Applications of Seismic Full-Waveform Inversion on Shallow-Seismic and Ultrasonic Data

presented at the NIC Symposium 2020

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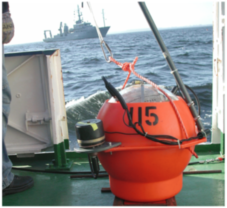
28.02.2020

Shallow marine data

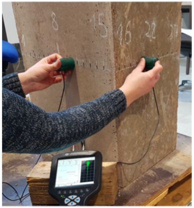


2 km

Shallow land data

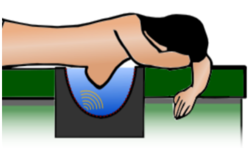
10 m

Non-destructive testing



50 cm

Medical imaging



10 cm

Agenda

Agenda

1. Introduction

2. Methodology and Challenges

3. Applications of FWI

3.1 Shallow marine guided waves

3.2 Near surface characterization using surface waves

3.3 Nondestructive testing

3.4 Medical imaging

4. Conclusions

Seismic wave propagation is complex

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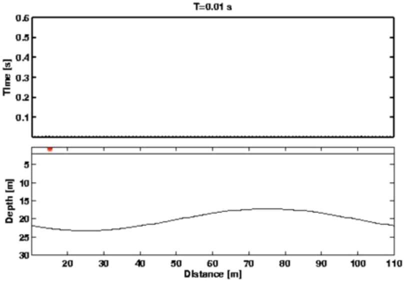
Observed seismograms contain signals of P-waves, S-waves, surface waves, mode conversions,...



Click on frame to play movie

Goals of FWI

Find all earth models that predict all signals by full wave modelling !

State of the art: Find one numerical model that predicts selected signals at low frequencies by full wave modelling.

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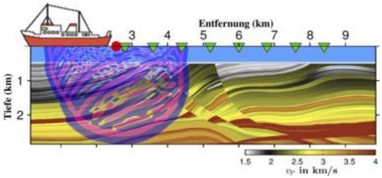

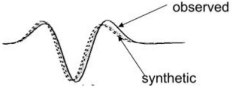

P–waves
S–waves
Surface waves

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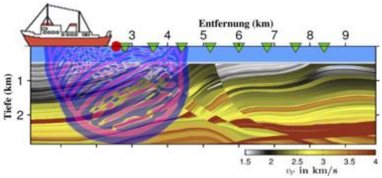
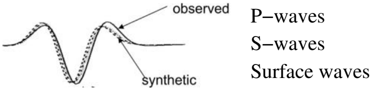


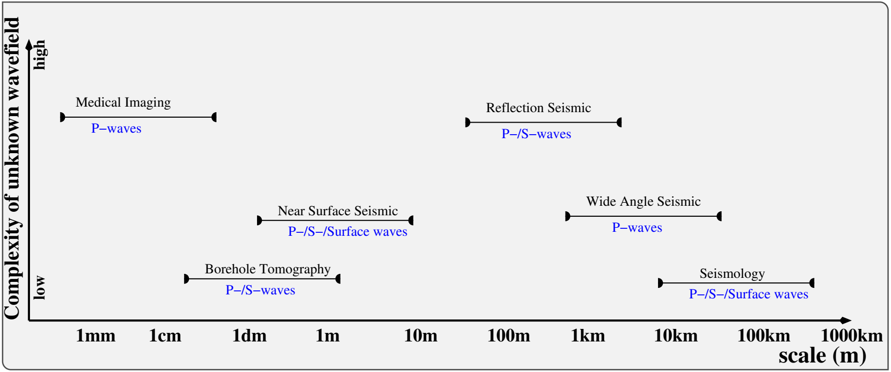


Benefits

1. **Improved resolution:** $\approx \frac{\lambda}{2}$ ☺
2. **Multi-parameter reconstruction:**
   a. P-wave velocity ☺
   b. S-wave velocity 😐
   c. Attenuation 😐
   d. Anisotropy 😐
   e. Density ☹
3. **Better petrophysical characterization of rocks**

Applications of FWI

In recent 20 years FWI has received great attention and has been applied sucessfully to a broad range of spatial scales and wave types



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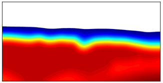
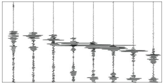
FWI: iterative data fitting procedure

Initial model m_0

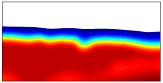


Field data d

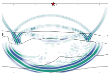


FWI: iterative data fitting procedure

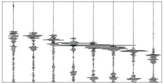
Initial model m_0



Forward modelling



Field data d



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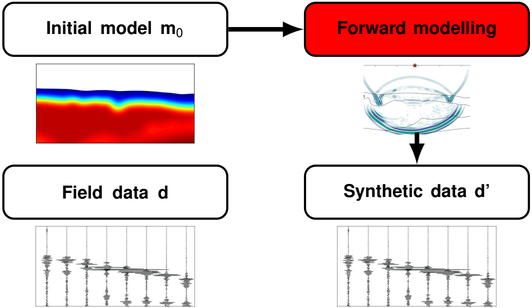

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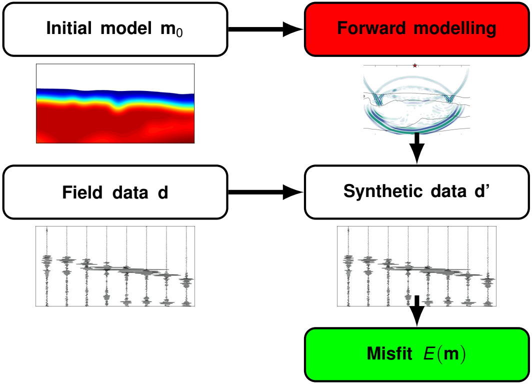

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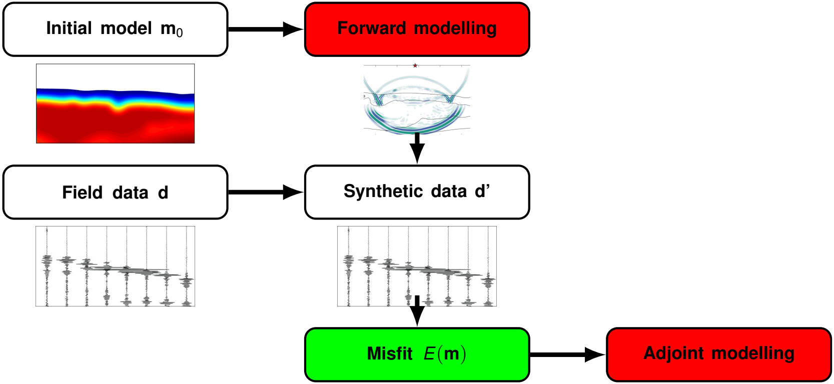

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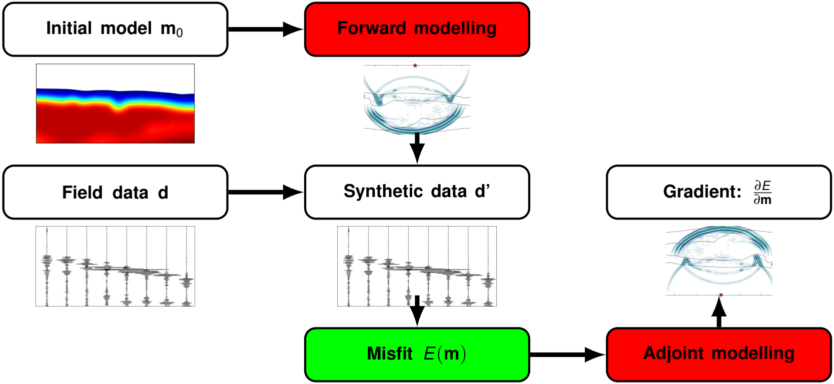

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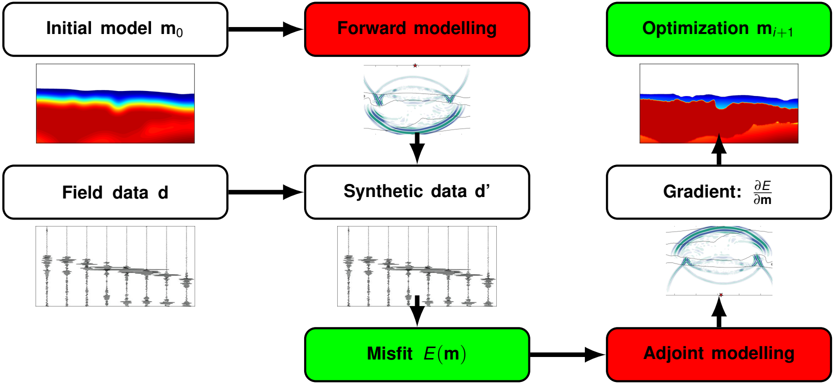

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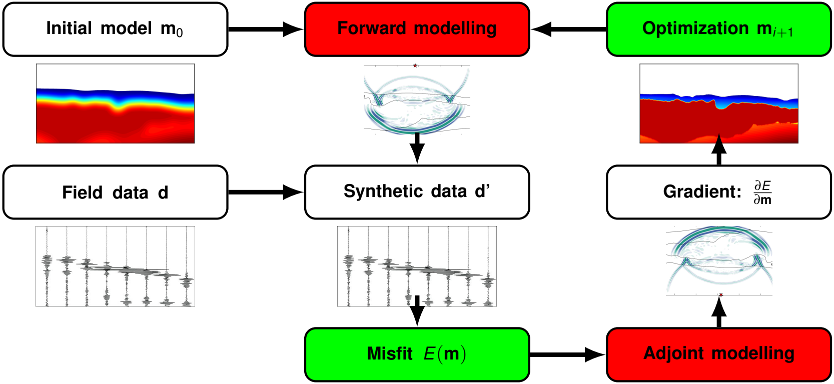

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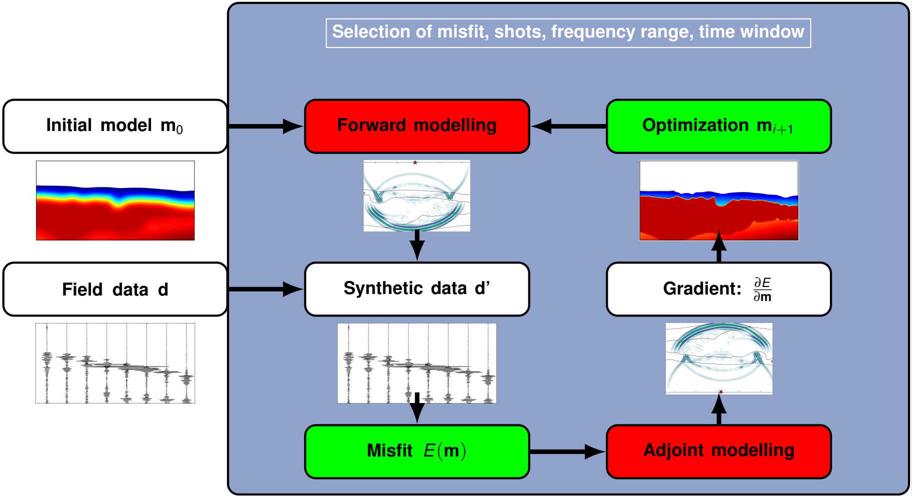
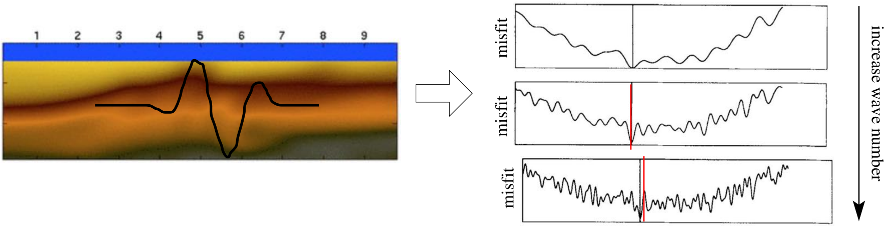


Challenges of FWI (1/6)

Mitigate non-linearities by multi-scale approach

- we need sufficient low wave numbers in the initial model or the observed data

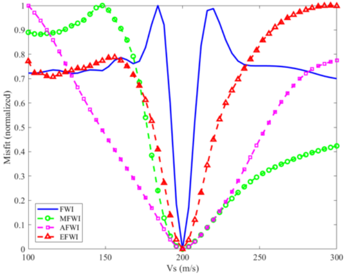
Low wave numbers in model or data... ... to find global minimum by multi–scale FWI



Challenges of FWI (2/6)

Suitable misfit definition

- to measure the misfit of the relevant signals
- **Normalized L2**, envelope, optimal transport,...
- defines the adjoint sources
- tradeoff between robustness (against noise, cycle skipping) and resolution



Challenges of FWI (3/6)

Appropriate physics for wave propagation

- to model the relevant signals
- multi-parameter reconstruction
- consider forward and adjoint equations

Acoustic

$$\frac{\partial^2 p}{\partial t^2} = c^2 \left(\frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2} + \frac{\partial^2 p}{\partial z^2} \right)$$

P–waves

Elastic

$$p_{ij} = \lambda \theta \delta_{ij} + 2\mu \epsilon_{ij}$$

$$\epsilon_{ij} = \frac{1}{2} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)$$

$$\rho \frac{\partial^2 u_i}{\partial t^2} = \frac{\partial p_{ij}}{\partial x_j} + f_i$$

P–waves, S–waves
Surface waves

Visco–elastic

$$\dot{\sigma}_{ij} = \frac{\partial v_k}{\partial x_k} \{ M(1 + L\tau^p) - 2\mu(1 + L\tau^s) \} + 2\frac{\partial v_i}{\partial x_j} \mu (1 + L\tau^s) + \sum_{l=1}^{L} r_{ijl} \quad \text{if } i = j$$

$$\dot{\sigma}_{ij} = \left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} \right) \mu (1 + L\tau^s) + \sum_{l=1}^{L} r_{ijl} \quad \text{if } i \neq j \; ,$$

$$\dot{r}_{ijl} = -\frac{1}{\tau_{\sigma l}} \left\{ (M\tau^p - 2\mu\tau^s) \frac{\partial v_k}{\partial x_k} + 2\frac{\partial v_i}{\partial x_j} \mu \tau^s + r_{ijl} \right\} \quad \text{if } i = j \; ,$$

$$\dot{r}_{ijl} = -\frac{1}{\tau_{\sigma l}} \left\{ \mu \tau^s \left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} \right) + r_{ijl} \right\} \quad \text{if } i \neq j \; .$$

$$\varrho \frac{\partial v_i}{\partial t} = \frac{\partial \sigma_{ij}}{\partial x_j} + f_i \; ,$$

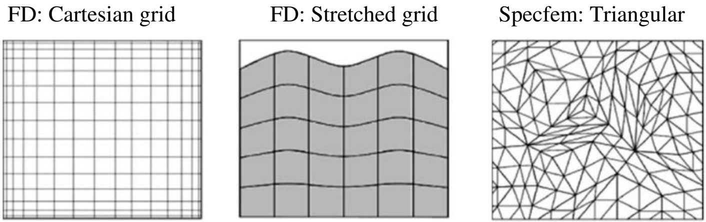
P–waves, S–waves
Surface waves
Attenuation

→ Computational requirements

Challenges of FWI (4/6)

Numerical solution and space discretization

- **Finite-Differences**, Spectral elements
- Boundary condition (free surface topography is challenge with FD)



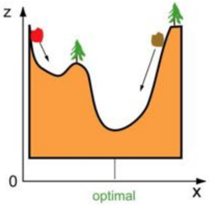
(Igel et al. 2011)

Challenges of FWI (5/6)

Optimization method

- efficient calculation of gradients by the adjoint method
- available methods: steepest-descent, conjugate gradient, L-BFGS, Gauß-Newton, Truncated Newton etc.
- consider global strategy if number of parameters is small (uncertainty estimation)

Gradient–based (local)



Global

Challenges of FWI (6/6)

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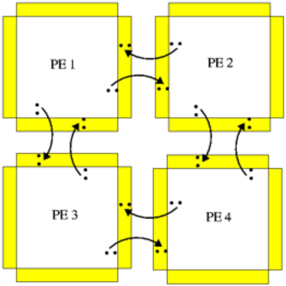
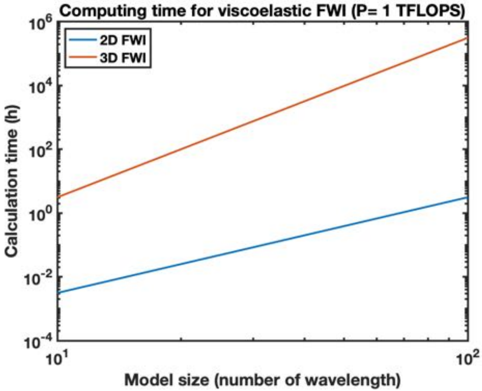
High Performance Computing

- Efficient forward and adjoint simulation on heterogeneous architectures (CPU/GPU)





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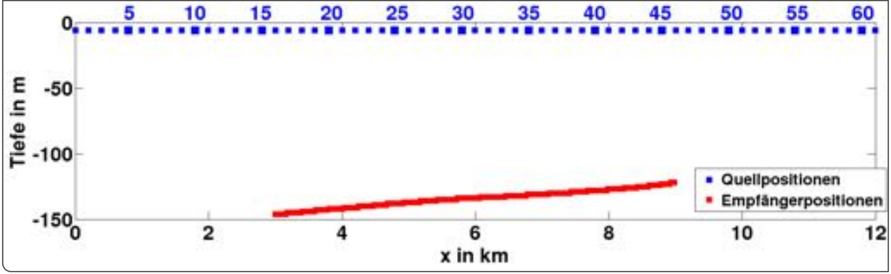
FWI of OBC data in shallow water

Acquisition geometry



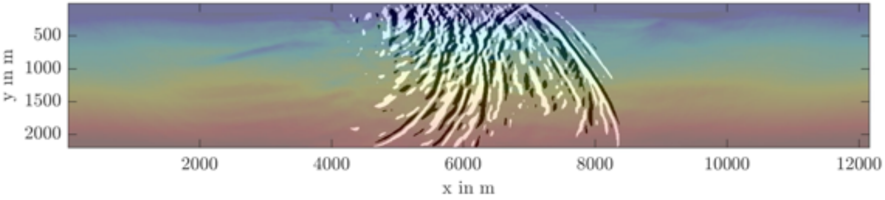
- Ocean-Bottom-Cable
- Length: 6 km, 240 Hydrophones
- 61 Airgun shots
- Water depth approx. 130m
- Maximum offset 9 km

(Kunert 2015, Kunert et al. 2016, Habelitz 2017)
Data was provided by Addax

FWI of OBC data in shallow water

Acoustic simulation of wavefield in the final FWI model

Click to play



(Habelitz 2017)

FWI of OBC data in shallow water

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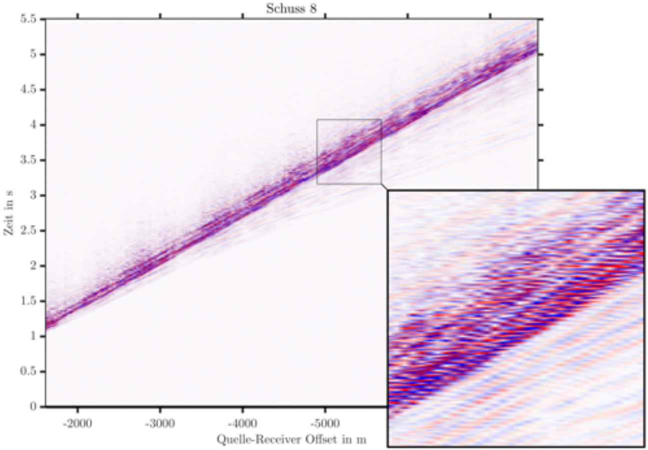
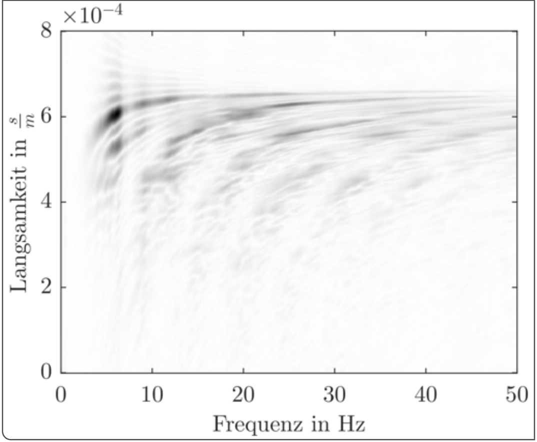
Shot gather



(Habelitz 2017)

FWI of OBC data in shallow water

Acoustic modes

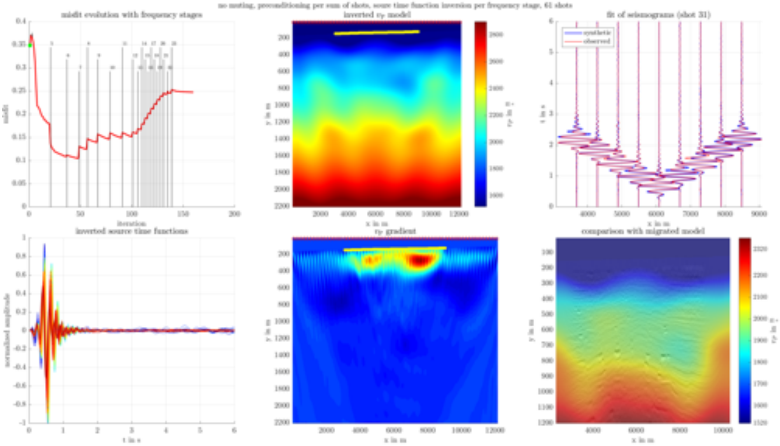


(Habelitz 2017)

FWI of OBC data in shallow water

Performance of FWI

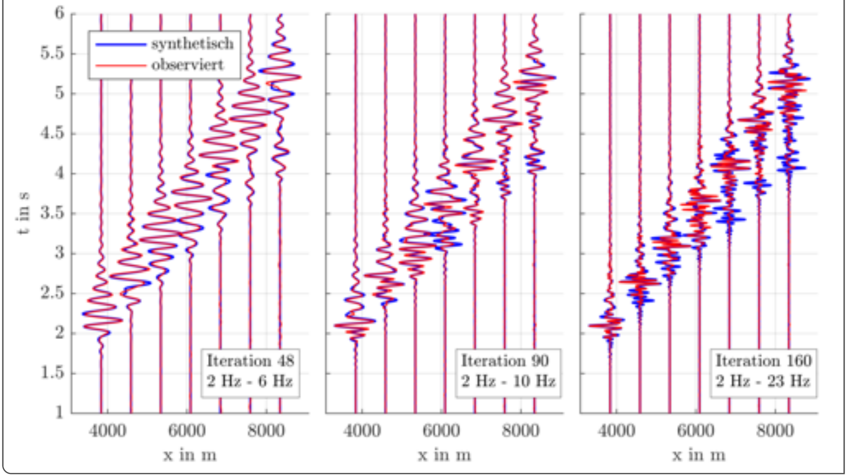
Click to play



(Habelitz 2017)

FWI of OBC data in shallow water

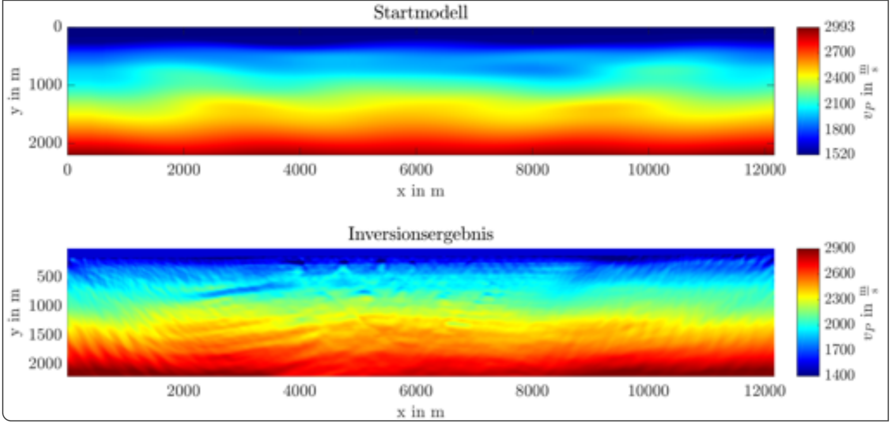
Data fit



(Habelitz 2017)

FWI of OBC data in shallow water

Final model



(Habelitz 2017)

FWI of OBC data in shallow water

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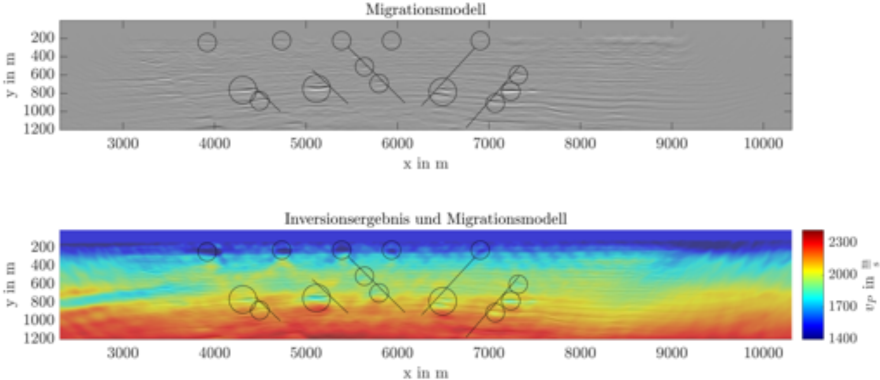
Final model



(Habelitz 2017)

FWI of OBC data in shallow water

Conclusions

- Acoustic FWI of guided waves in shallow water was successful
- Higher resolution of Vp model reveals gas accumulations and pathways along faults
- Consistent with migrated images of reflected waves (independent data)

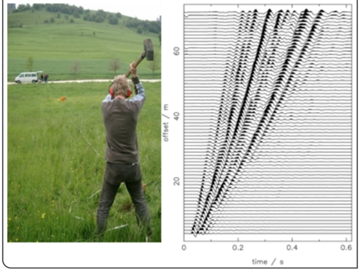
Agenda

FWI for near surface characterization

Shallow seismic surface waves are useful for geotechnical site characterization

- easily excited by a hammer blow
- surface waves are strong signals
- highly sensitive for **S-wave velocity**
- depth of investigation up to 10-15 m

Field data acquisition



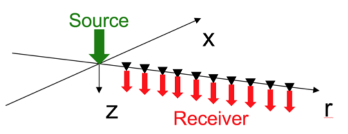
FWI of surface waves is especially useful to infer <u>small-scale lateral variations</u> of V_S.

Field laboratory glider field Rheinstetten

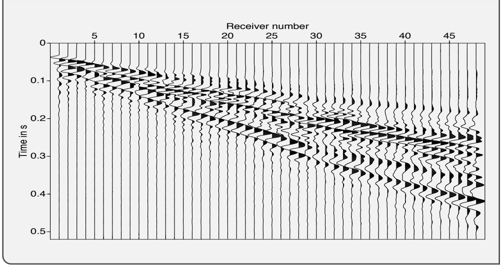
Profile crosses known trench ”Ettlinger Linie” excavated in the 18th century.
The trench is 5m wide and 2m deep.

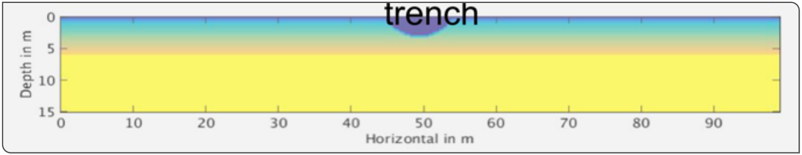
Rayleigh waves

Acquisition



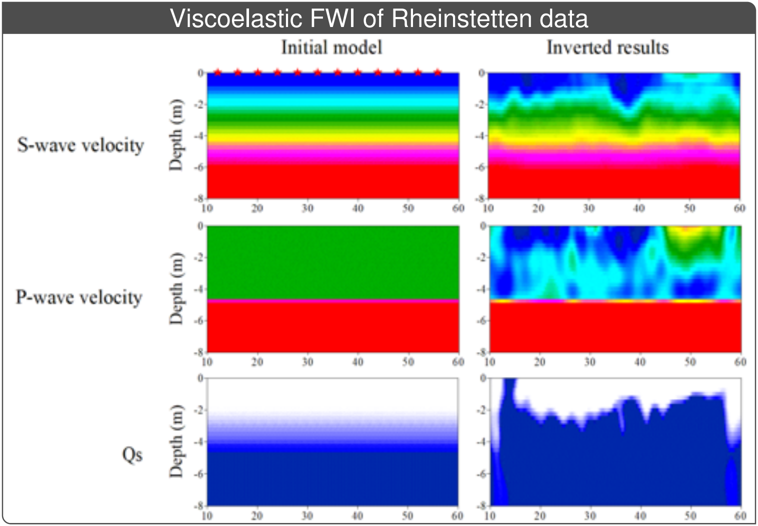
Field data





Click to play

First visico-elastic FWI of field data



(Gao et al. 2020)

First visco-elastic FWI of field data

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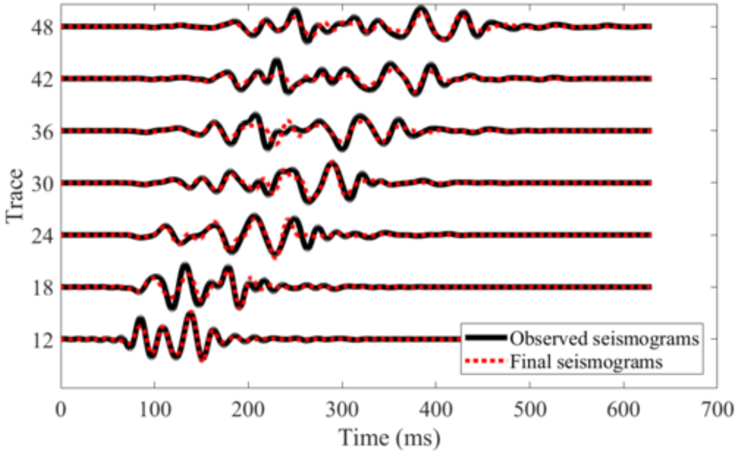
Synthetic and field data



(Gao et al. 2020)

Visco-elastic FWI for near surface characterization

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Conclusions

- Visco-elastic FWI can resolve small-scale structures in P-wave and S-wave velocity in the near surface
- Further research is necessary to improve models of attenuation and density

Agenda

Motivation

Non-destructive testing (NDT):

- Crucial task to prevent failures of building materials
- Current methods are limited in recovering material parameters

IDEA

Full-waveform inversion can help to improve imaging of flaws and other anomalies in building materials

2D reconstruction test

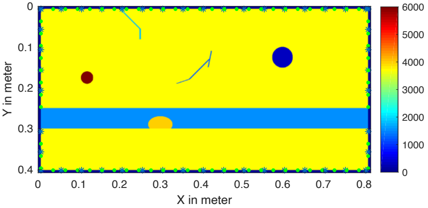
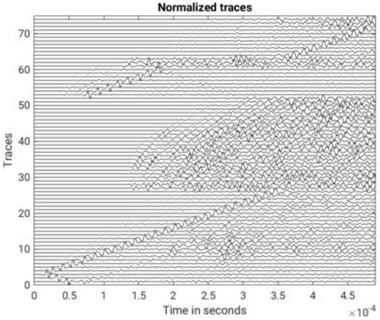


Figure 1: 2D model with pipe and additional perturbations.



Start animation:

forward simulation

Results of elastic FWI

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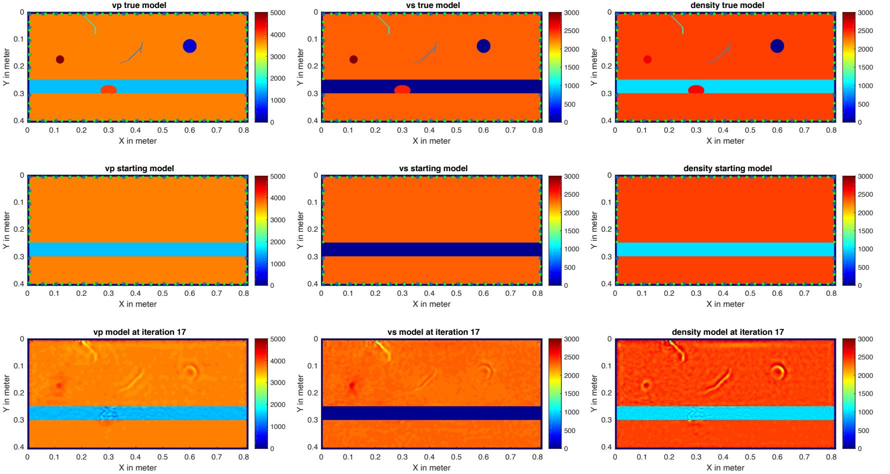

Data fit

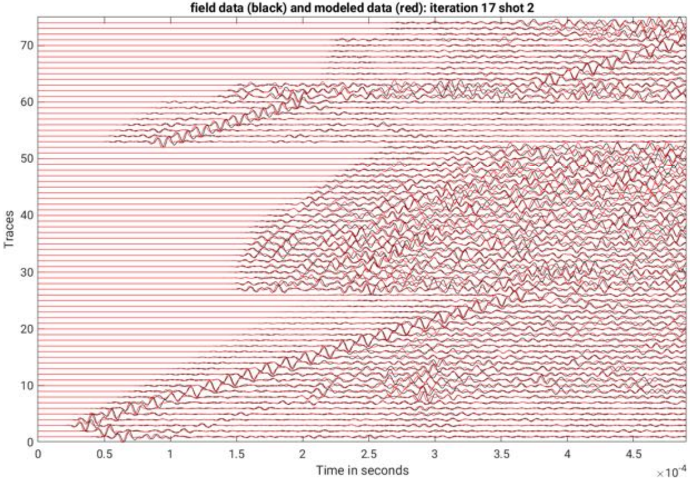

Figure 2: Initial data (red) and final data (black).

Application of elastic FWI for NDT

Conclusions

- High potential in recovering multi-parameter models with high resolution
- First test with measured data are promising
- Models with complex 3D pertubations and geometries will require 3D FWI

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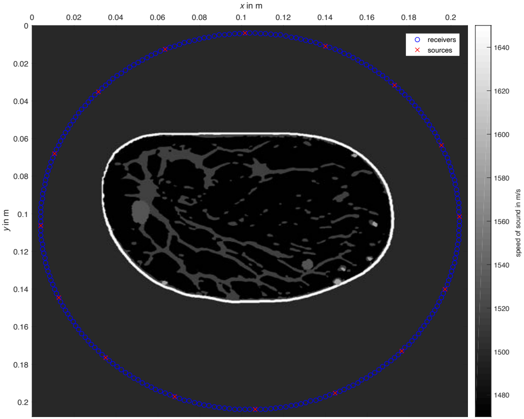
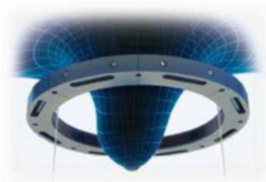
Acquisition geometry

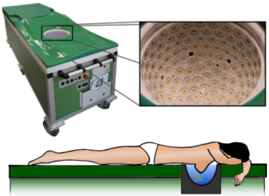
Click on frame to play movie



2D acquisition geometry used in the reconstruction test.
The ring array is equipped with 256 receivers and 16 sources.



Measurement with a 2D ring transducer
(Sandhu et al., 2015)

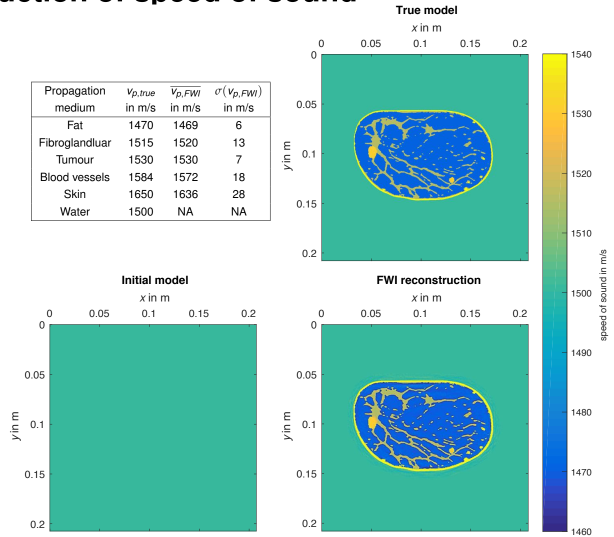


Prototype of a ultrasound device with a full
3D acquisition geometry (Ruiter et al., 2017).

(Kühn 2018)

Reconstruction of speed of sound

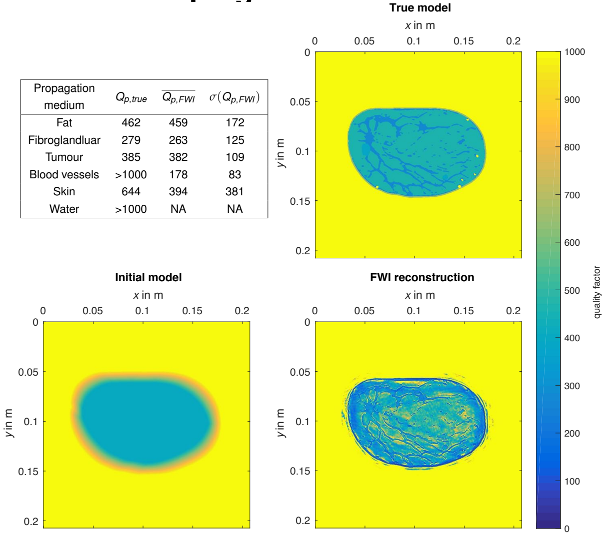
Propagation medium	$v_{p,true}$ in m/s	$\overline{v_{p,FWI}}$ in m/s	$\sigma(v_{p,FWI})$ in m/s
Fat	1470	1469	6
Fibroglandluar	1515	1520	13
Tumour	1530	1530	7
Blood vessels	1584	1572	18
Skin	1650	1636	28
Water	1500	NA	NA



True, initial and inverted speed of sound models (Kühn 2018)

Reconstruction of damping

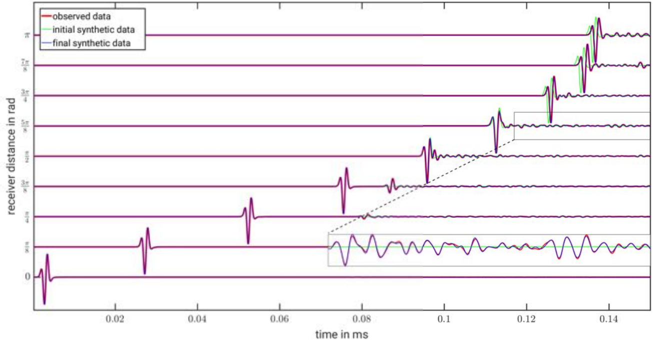
Propagation medium	$Q_{p,true}$	$\overline{Q_{p,FWI}}$	$\sigma(Q_{p,FWI})$
Fat	462	459	172
Fibroglandluar	279	263	125
Tumour	385	382	109
Blood vessels	>1000	178	83
Skin	644	394	381
Water	>1000	NA	NA



True, initial and inverted quality factor models (Kühn 2018)

Data fit

Data for the true, initial and inverted model



(Kühn 2018)

Visco-acoustic FWI for medical imaging

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Conclusions

- Forward modelling is very expensive due to the high frequencies in medical imaging
- 3D applications are still prohibitive
- 2D visco-acoustic FWI of synthetic data with good illumination works very well
- Detailed models of P-velocity and attenuation can be recovered

Agenda

Conclusions

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Summary

First applications revealed that FWI is applicable on different wave types acquired on a broad range of spatial scales. We are still in the early stage of the development of this technology.

Current directions of research

- Application to 3D seismic data
- Reduction of number of forward modellings for 3D applications
- Multi-parameter reconstruction techniques using higher order optimization methods
- Quantification of uncertainties

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Thank you for your attention!

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