3D REGULARIZED SPEED-MAP RECONSTRUCTION IN ULTRASOUND TRANSMISSION TOMOGRAPHY

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Aim

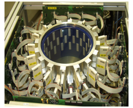
- for breast cancer diagnostics
- sound-speed closely related to the pathological tissue state
- stand-alone imaging application or for correction of reflectivity imaging algorithm

Challenge

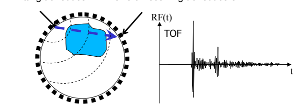
- Classical approach
  - -2D ring of transducers
  - -large (high) transducers – high SNR
  - -dense distribution of transducers
  - -only 2D information
  - -filtered backprojection (similarly to CT)
- Presented approach
  - -3D distribution of transducers
  - -small transducers – low SNR
  - -sparse distribution of transducers
  - -complete 3D information at once
  - -regularized algebraic reconstruction

Data acquisition

- tank filled with water
- transducers on surface
- each time one transducer in the emitter mode, all other transducers record the received RF signals
- all combinations of sending and receiving elements
- unfocused wave
- 6 motor positions



Algebraic sound-speed reconstruction



Contributions of voxels on the path: $TOF = \sum_i T_i$ $\quad T_i = d_i \frac{1}{c_i}$ $\quad TOF = \sum_i d_i s_i$

TOF	time-of-flight – time span between emitting and receiving of the first pulse
T_i	time-of-flight through i-th voxel
d_i	path length through i-th voxel
c_i	sound-speed in i-th voxel
s_i	time-of-flight per unit distance in i-th voxel (unknowns)

Path 1: $TOF_1 = \sum_{j=1}^{J} d_{1j} s_j$

Path 2: $TOF_2 = \sum_{j=1}^{J} d_{2j} s_j$

…

Path K: $TOF_K = \sum_{j=1}^{J} d_{Kj} s_j$

$$\left[d_{kj} \right] \cdot \left[s_j \right] = \left[TOF_k \right]$$

… overdetermined system of linear equations: $\mathbf{Rf} = \mathbf{p}$

Regularization

Why:

- errors in transmission pulse detection, hence also in TOF (wave front aberration, noise)
- some equations can be left out as outliers (wave front aberration, noise) => smaller degree of equation-set overdetermination
- sparse transducer distribution (technical limitations)

Solution formulation:

- incorporation of the spatial context in the reconstruction
- edge preserving regularization:

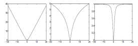
$$\mathbf{f} = arg \min_{\mathbf{f}} (\mathcal{J}_1(\mathbf{f}) + \lambda^2 \mathcal{J}_2(\mathbf{f}))$$

$$\mathcal{J}_1(\mathbf{f}) = \frac{1}{2} \|\mathbf{p} - \mathbf{Rf}\|^2$$

$$\mathcal{J}_2(\mathbf{f}) = \sum_k \phi[(D_x f)_k / \delta] + \sum_k \phi[(D_y f)_k / \delta] + \sum_k \phi[(D_z f)_k / \delta]$$

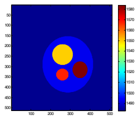
$\mathcal{J}_1(\mathbf{f})$	least-squares term
$\mathcal{J}_2(\mathbf{f})$	regularization term
$D_x f, D_y f, D_z f$	differences between neighboring voxels
δ, λ	regularization parameters
ϕ	potential (penalization) function:

Possible potential functions:

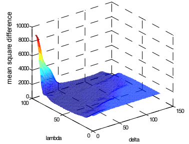


Results on synthetic data

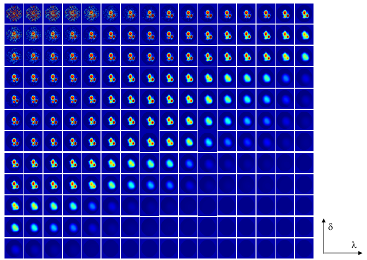
Synthetic phantom:



Estimation of regularization parameters:

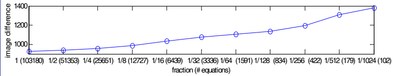


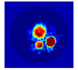
Corresponding reconstructed images:



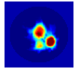
Results on synthetic data

Robustness with respect to degree of equation-set overdetermination:

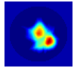




all equations



1/16 of equations

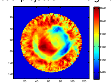


1/256 of equations

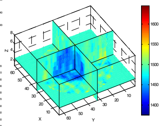
Results on recorded phantom data

breast phantom:

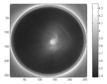
backprojection FDK alg. result:



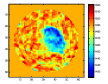
3D reconstruction example:



reference reflectivity img.:



regularized alg. result:



Conclusions

- algebraic reconstruction for sparse distribution of transducers possible with regularization
- regularization parameters – compromise between edge preserving and spatial consistency
- optimal regularization parameters found for simulated data (with SNR same as in reality – 11dB)
- optimal regularization parameters – valley, not separate point
- image reconstruction still reasonable with a low fraction of the complete equation set => wide space for selection of only "good" equations (RF signals)
- phantom measurements gave clear breast delineation
- regularized reconstruction provided better breast delineation than FDK filtered backprojection
- need for better evaluation
  - need for measurements on sound-speed phantom with known ground-truth sound-speed values
  - need for more realistic simulation used for synthetic data generation
- part of volume processed so far due to memory limitations – need for distributed equation solver

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