Photoacoustic Tomography Using the k-Wave Toolbox

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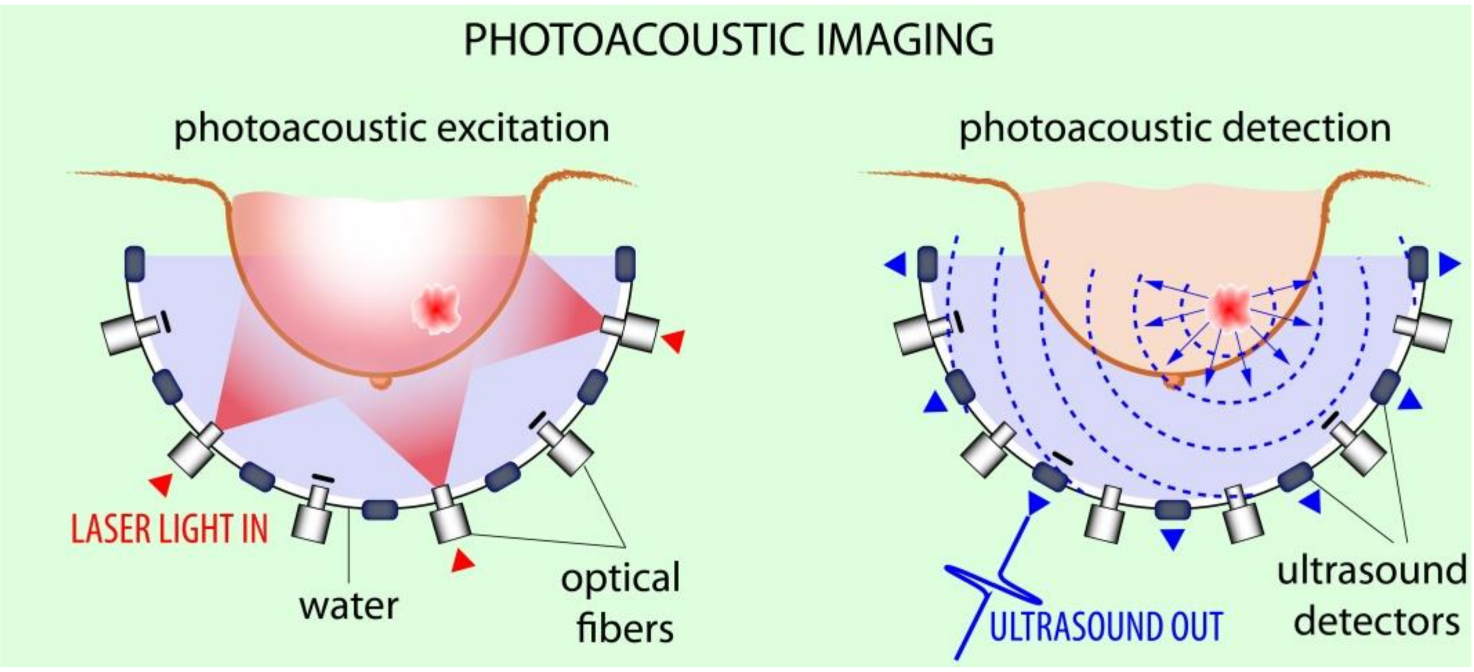
Overview

The photoacoustic tomography (PAT) is based on the fact that the chromophones in specific tissue, such as hemoglobin in veins and tumors, absorb the laser light. The absorbed light is transformed into heat and causes the thermoelastic expansion. This generates broadband ultrasonic waves in the tissue that can be captured by the ultrasound sensors.

The tumor tissue is rich on hemoglobin which leads to a stronger absorption of the near-infrared light than in the surrounding tissue. This provides a promising base for the breast tumor detection and comprises a strong advantage against the X-ray screening such as mammography.



Calculating Initial Acoustic Pressure Distribution

The expansion of the hemoglobin in veins and the tumors forms a pressure field p_0 inside the tissue. The process of the ultrasound measurement during the PAT can be described by following equation:

$$f = Ap_0 + \epsilon$$

where A is the forward operator which maps initial pressure p_0 from domain into a signal of time-varying pressure on sensors f. The ϵ represents error caused by temporal and spacial sub-sampling and limited position and size of the sensors.

Since direct inversion in high resolution produces artefacts, a variational image reconstruction technique based on minimization is used:

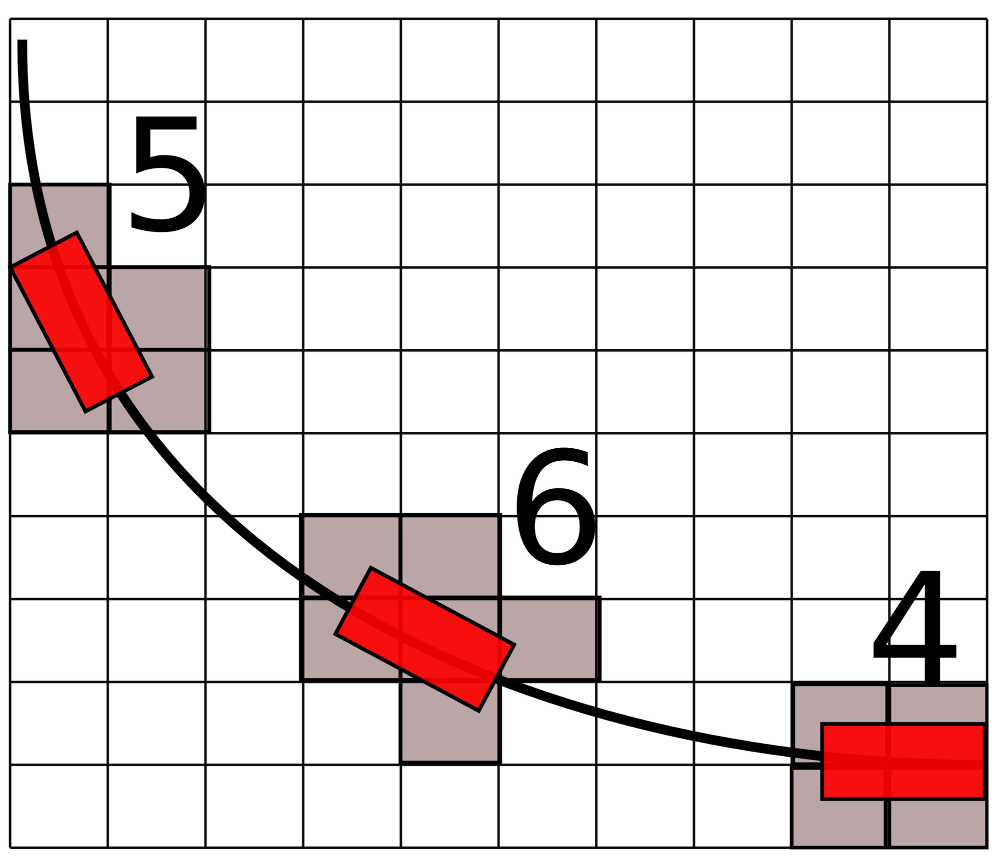
$$p_{rec} = \underset{p_0}{\operatorname{argmin}} \left\{ \tfrac{1}{2} ||Ap_0 - f||_2^2 \right\}$$

This minimization can be solved by a gradient descend algorithm using a step η ensuring the convergence and mapping from the pressure on sensors to initial pressure distribution A^*. The A^* has to be Hermitian adjoint to A.

$$p_{rec}^{k+1} = p_{rec}^{k} - \eta A^* \left(Ap_{rec}^{k} - f \right)$$

Sensor Model in High Resolution

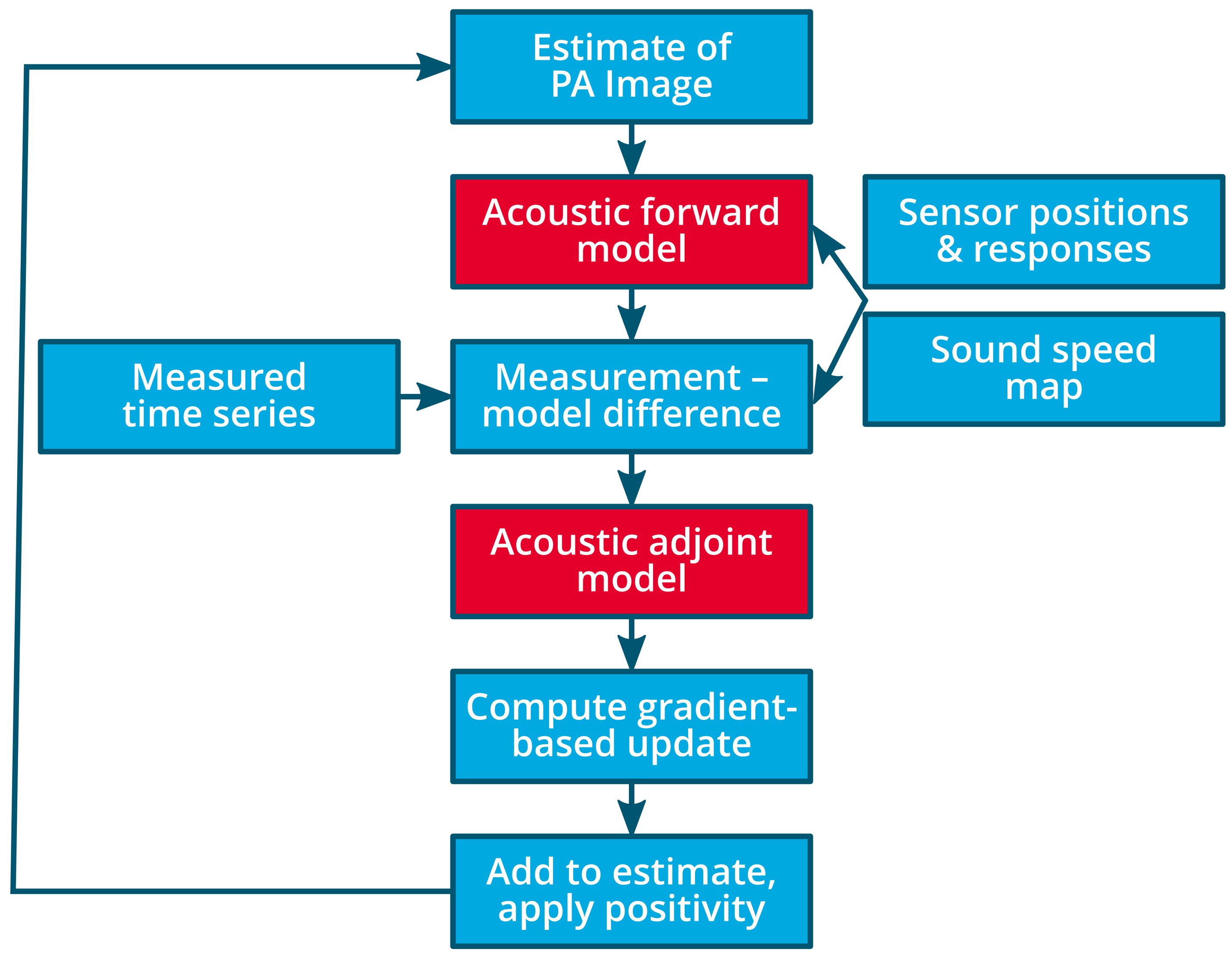
The k-Wave simulation records time varying pressure inside specific simulations voxels, given by the sensor mask. It is required to apply sensor characteristic on recorded signal for authentic representation of A.



The sensor mapping maps the signal of each sensor (red) from voxels (gray) that the sensor occupies. This reduces the size of the recorded signal but causes write conflicts in multi-thread execution.

Iterative Reconstruction Scheme

A single iteration of the gradient descent algorithm is shown below.



The blue blocks are tasks executed in Matlab. This tasks require a lots of memory and has to be run on Salomon's Fat Node. The red tasks are executed using an MPI code over 16 Salomon nodes.

Current Simulation Setup

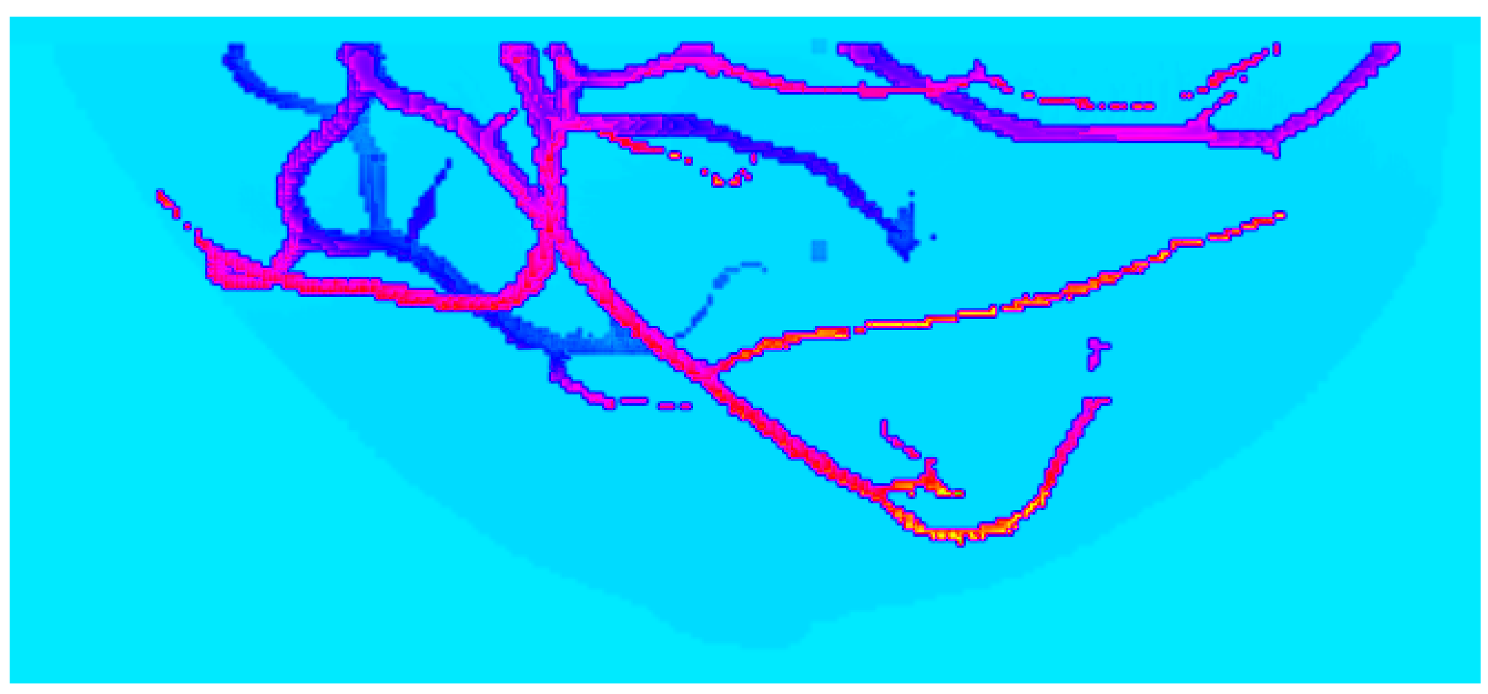
The PAT of single breast uses a sensor bowl with a radius of 10 cm, and broadband ultrasound sensors with a central frequency of 0.5 MHz. The simulation domain represents a cuboid with dimensions 20 $\times$ 20 $\times$ 14 cm and should support maximal frequency of 1.75 MHz. With four grid points per wavelength, the computational grid is composed of 1024 $\times$ 1024 $\times$ 672 grid points and has to compute 5220 timesteps. The average times of particular steps per iteration are shown in table below.

Task	Queue	Nodes	Time
Image Estimation	qfat	4	13 min
Forward Model	qprod	16	4 hours 57 min
Model Difference	qfat	4	41 min
Adjoint Model	qprod	16	4 hours 38 min
Compute Update	qfat	4	17 min
Total			10 hod 46 min

For the full reconstruction, 25 iterations of this gradient descent algorithm are performed. Furthermore, 30 evaluation of both acoustic models have to be used for the estimation of ideal gradient descent step. The whole reconstruction consumed approximately 160 000 core-hours.

Result Example

The figure below shows a side view of the reconstructed image of health breast phantom. The dark blue and red parts represents original pressure distribution in veins.



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