Portable HPC Toolbox for Simulation and Inversion of Waves

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Simulation & Inversion

HPC Library LAMA

Load Balancing

Applications

Agenda

Goals of FWI

Find all possible models that explain the full data by full wave modelling !

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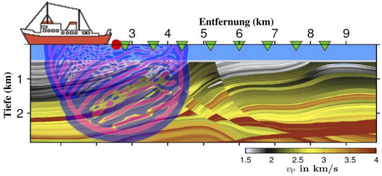
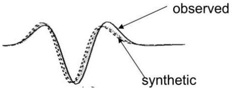




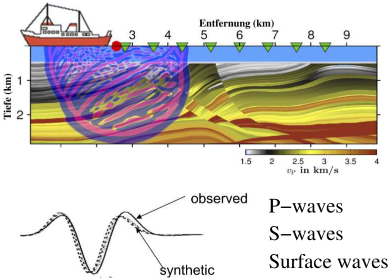
P–waves

S–waves

Surface waves

Goals of FWI

Find all possible models that explain the full data by full wave modelling !



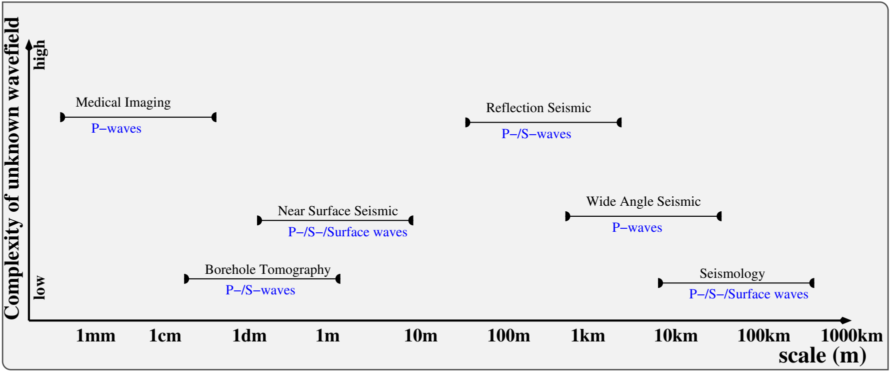
P–waves
S–waves
Surface waves

Benefits

1. **Improved resolution: $\approx \frac{\lambda}{2}$**
2. **Possibility of multi-parameter reconstruction:**
   a. P-wave velocity
   b. S-wave velocity
   c. Attenuation
   d. Anisotropy
   e. Density
3. **Future 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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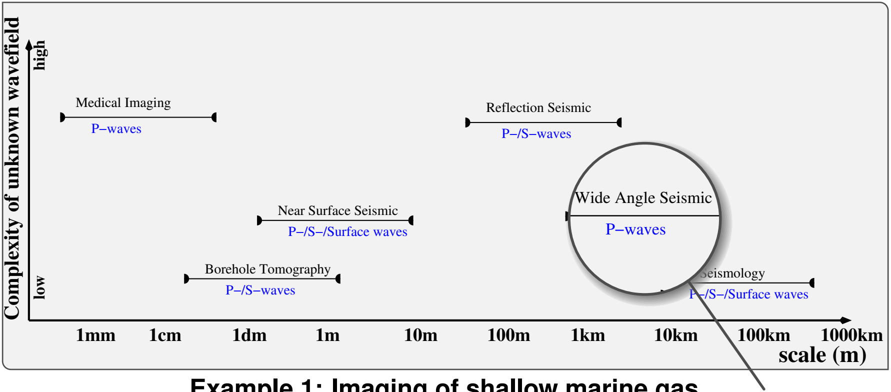

Example 1: Imaging of shallow marine gas
Target depth: 0.15-1.0 km, Acoustic, 200 λ

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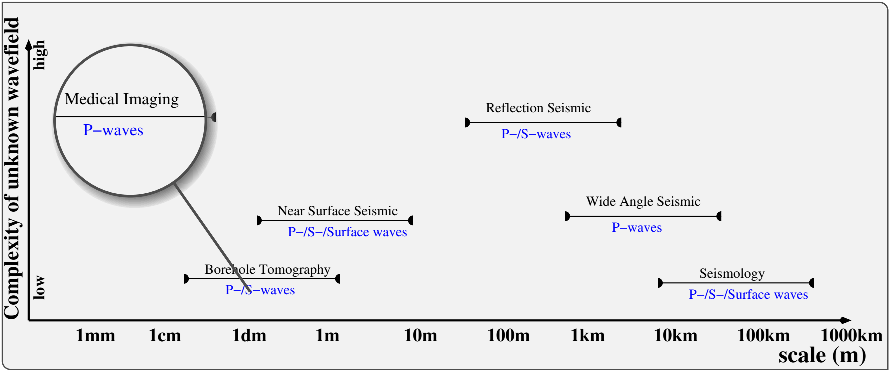
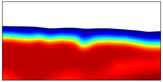


Example 2: Medical imaging (synthetic)

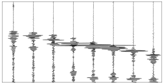
Target depth: 5-15 cm, Visco-acoustic, 330 λ

FWI: iterative data fitting procedure

Initial model m_0



Field data d



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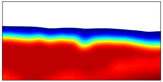
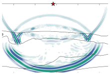
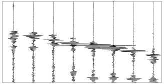
Initial model m_0



Forward wavefield



Field data d



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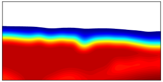

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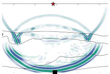
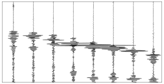
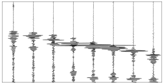


Synthetic data d'



Field data d



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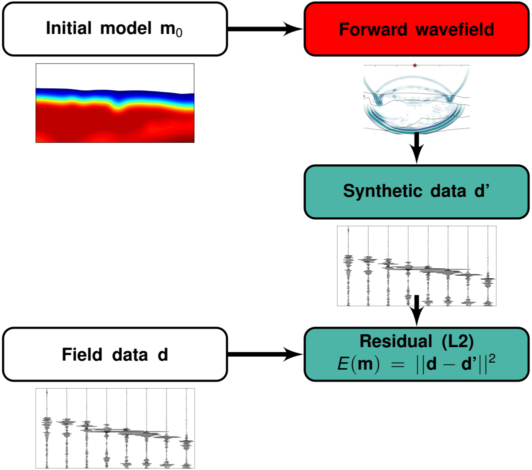

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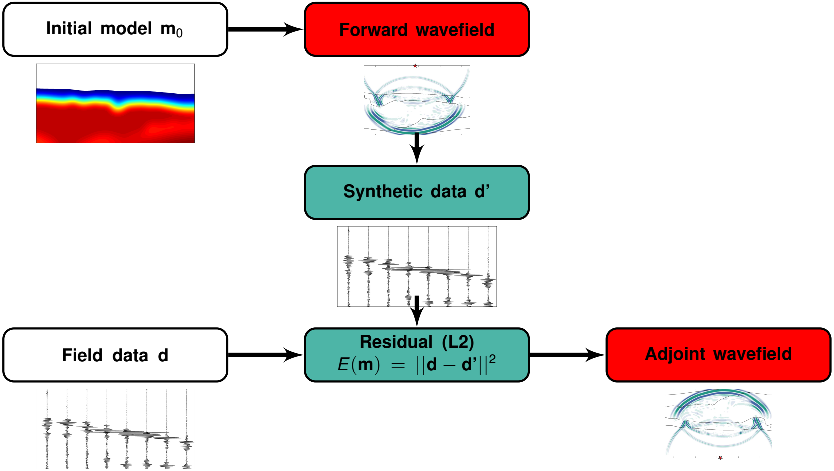

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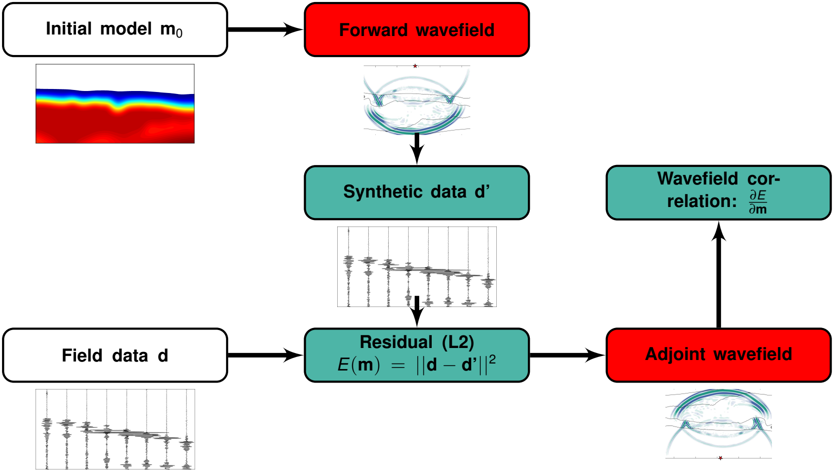

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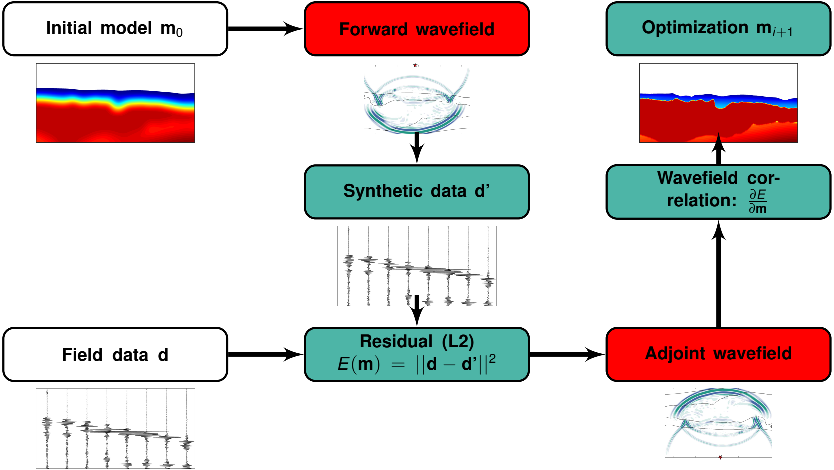

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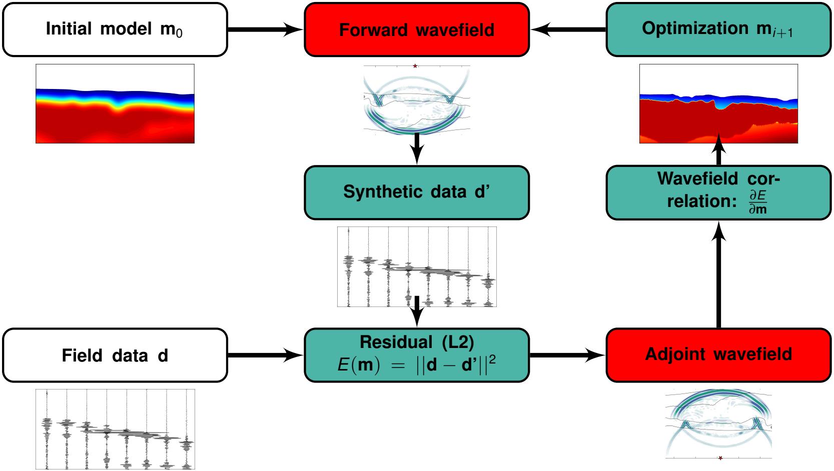

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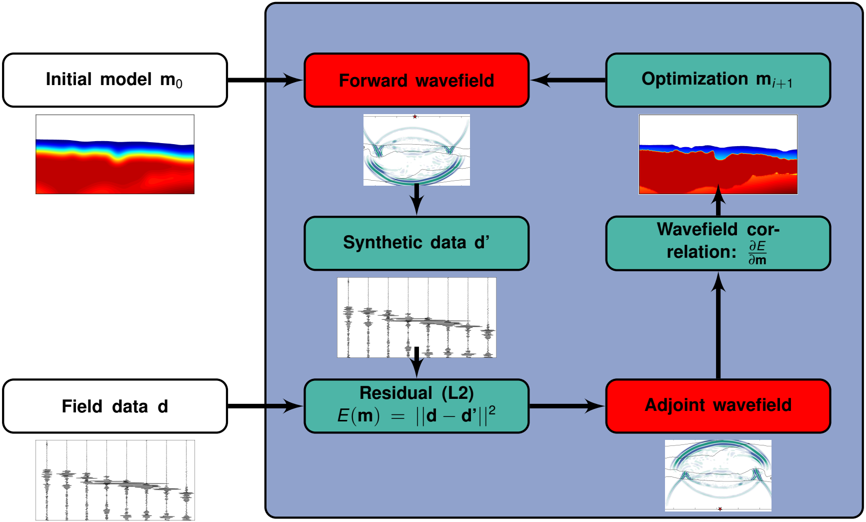

Agenda

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2. HPC Toolbox

3. Applications of FWI

3.1 Imaging of shallow marine gas

3.2 Medical imaging

4. Conclusions

Simulation of waves is essential

Finite-Difference (FD) forward solver

- acoustic, elastic, viscoelastic, (anisotropic)
- 2D and 3D

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

$$\begin{aligned}
\dot{\sigma}_{ij} &= \frac{\partial v_k}{\partial x_k} \left\{ M (1 + L\tau^p) - 2\mu (1 + L\tau^s) \right\} + 2 \frac{\partial v_i}{\partial x_j} \mu (1 + L\tau^s) + \sum_{l=1}^{L} r_{ijl} \quad \text{if } i = j \\
\dot{\sigma}_{ij} &= \left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} \right) \mu (1 + L\tau^s) + \sum_{l=1}^{L} r_{ijl} \qquad \text{if } i \neq j \quad ,
\end{aligned}$$

$$\begin{aligned}
\dot{r}_{ijl} &= -\frac{1}{\tau_{\sigma l}} \left\{ (M\tau^p - 2\mu\tau^s) \frac{\partial v_k}{\partial x_k} + 2 \frac{\partial v_i}{\partial x_j} \mu \tau^s + r_{ijl} \right\} \qquad \text{if } i = j \quad , \\
\dot{r}_{ijl} &= -\frac{1}{\tau_{\sigma l}} \left\{ \mu \tau^s \left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} \right) + r_{ijl} \right\} \qquad \text{if } i \neq j \quad .
\end{aligned}$$

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

P–waves, S–waves
Surface waves
Attenuation

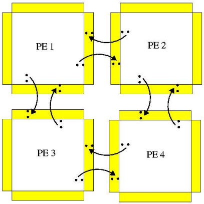
$\longrightarrow$ Computational requirements

C++ HPC Toolbox

HPC Tools

1. Matrix-Vector Finite-Difference (FD) solver for 2D/3D acoustic/elastic/viscoelastic media for forward and adjoint PDEs
2. LAMA with optimized FD stencil operations
3. Load balancing/Partitioning
4. Applications on heterogeneous architectures (CPU/GPU)

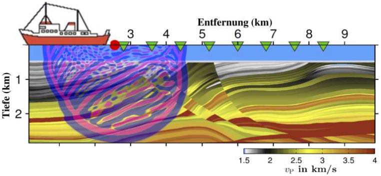
Domain Decomposition

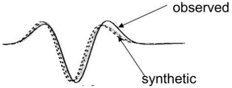


Cluster

(Foto:KIT)

Spatial variation of computational load





P–waves

S–waves

Surface waves

Variation of computational load

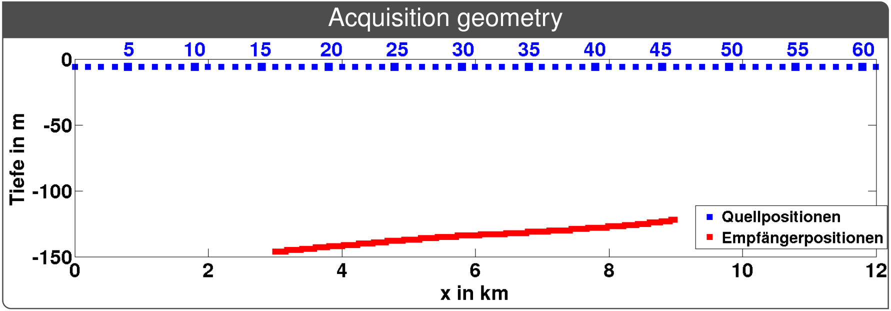
- ~~Spatial variation of grid spacing~~
- PML absorbing boundaries
- Simulation accuracy depending on illumination
- Discretization per wavelength (FD order)
- Physics of wave propagation

Work in progress...

- Implementation using a 2D marine viscoelastic model
- Calculation of computational weights
- Partitioning and performance analysis

Agenda

FWI of OBC data in shallow water



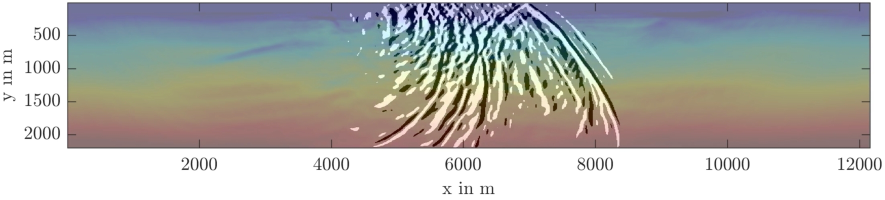
- Ocean-Bottom-Cable
- Length: 6 km, 240 Hydrophones
- 61 Airgun shots
- Water depth approx. 130m
- Maximum offset 9 km

(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

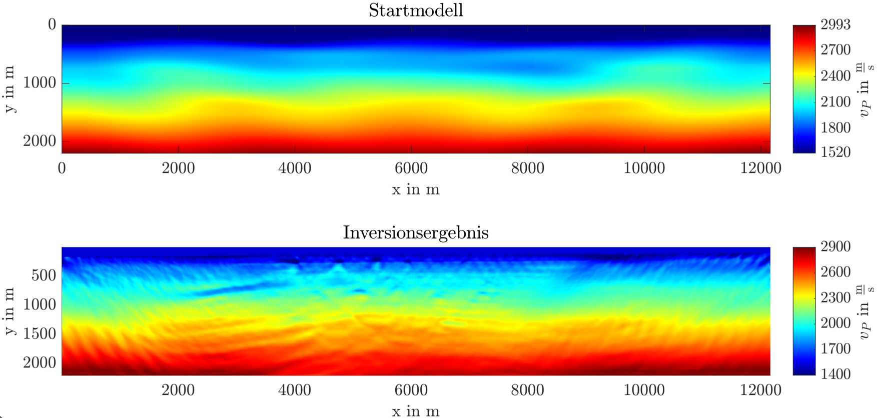
Click to play



(Habelitz 2017)

FWI of OBC data in shallow water

Final model



(Habelitz 2017)

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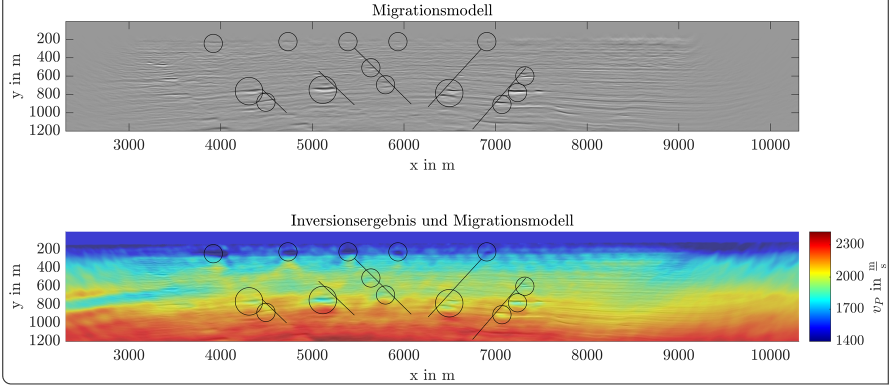
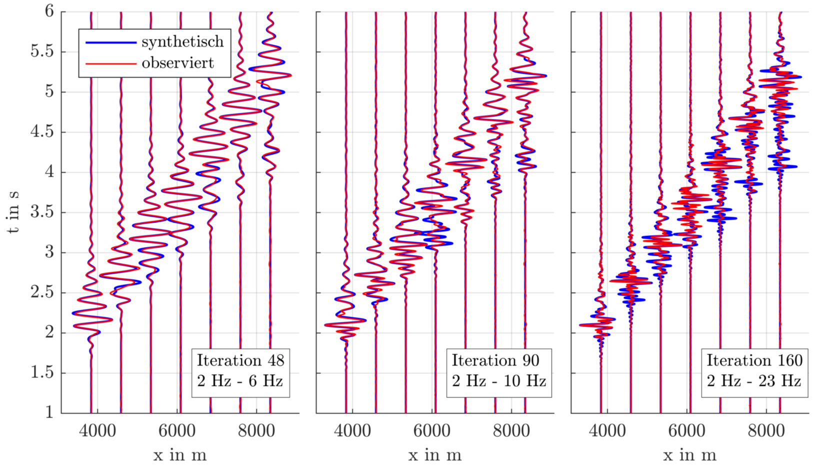
Final model



(Habelitz 2017)

FWI of OBC data in shallow water

Data fit



(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)

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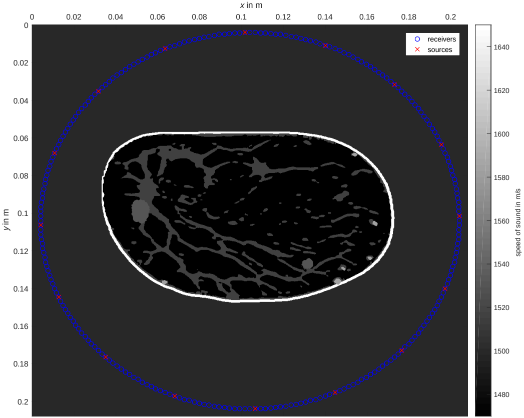
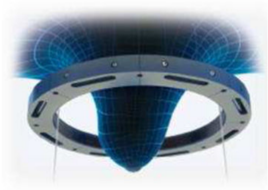
Acquisition geometry

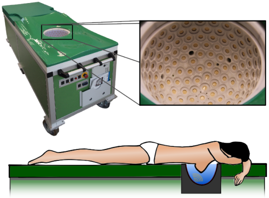
Click on frame to play movie



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)

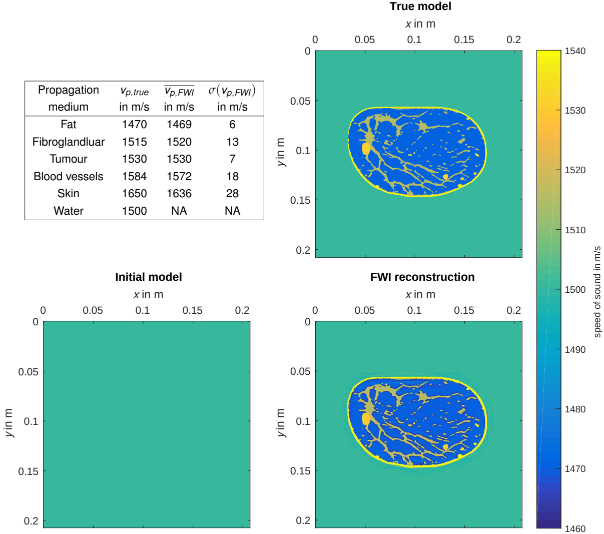


Prototype of a ultrasound device with a full
3D acquisition geometry (Ruiter et al., 2017).

(Kühn 2018)

Reconstruction of speed of sound

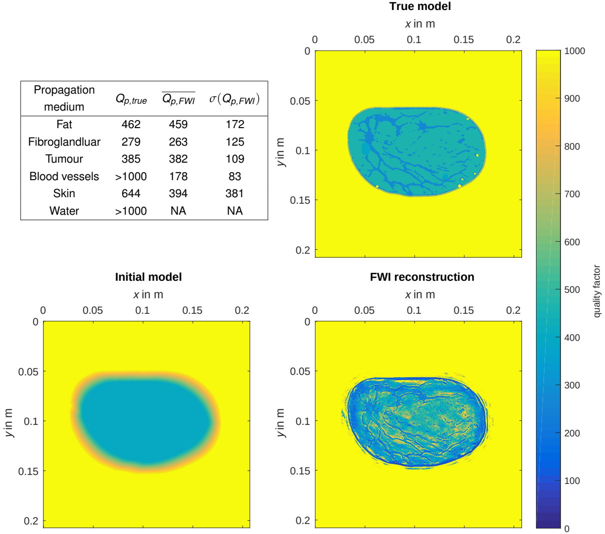
Propagation medium	$v_{p,true}$ in m/s	$\overline{v_{p,FWI}}$ in m/s	$\sigma(v_{p,FWI})$ in m/s
Fat	1470	1469	6
Fibroglandluar	1515	1520	13
Tumour	1530	1530	7
Blood vessels	1584	1572	18
Skin	1650	1636	28
Water	1500	NA	NA



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)

Visco-acoustic FWI for medical imaging

Conclusions

- 2D visco-acoustic FWI of synthetic data with good illumination works well
- Forward modelling is very expensive due to the high frequencies
- 3D applications are still prohibitive

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Conclusions

FWI

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.

Contribution of HPC toolbox WAVE

- Open-source modularized C++ library for FD simulation and optimization
- Performs well on different architectures
- Load balancing and partitioning
- Framework for joint-inversion with full signals/waves from other geophysical methods (EM, Gravity, ERT)

Acknowledgement

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Federal Ministry
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and Research

Thank you for your attention

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http://www.gpi.kit.edu/

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