Tomography across scales:
Knowledge transfer from seismology to imaging breast tissue with ultrasound

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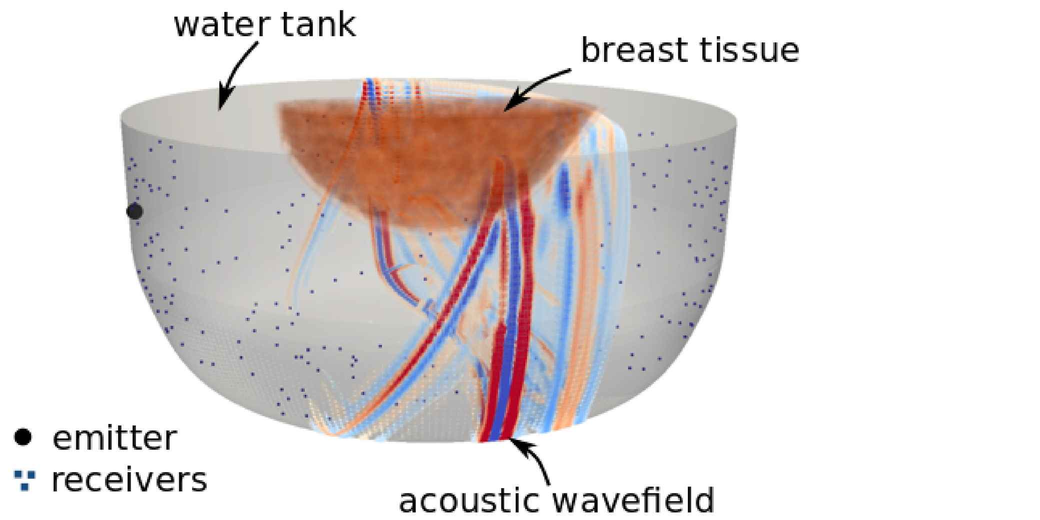
Ultrasound Computer Tomography

Ultrasound Computer Tomography (USCT) is an emerging technique for breast cancer screening. Ultrasonic waves are propagated through the tissue and recorded by a set of transducers that are surrounding the breast. The experiment collects transmission and reflection data, which are used to obtain quantitative images of acoustic properties of the tissue. This information is useful to characterize the breast tissue, and improves the specificity of standard imaging modalities.

Goal: Providing a diagnostic tool with high accuracy and clinically affordable time-to-solution (target: ~15 min/patient).



Motivation

Despite the vast scale differences, experiments in seismology and USCT share many similarities. In both fields, the relative wave speed variations are comparable and the number of propagated wavelengths in the domain has the same order of magnitude. Because the wave equation is scale invariant, the cross-fertilization between both fields will benefit imaging methods on all scales.

To foster the knowledge and technology transfer, this work presents methods from seismic tomography that we have recently introduced to USCT.

Similarities and Differences

Scale characteristics of typical experiments (Pratt, 2017):

	Exploration geophysics		USCT	
	Low frequency	High frequency	Low frequency	High frequency
Frequencies	2.5 Hz	25 Hz	1 MHz	3 MHz
Propagation distance	16 km	16 km	15 cm	15 cm
Background velocity	4000 m/s	4000 m/s	1500 m/s	1500 m/s
Number of wavelengths	10	100	100	300

Medium: Breast tissue is considered an acoustic medium with relatively low variations (<5%).

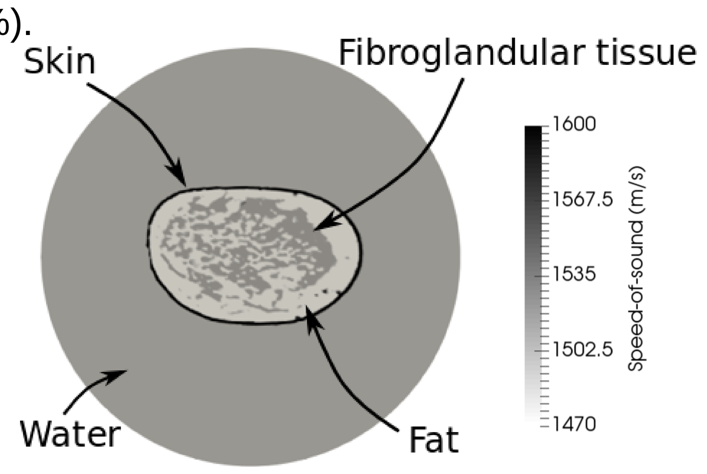


Figure 1. Synthetic phantom generated from MR data (Lou et al., 2017).

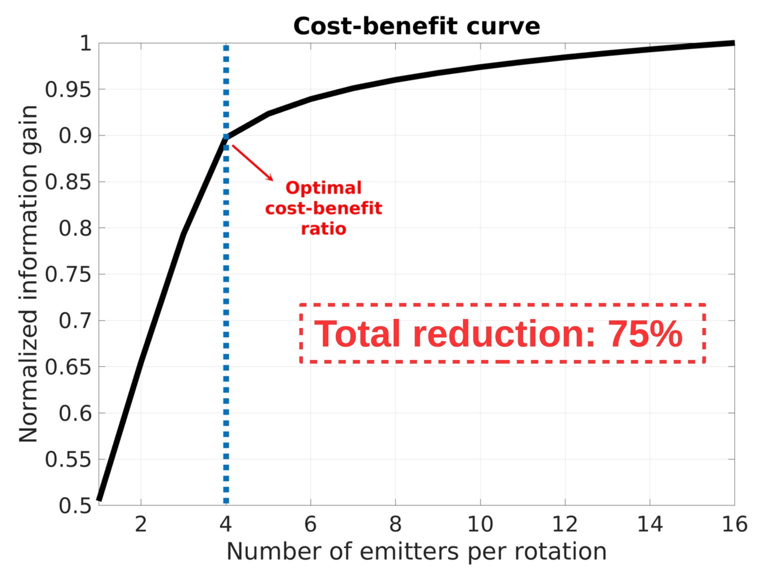
Optimal Experimental Design

We apply the Sequential Optimal Experimental Design (SOED) method to optimize the position and number of transducers, in terms of accuracy and cost, to image both reflection and transmission information. Using the Bayesian approach, we define the quality of a design as the determinant of the joint posterior covariance matrix, which defines the volume of the uncertainty ellipsoid of the parameters to estimate. SOED provides cost-benefit curves that quantify the information gain versus the computational cost. These are useful to control the trade-off between accuracy and practicality.

Lab data example:

Dataset (Camacho et al. 2012):
- >> 16 emitters x 176 receivers x 23 rotations
- >> Dominant frequency: 3.5 MHz
- >> Phantom: homogeneous background with 2 inclusions + 2 needles

Goal: Identify the most informative emitters to avoid redundant data.



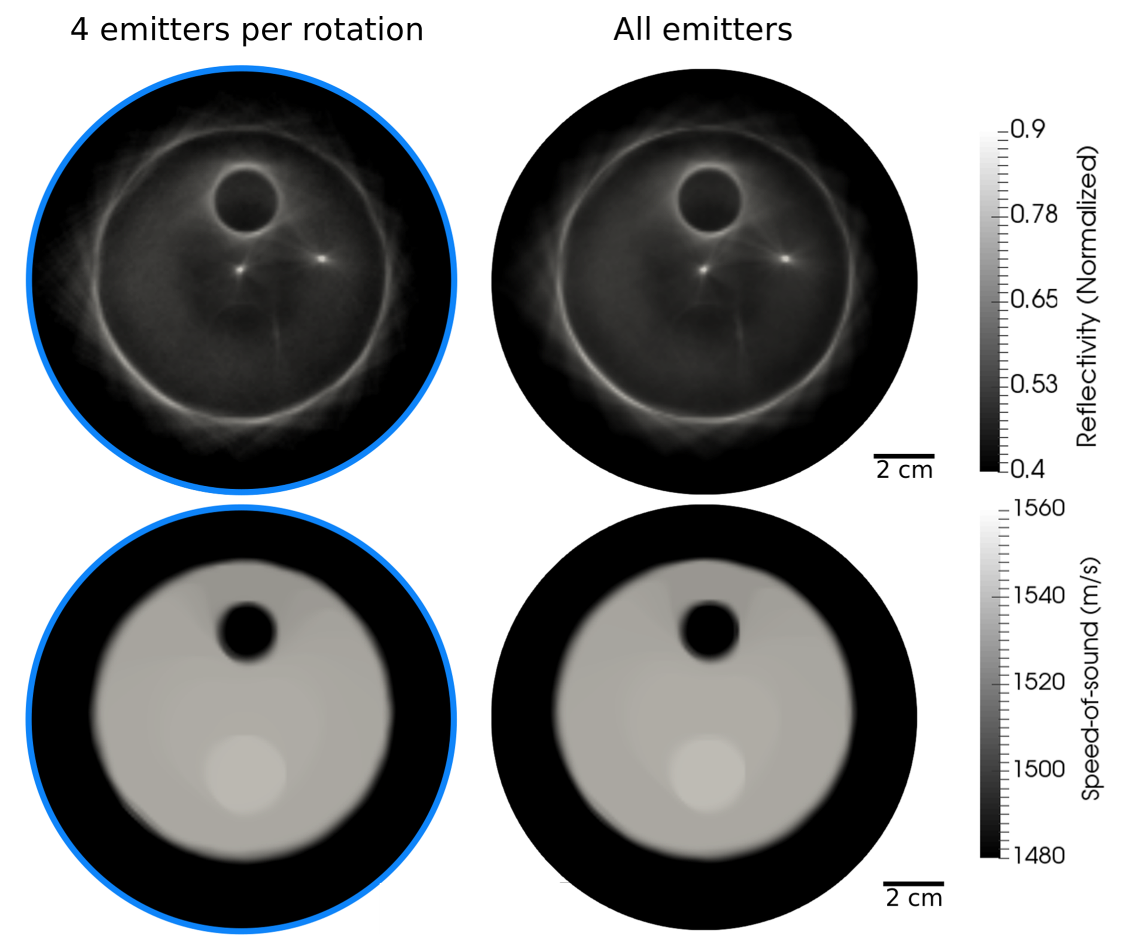
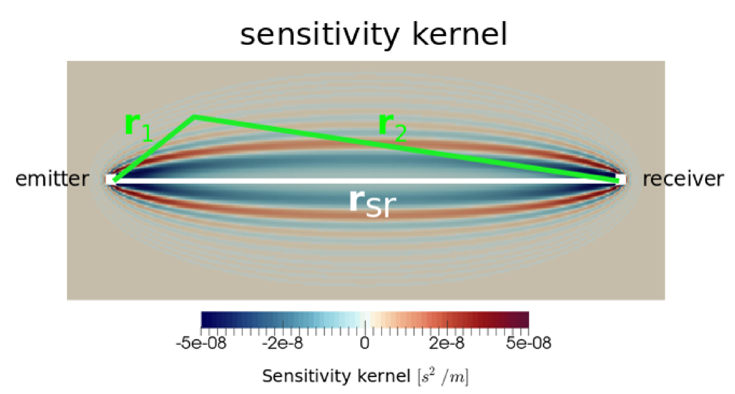


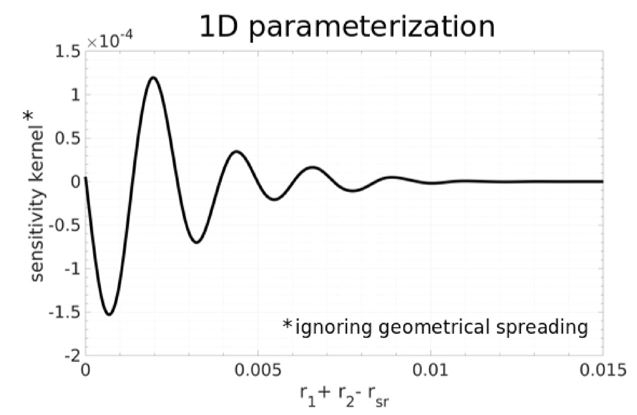
Figure 2. Reconstructions using the optimal emitter configuration (left column) and the full dataset (right column). B-mode technique (equivalent to Kirchoff migration) is used for reflectivity, and finite-frequency travel-time tomography for speed-of-sound.

Finite frequency travel-time tomography

We employ a linearized finite-frequency travel-time tomography approach for speed-of-sound reconstruction. Using the cross-correlation travel-time misfit functional, we compute the sensitivity kernels analytically using adjoint techniques. The background model is a homogeneous velocity model representing water, for which a calibration dataset is always available in USCT.

These sensitivity kernels can be represented by a 1D function. This avoids the explicit computation of the Jacobian matrix, which often requires large memory.





Potential: Our method can operate almost in real time while still including finite-frequency effects. It can also retrieve useful 3D information from 2D acquisition systems.

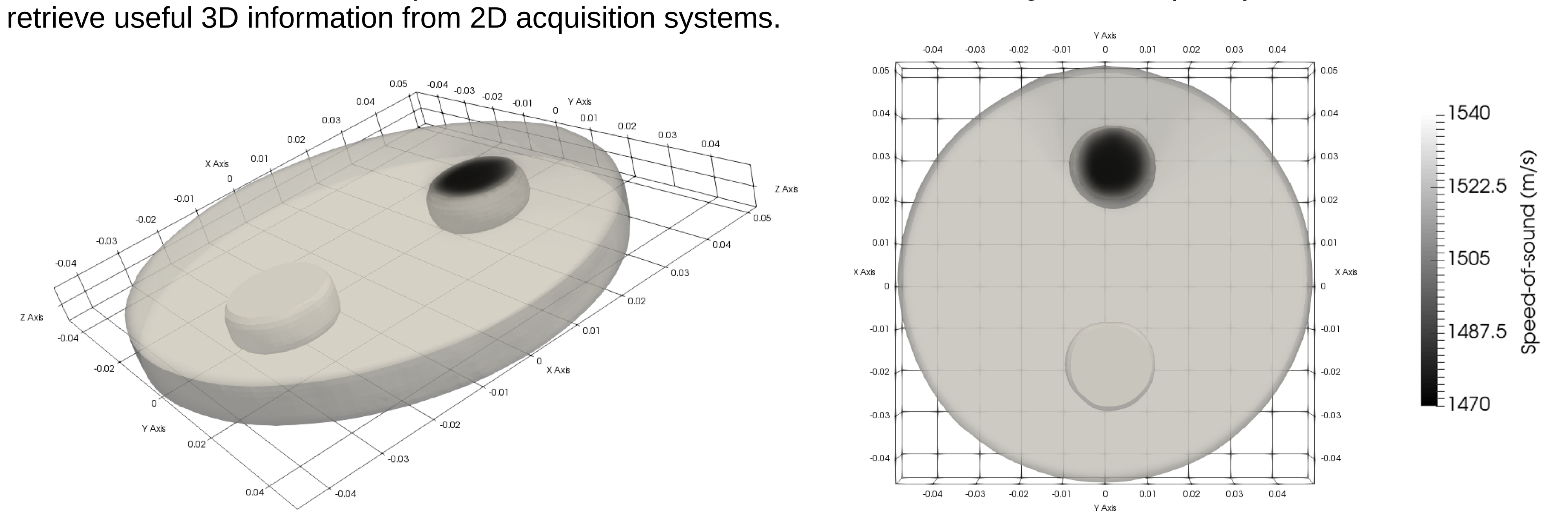


Figure 3. 3D reconstruction using the same dataset as in Figure 1.

Full Waveform Inversion

Over the last decade, full-waveform inversion has become the workhorse of seismic inversions from the exploration to global scale. Despite its huge potential for USCT, current computer and acquisition hardware impose significant challenges regarding the expected time-to-solution and availability of low-frequency transducers.

The images below show results of a synthetic inversion using the same aperture as in Camacho et al. (2012) with a center frequency of 250 kHz, and the numerical breast phantom provided by Lou et al. (2017). The computations were carried out with the spectral-element package Salvus (Afanasiev et al., 2018).

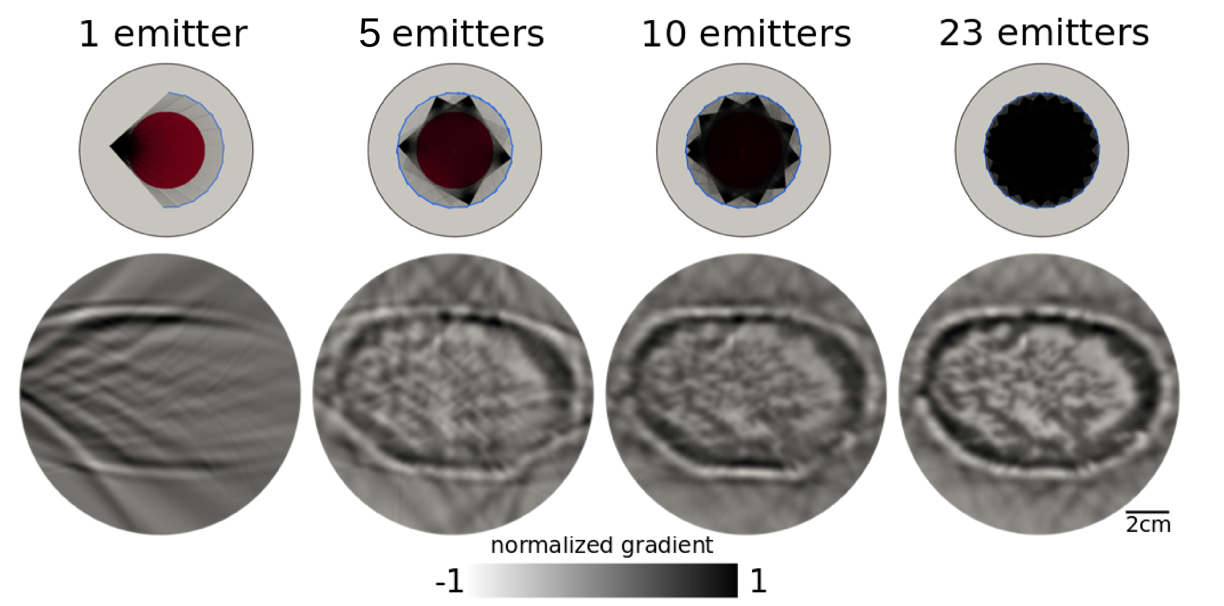


Figure 4. To reduce the computational cost per iteration and to exploit redundancies in the data, we use mini-batches of the emitters to approximate the misfit and its gradient. The top row illustrates batches of different sizes and their ray coverage within the region of interest (red), and the bottom row shows The sample average gradients quickly converge with only a small number of emitters.

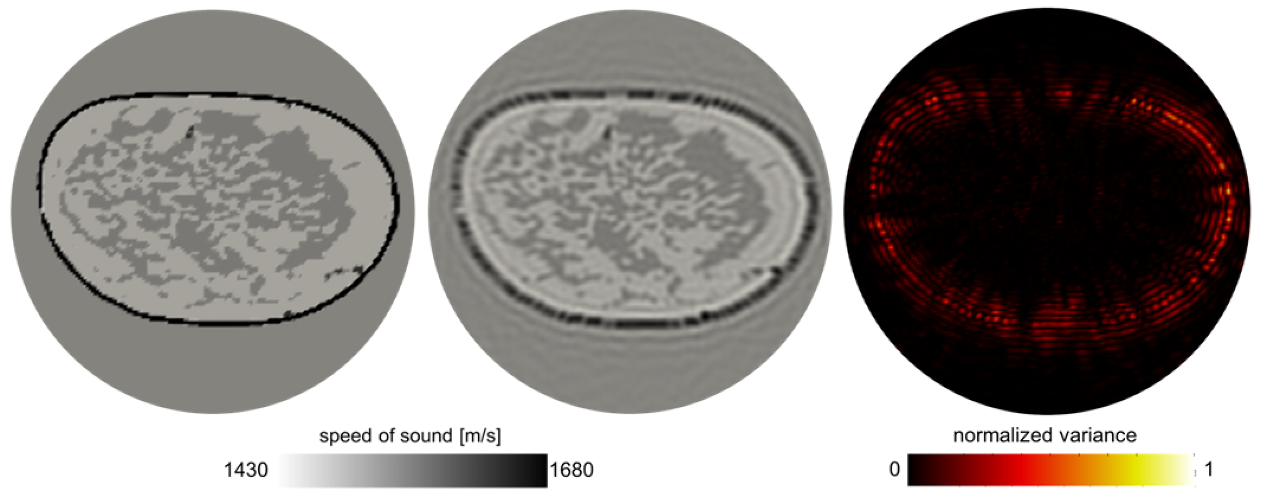


Figure 5. The full-waveform reconstruction after 42 mini-batch iterations reveals fine-scale tissue structure and matches very well with the true model. An estimate of the posterior variance based on a Gaussian approximation confirms the high resolution within the center of the phantom as well as inaccuracies close to the skin.

Conclusions

Seismology and medical ultrasound share many similarities that allow the knowledge transfer from one field to the other. However, major differences reside in the trade-off between accuracy and practicality that medical practice demands. To be meaningful, therefore, the transferred knowledge must recognize these differences, selecting and adapting the methods accordingly.

References:

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