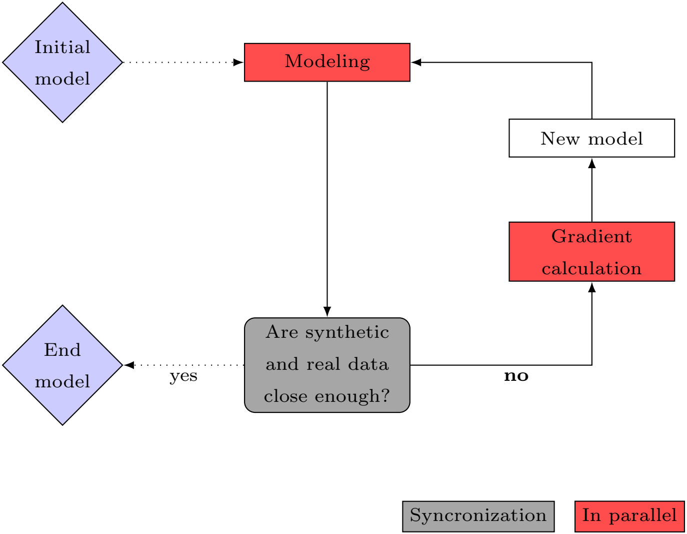
Solved using an iterative method

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



$\mathbf{m}_k$	model at iteration k
$\mathbf{g}_k$	gradient of $S(\mathbf{m})$ at iteration k
$\mathbf{H}_k$	Hessian of $S(\mathbf{m})$ at iteration k
α_k	step length at iteration k

Schematic View of FWI



Time-lapse Full Waveform Inversion

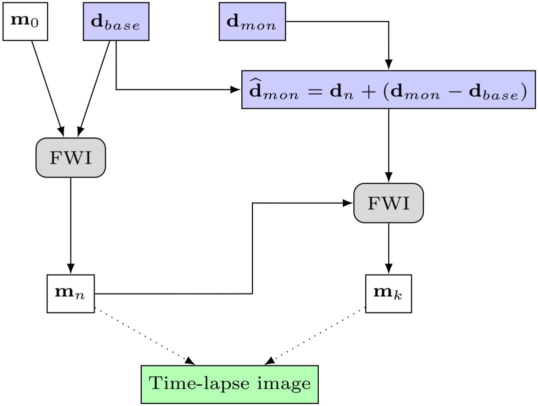
Goal

Use full waveform inversion to quantify changes in time for parameters affecting wave propagation.

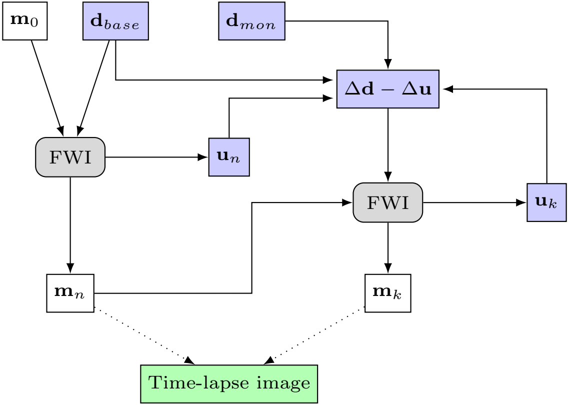
May be used

- as monitoring tool during the life-time of a reservoir
- to monitor injection of CO_2 in CCS experiments
- quantify amount of injected CO_2

Approach 1


$\mathbf{m}_0$
$\mathbf{d}_{base}$
$\mathbf{d}_{mon}$
$\widehat{\mathbf{d}}_{mon} = \mathbf{d}_n + (\mathbf{d}_{mon} - \mathbf{d}_{base})$
FWI
FWI
$\mathbf{m}_n$
$\mathbf{m}_k$
Time-lapse image

Approach 2


$\mathbf{m}_0$
$\mathbf{d}_{base}$
$\mathbf{d}_{mon}$
$\Delta\mathbf{d} - \Delta\mathbf{u}$
FWI
$\mathbf{u}_n$
FWI
$\mathbf{u}_k$
$\mathbf{m}_n$
$\mathbf{m}_k$
Time-lapse image

TLFWI at a glance

- Need to perform at least two inversions
  $\rightarrow$ Costly method

TLFWI at a glance

- Need to perform at least two inversions
  → Costly method
- The method may introduce artifacts in the time-lapse images due to for instance
  - non-linearity
  - ill-posedness
  - data differences

  → Often called *time-lapse artifacts*

From two to three dimensions

The real world is 3D, so we need to approximate it in 3D...

...but it is not easy

Some of the difficulties are

- More unknowns in the inverse problem, but not necessarily more data (i.e. more degrees of freedom, “more” ill-posed)
- Numerical methods scale extremely bad (i.e. long runtimes)
- Not everything can be done in memory

The major problem: the gradient

$$g(\mathbf{x}) = \int_T \overrightarrow{\psi}(\mathbf{x}, t) \overleftarrow{\psi}(\mathbf{x}, t)\, dt, \qquad (\mathbf{x}, t) \in (\mathbb{R}^3 \times T)$$

The major problem: the gradient

$$g(\mathbf{x}) = \int_T \overrightarrow{\psi}(\mathbf{x},t)\overleftarrow{\psi}(\mathbf{x},t)\,dt, \qquad (\mathbf{x},t) \in (\mathbb{R}^3 \times T)$$

- We need the wave fields at each time step to compute the cross correlation
  → Impossible: Would require something like >1000TB of data storage for a small survey

The major problem: the gradient

$$g(\mathbf{x}) = \int_T \overrightarrow{\psi}(\mathbf{x}, t) \overleftarrow{\psi}(\mathbf{x}, t)\, dt, \qquad (\mathbf{x}, t) \in (\mathbb{R}^3 \times T)$$

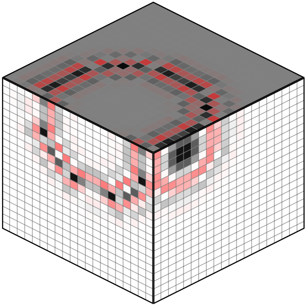
- We need the wave fields at each time step to compute the cross correlation
  $\rightarrow$ Impossible: Would require something like >1000TB of data storage for a small survey
- Large data transfer rates on the computer clusters are not possible

The major problem: the gradient

$$g(\mathbf{x}) = \int_T \overrightarrow{\psi}(\mathbf{x},t)\overleftarrow{\psi}(\mathbf{x},t)\,dt, \qquad (\mathbf{x},t) \in (\mathbb{R}^3 \times T)$$

- We need the wave fields at each time step to compute the cross correlation
  $\rightarrow$ Impossible: Would require something like >1000TB of data storage for a small survey
- Large data transfer rates on the computer clusters are not possible
- **Solution:** Need to reconstruct the wave fields when they are needed, but how do we do that?

Reconstruction of the wave fields

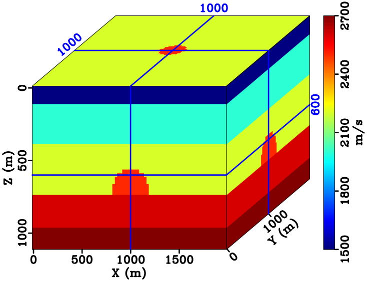


- Each boundary of the cube is stored to disc during the forward modeling
- To decrease data transfer, not all time-steps are saved
- In the backpropagation of the wave fields, we are reconstructing the forward field by feeding in each side of the cube, and use interpolation (to “reconstruct” the non-saved steps) where it is required

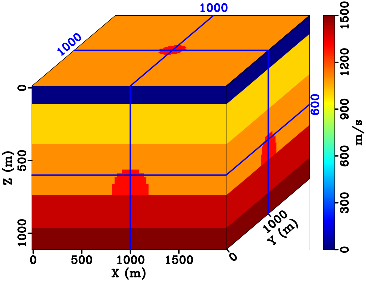
Pros and cons

- We are keeping the need for storage at a minimum
- The necessary data transfer is “small”
- Back-propagation becomes (at least) twice as costly
- We are not able to reconstruct the field exactly, since we only have information on the boundaries

Simple layered model



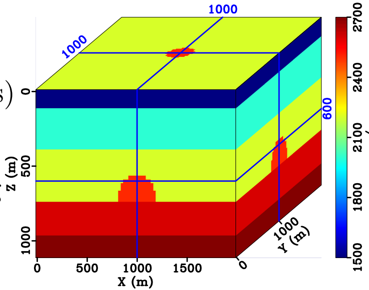
(a) True V_p



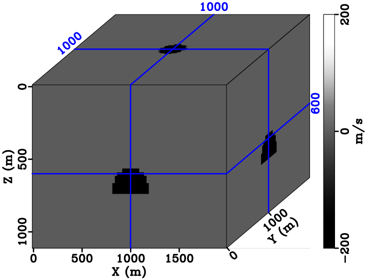
(b) True V_s

Simple layered model

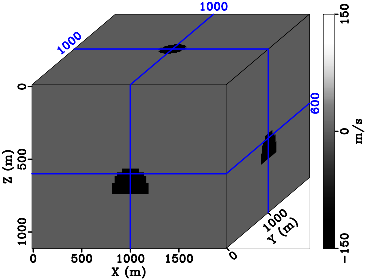
- Square receiver grid (4900 receivers)
- Receiver grid size: 2×2 km^2
- 324 shots with 100m shot sampling in x- and y-direction
- Grid sampling: 25m
- Source: Ricker wavelet with center frequency 6.0Hz



Simple layered model

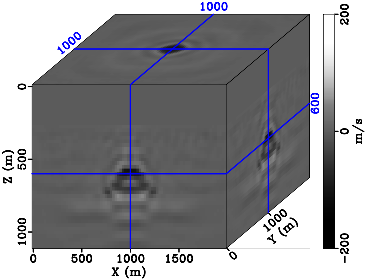


(a) Time-lapse V_p

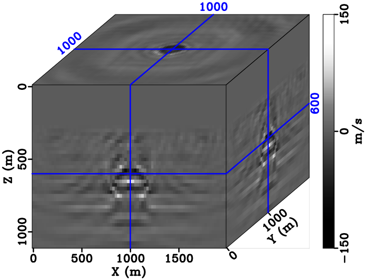


(b) Time-lapse V_s

Simple layered model: Approach 1

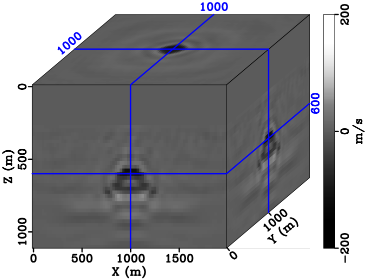


(a) Time-lapse V_p

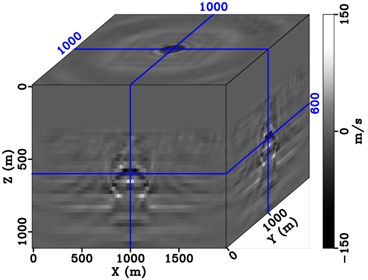


(b) Time-lapse V_s

Simple layered model: Approach 2

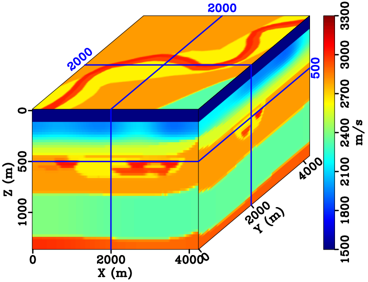


(a) Time-lapse V_p



(b) Time-lapse V_s

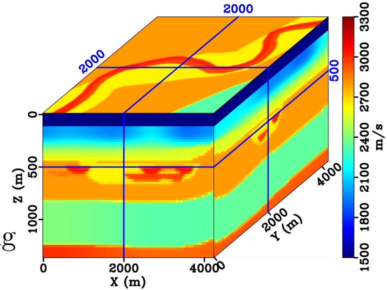
Model with channel system



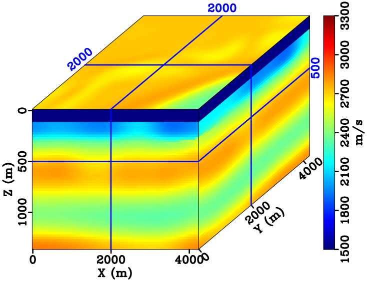
(a) True V_p (b) True V_s

Model with channel system

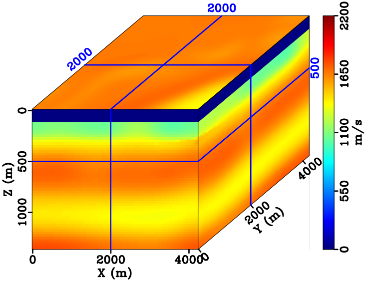
- 16 ocean-bottom cables
- Cable length: 4.0km
- Cable separation: 250m
- Total number of receivers: 2560
- 441 shots with 100m shot sampling in x- and y-direction
- Grid sampling: 25m
- Source: Ricker wavelet with center frequency 6.0Hz



Model with channel system

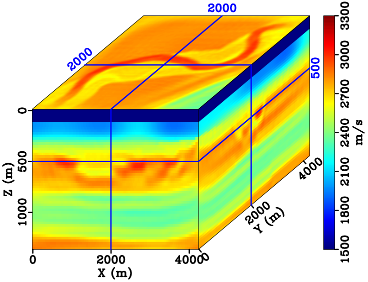


(a) Initial V_p

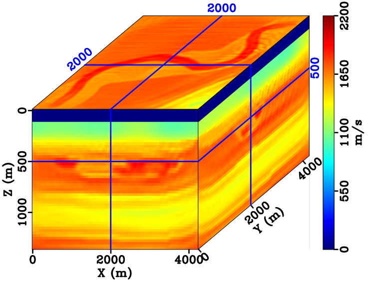


(b) Initial V_s

Model with channel system

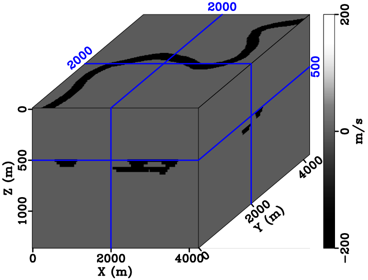


(a) Inverted V_p

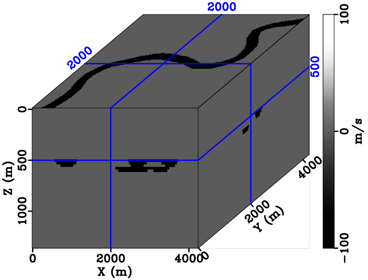


(b) Inverted V_s

Model with channel system

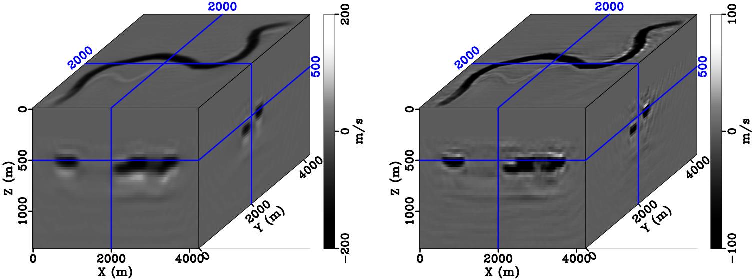


(a) Time-lapse V_p



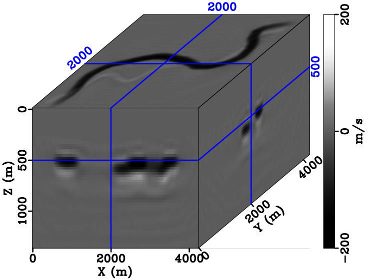
(b) Time-lapse V_s

Model with channel system: Approach 1

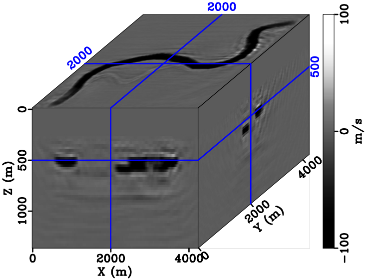


(a) Time-lapse V_p (b) Time-lapse V_s

Model with channel system: Approach 2



(a) Time-lapse V_p



(b) Time-lapse V_s

Conclusions

- It is possible to do FWI in 3D within acceptable computing times
- FWI may be used to detect time-lapse effects in 3D
- Possible to invert for time-lapse changes in V_p and V_s using OBCs
- Small differences in the two time-lapse approaches

Acknowledgements

We thank the Norwegian Research Council, BIGCCS, and the ROSE consortium for financing this research.