Active Noise Tomography for Medical Ultrasound

Ines Elisa Ulrich, Christian Boehm, Andreas Fichtner
Institute of Geophysics, ETH Zürich
ines.ulrich@erdw.ethz.ch

ETH zürich

What is the idea?

- In medical ultrasound **random field interferometry** is widely unknown.
- But wavephysics apply on any scale!

⟶ Why not try a **new application for noise tomography?**

- In particular: **ultrasound computed tomography** (USCT) used in breast cancer screening.
- We want to tackle three challenges inherent to USCT:

(1) reduce acquisition time, (2) improve coverage, (3) eliminate unknown source wavelet

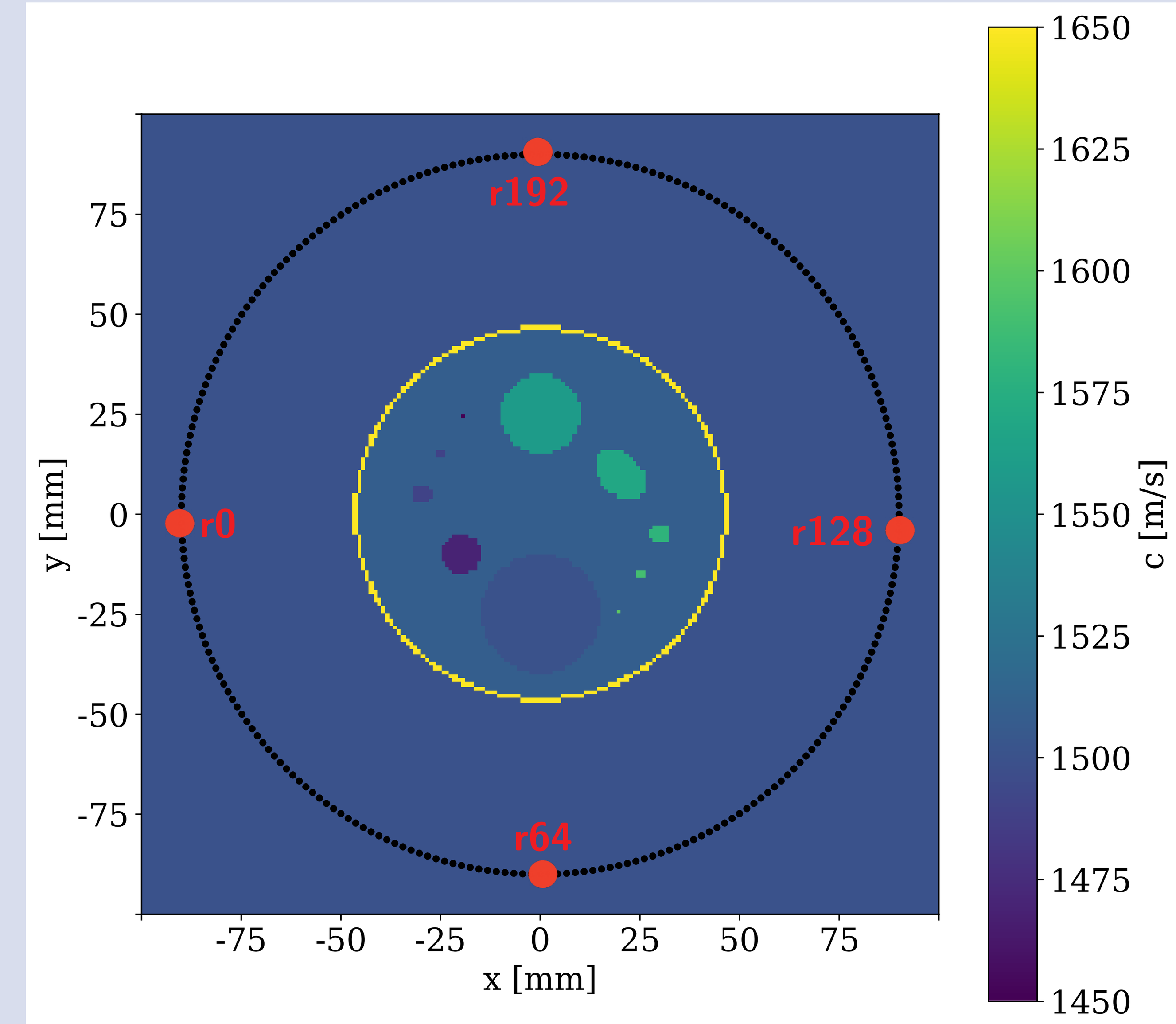
- Noise tomography offers the possibility to extract travel times between receiver pairs using cross-correlation functions instead of using individual source-receiver pairs.

⟶ **Cross-correlation functions eliminate a priori unknown source wavelets and are faster computed than travel times for every source-receiver pair**

⟶ **Retrieving the Green's functions allow us to increase the coverage**

Numerical setup of an USCT application

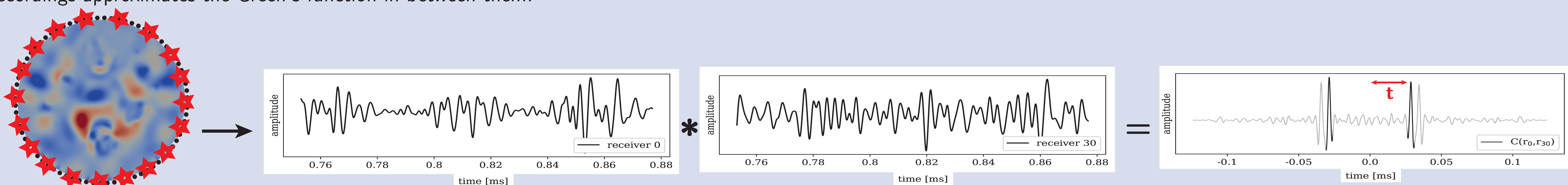
- Numerical phantom simulates horizontal slice through a breast.
- 2D ring array of transducers scans entire domain.
- A horizontal slice is modelled by a numerical phantom with varying speed of sound values.
- Medical setup allows for a full illumination of the medium.



What is the challenge?

In medical applications there are **no ambient noise sources** ⟶ Can a random wavefield be generated **actively**?

Yes! A joint firing of all the sources on a transducer array with time lags and varying amplitudes generates a **random wavefield** in which the cross-correlation function of two recordings approximates the Green's function in between them!



Active generation of a random wavefield

Cross-correlation of two recordings of the random wavefield

The travel time **t** between receiver positions maximizes the cross-correlation function

Take away

- There are applications of noise tomography outside of geophysics!
- Active noise tomography generates a random wavefield from a joint firing of available transducers.
- Source imprints on the waveforms are eliminated in the cross-correlation function.
- Calibration of sources is not needed anymore.

Interested to find out more? Suggestions/ ideas?

Feel free to visit my poster or talk to me in the video chat.

get the paper [1]:

[1] Ulrich, I.E., Boehm, C., Fichtner, A., "Random field interferometry for medical ultrasound", Proceedings of SPIE, 1319, 2020

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1. Introduction

In medical imaging, **random field interferometry** to extract travel times is widely unknown. We propose to apply the interferometry principle to extract travel time measurements between transducer pairs for an **ultrasound computed tomography setup** (USCT) frequently used in breast cancer screening.

USCT usually works with a collection of ultrasound scans that measure the pressure field emitted by individual transducers. To calibrate the sources, reference measurements are needed. By applying random field interferometry we are able to substitute the sequence of individual emitters by an **actively generated random wavefield** of simultaneously firing transducers. The **cross-correlation function of two receivers then approximates the Green's function** in between them and can be used to extract the travel time. Instead of solely relying on transmission data, reflections off the device boundary are included.

2. Methods

We shortly present the well known interferometry principle on the basis of Green's function retrieval via cross-correlation of two uncorrelated signals.

For a random wavefield, we assume the sources $f(\boldsymbol{x}')$ and $f(\boldsymbol{x}'')$ to be uncorrelated in time, such that

$$f^*(\boldsymbol{x}')f(\boldsymbol{x}'') = S(\boldsymbol{x}')\delta(\boldsymbol{x}'-\boldsymbol{x}''), \qquad (1)$$

where $S(\boldsymbol{x}')$ is the spectral density of the sources and $\delta(\boldsymbol{x}'-\boldsymbol{x}'')$ is the Delta function and * denotes complex conjugation. With this and following [1], we can write the forward wavefield between two measurement locations $\boldsymbol{x}_A$ and $\boldsymbol{x}_B$ as a cross-correlation $C(\boldsymbol{x}_A,\boldsymbol{x}_B)$ of the pressure wavefield at these locations in the frequency domain as

$$C(\boldsymbol{x}_A,\boldsymbol{x}_B) = p(\boldsymbol{x}_A)p^*(\boldsymbol{x}_B) = \int_D G(\boldsymbol{x}_A,\boldsymbol{x})G^*(\boldsymbol{x}_B,\boldsymbol{x})S(\boldsymbol{x})d\boldsymbol{x}. \qquad (2)$$

Here, $G(\boldsymbol{x}_A,\boldsymbol{x})$ and $G(\boldsymbol{x}_B,\boldsymbol{x})$ are the Green's functions relating the pressure wavefield at a measurement point to its sources that are assumed to be uncorrelated in time in the sense of eq. (1). Ultimately, we are interested in obtaining the Green's function $G(\boldsymbol{x}_A,\boldsymbol{x}_B)$ between two measurement points by making use of the cross-correlation function $C(\boldsymbol{x}_A,\boldsymbol{x}_B)$. Taking further assumptions on the nature of the wavefield and the properties of the domain, theoretical derivations [2] have proven that the **cross-correlation function is proportional to the Green's function** between two receiver positions and its time-reversed version $G^*(\boldsymbol{x}_A,\boldsymbol{x}_B)$ and takes the form [3]

$$G(\boldsymbol{x}_A,\boldsymbol{x}_B) - G^*(\boldsymbol{x}_A,\boldsymbol{x}_B) \propto i\omega C(\boldsymbol{x}_A,\boldsymbol{x}_B). \qquad (3)$$

Specific source imprints have been eliminated by the impulse responses of the Green's functions. This allows us to retrieve the wavefield between two receivers as if one receiver was an impulsive source and the other would record the emitted wavefield. The travel time between two receivers is then defined as the time delay that maximizes the cross-correlation function.

3. From seismology to medical imaging: similar problems, different length scales

In both, seismic imaging and medical imaging, we seek to infer the structure of a medium. The most striking difference, which is a direct consequence of the different length scales, is the frequency range deployed. In ambient noise applications, the length scales are on the order of **10-100 km** and frequencies range between **0.05 Hz-1 Hz**. In medical ultrasound, interesting propagation distances are on the order of **centimeters** with frequencies usually in the range **1 MHz-3 MHz**. The speed of sound of tissue is close to the speed of sound in water of **1500 m/s**. This results in a **large number of wavelength** in the transmission path increasing the computational costs. Moreover, **attenuation losses** in human tissue are more significant that in rocks [4].

For the proposed translation of the random field interferometry to medical length scales, the first challenge is the fact that **ambient noise sources are lacking in the medical application**. However, we have much more control on the location and the nature of the sources, thus a random wavefield can be **generated actively** by a joint firing of all the ultrasound emitters over a certain period of time. Reflections from the tank walls increase the randomness of the wavefield.

3. Proof of concept

To verify the algorithm, we attempt to reconstruct a 2D homogeneous background model simulating the numerical domain filled only with water. The data was acquired with a circular array of **256 transducers** as depicted in Figure 2, and a source signal generated with a central frequency of **1 MHz**. Knowing the receiver positions, the analytical solution for a homogeneous domain filled with water can be calculated. To evaluate the accuracy of the cross-correlation travel times, we compare them to the exact analytical solution and calculate the difference. Although the difference is not zero, Figure 1 suggests that the relative deviation of the cross-correlation travel times to the analytical solution is sufficiently small when compared to the influence of speed of sound variations within a numerical breast phantom (Figure 1 red curve) with respect to a homogeneous background model.

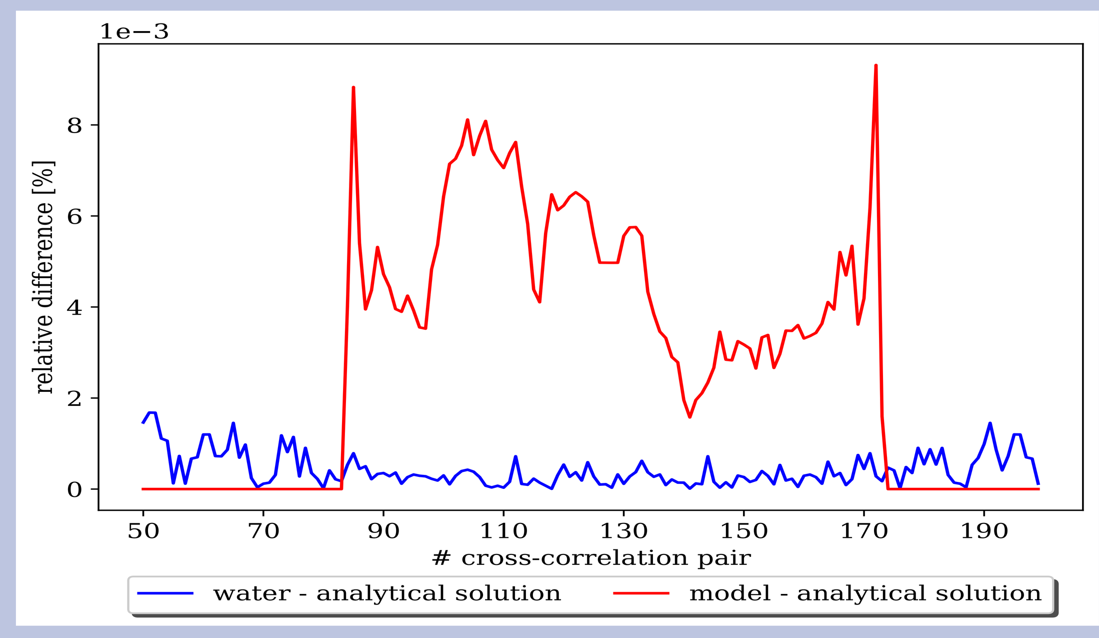

Figure 1. The relative difference between the cross-correlation travel times for water and the analytical solution for a homogeneous domain. In red, the relative difference of the travel time data derived directly from the numerical model (Figure 2) with respect to a homogeneous background is shown.

4. Phantom reconstruction

The goal of this work is to demonstrate that cross-correlation travel times from an actively generated random wavefield are sufficiently accurate to be used as data in a speed of sound inversion to reconstruct the spatial distribution of the speed of sound. To this end, we simulate numerical wavefield data with a central frequency of 1 MHz and 256 transducers using a **numerical model** representing a **coronal slice through a breast** as shown in Figure 2. To reconstruct the phantom, **travel time shifts between the cross-correlation times of flight and the analytical solution for a domain filled with water are calculated.** These travel time shifts are then used in a straight-ray time of flight inversion, which successfully resolves the larger structures of the phantom.

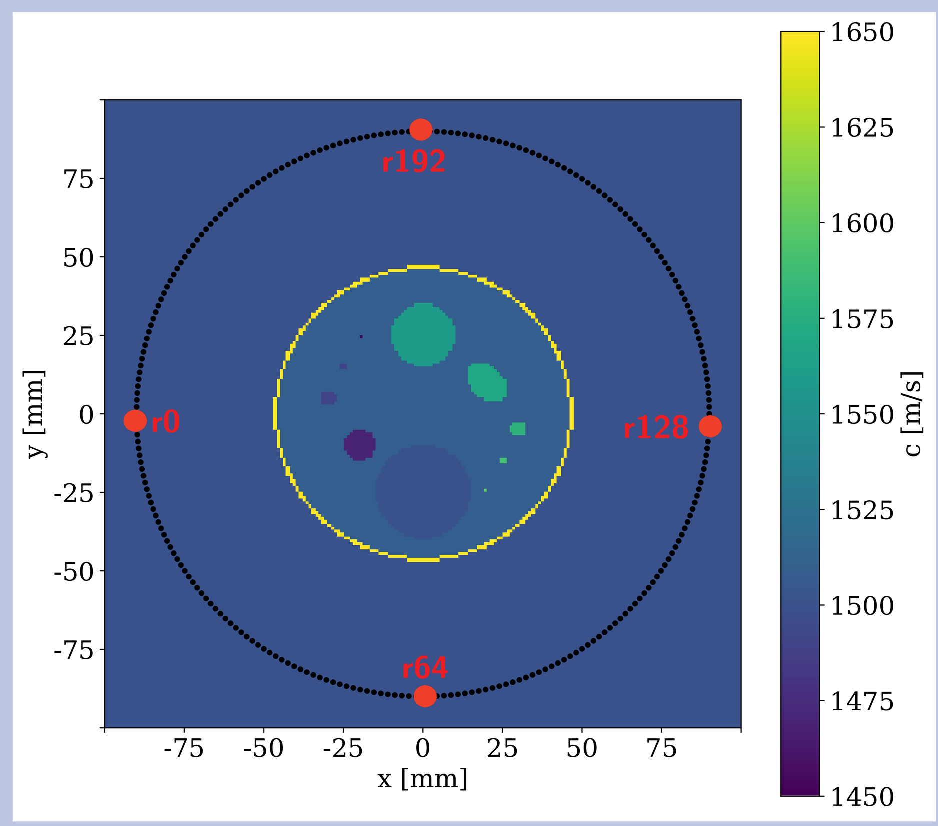

Figure 2. The 2D numerical phantom, modelling a coronal slice through the breast. The transducer array contains 256 sources and receivers marked by •.

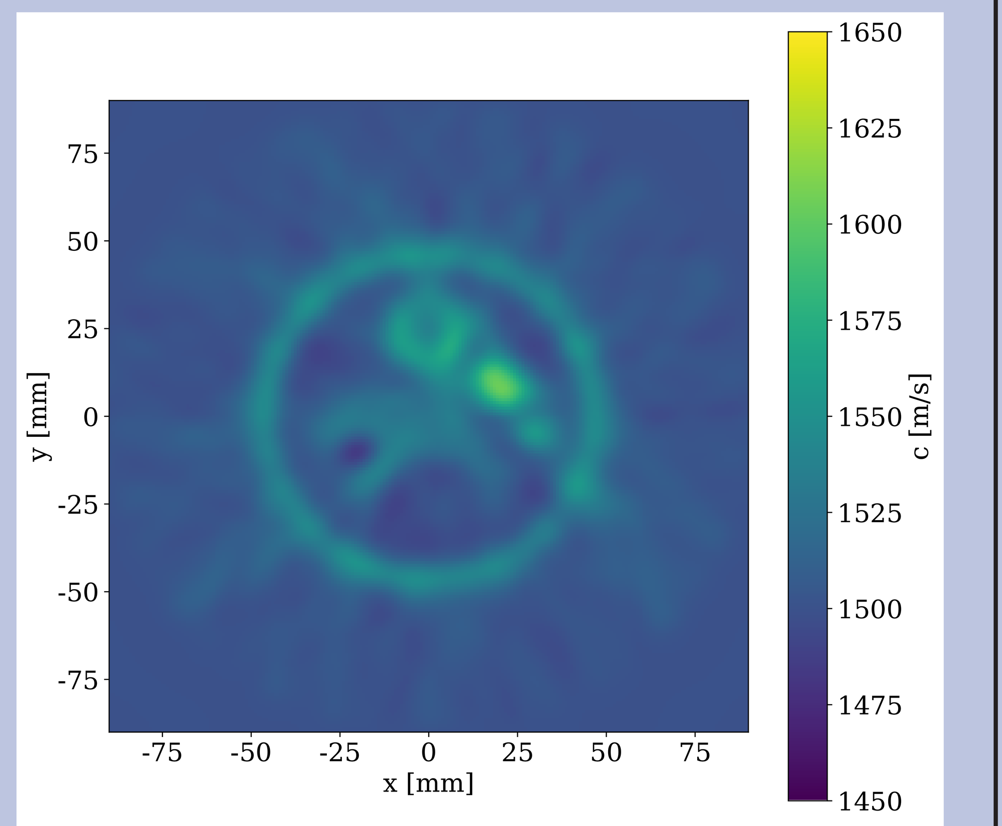

Figure 3. The reconstructed speed of sound map resulting from a straight-ray time-of-flight inversion. The problem has been regularized using second order Tikhonov regularization.

5. Conclusion

Applying random field interferometry to medical ultrasound opens new perspectives to **shorten** and **facilitate** the acquisition of a USCT data set. We made use of the fact that the cross-correlation function approximates the Green's function between two receivers in a random wavefield. We showed that **by cross-correlating receiver pairs in an actively generated random wavefield, travel times between any two receiver positions are obtained**. The proposed method has therefore three major benefits for the USCT setup:

(i) The cross-correlation eliminates time shifts caused by the a priori unknown source wavelet such that
(ii) Reference measurements to calibrate the sources are redundant;
(iii) The limited illumination of the target caused by the small opening angle of ultrasound transducers can be increased.

References

[1] Sager, K., Ermert, L., Boehm, C., and Fichtner, A., "Towards full waveform ambient noise inversion," Geophysical Journal International 212, 566–590 (10 2017)
[2] Wapenaar, K. and Fokkema, J., "Green's function representations for seismic interferometry," Geophysics 4(71) (2006)
[3] Fichtner, A., Nakata, N., and Gualteri, L., Seismic ambient noise, Cambridge University Press (2019)
[4] Pratt, R. G., Medical ultrasound tomography: lessons learned from geophysics, MUST proceedings 2017
[5] Ulrich, I.E., Boehm, C., Fichtner, A., "Random field interferometry for medical ultrasound", Proceedings of SPIE, 1319 (2020)

get the paper [5]: