Sparsity-promoting photoacoustic imaging with source estimation

Rajiv Kumar[1], Diego Dumani[2,3], Shashin Sharan[1], Mathias Louboutin[4], Rongrong Wang[5], Stanislav Emelianov[2,3], Felix J. Herrmann[1,2,4]

[1]School of Earth & Atmospheric Sciences and [2]School of Electrical and Computer Engineering, Georgia Institute of Technology
[3]Department of Biomedical Engineering, Georgia Institute of Technology and Emory University
[4]School of Computational Science and Engineering, Georgia Institute of Technology
[5]Department of Computational Mathematics, Science and Engineering, Michigan State University

Motivation

Photoacoustics has emerged as a high-contrast imaging modality that provides optical absorption maps inside of tissues, therefore complementing morphological information of conventional ultrasound [1]. The laser-generated photoacoustic waves are usually envelope-detected, thus disregarding the specific waveforms generated by each photoabsorber [2]. We propose an image reconstruction method that allows the estimation of each photoabsorber's source-time function, thus providing additional information even when the number of transducers is reduced.

Methodology

Assuming that the photoacoustic pressure wave sources are localized in space with finite energy in time, we solved a strongly convex problem:

Minimize $\mathbf{Q}$

$$\|\mathbf{Q}\|_{2,1} + \frac{1}{2\mu}\|\mathbf{Q}\|_F^2$$

Subject to

$$\|\mathcal{F}[\mathbf{m}](\mathbf{Q}) - \mathbf{d}\|_2 \leq \epsilon$$

where $\|.\|_F$ is the Frobenius norm

for the unknown source wave field $\mathbf{Q}$ while fitting the observed data $\mathbf{d}$ within the noise level ϵ using a linearized Bregman algorithm [4]. We used a gradient descent accelerating method, specifically a quasi-Newton method, to accelerate the iteration converge and achieve a computationally efficient algorithm.
F[m] is the acoustic equation modelling operator, parameterized by the slowness (inverse of speed) square $\mathbf{m}$ of the medium. The parameter μ controls the tradeoff between the sparsity promoting terms and the strong convexity term.

To validate the proposed framework, we generated a vessel phantom (Fig. 1) using finite element simulations and the k-Wave toolbox [5]. A 360° circular array was simulated to receive the photoacoustic waveforms. The algorithm was tested using dense sampling (Fig. 2) and sparse sampling (Fig. 3). Additionally, a phantom with heterogenous speed of sound (Fig. 4) was simulated.

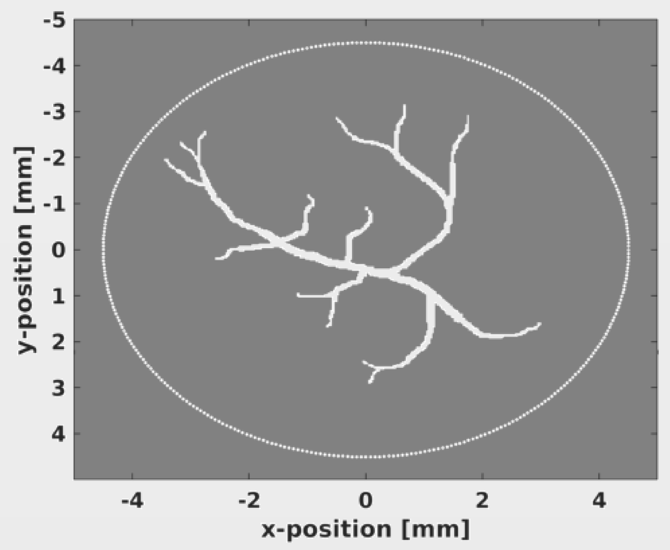

Fig. 1. (a) Vessel phantom used for simulations. The circular array of transducers is represented by white dots

Two-dimensional source estimation

Two-dimensional reconstruction and source estimation simulation using circular arrays with varying number of detectors.

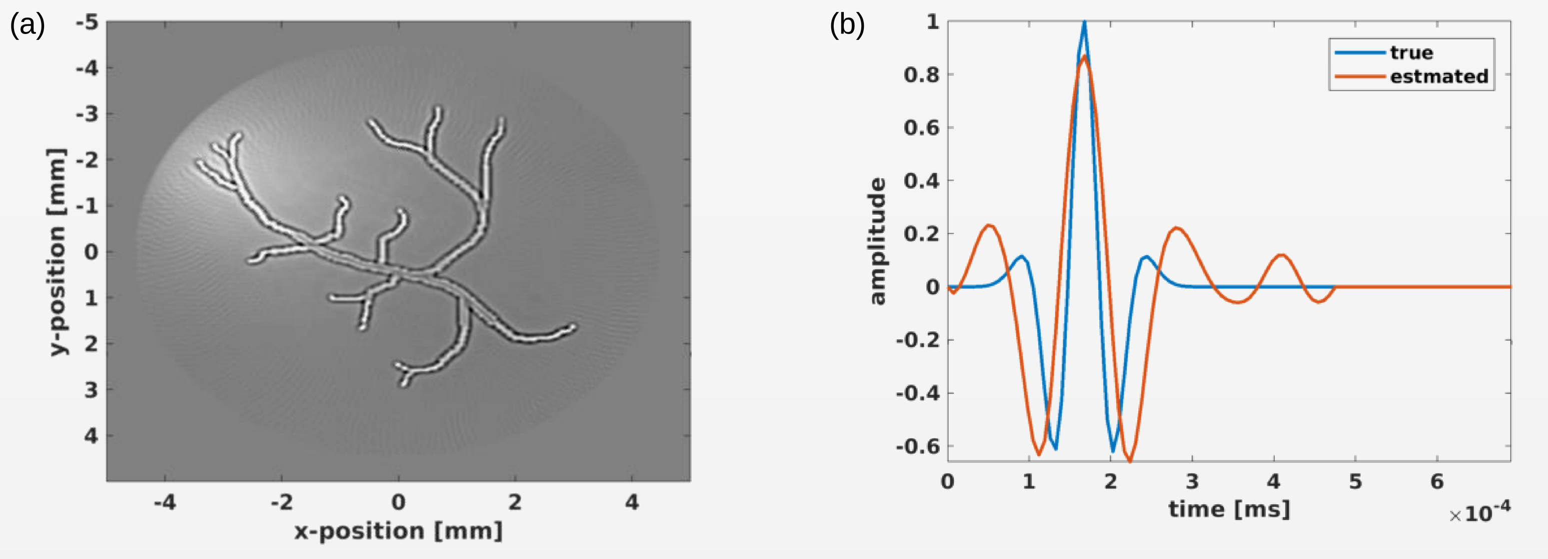

Fig. 2. (a) Image reconstructed using our proposed method with an array of 360 transducers (1° separation). (b) A source-time waveform at a location within the vessel

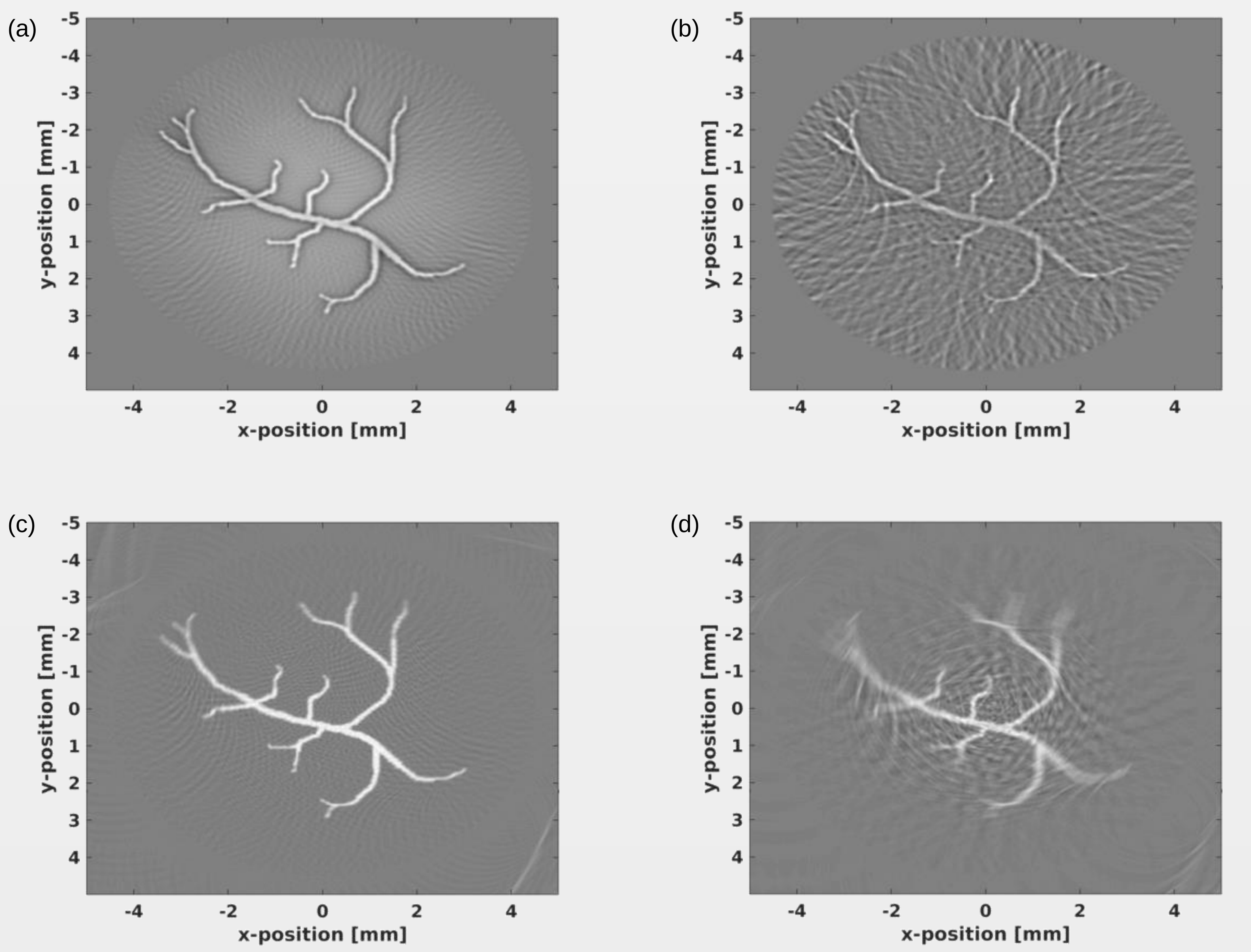

Fig. 3. Receiver sparsity experiment showing reconstructed images with an array of transducers with (a) 2-degree and (b) 6-degree separation using proposed method. Images reconstructed using conventional backprojection are also show using transducers at every (c) 2 degrees and (d) 6 degrees..

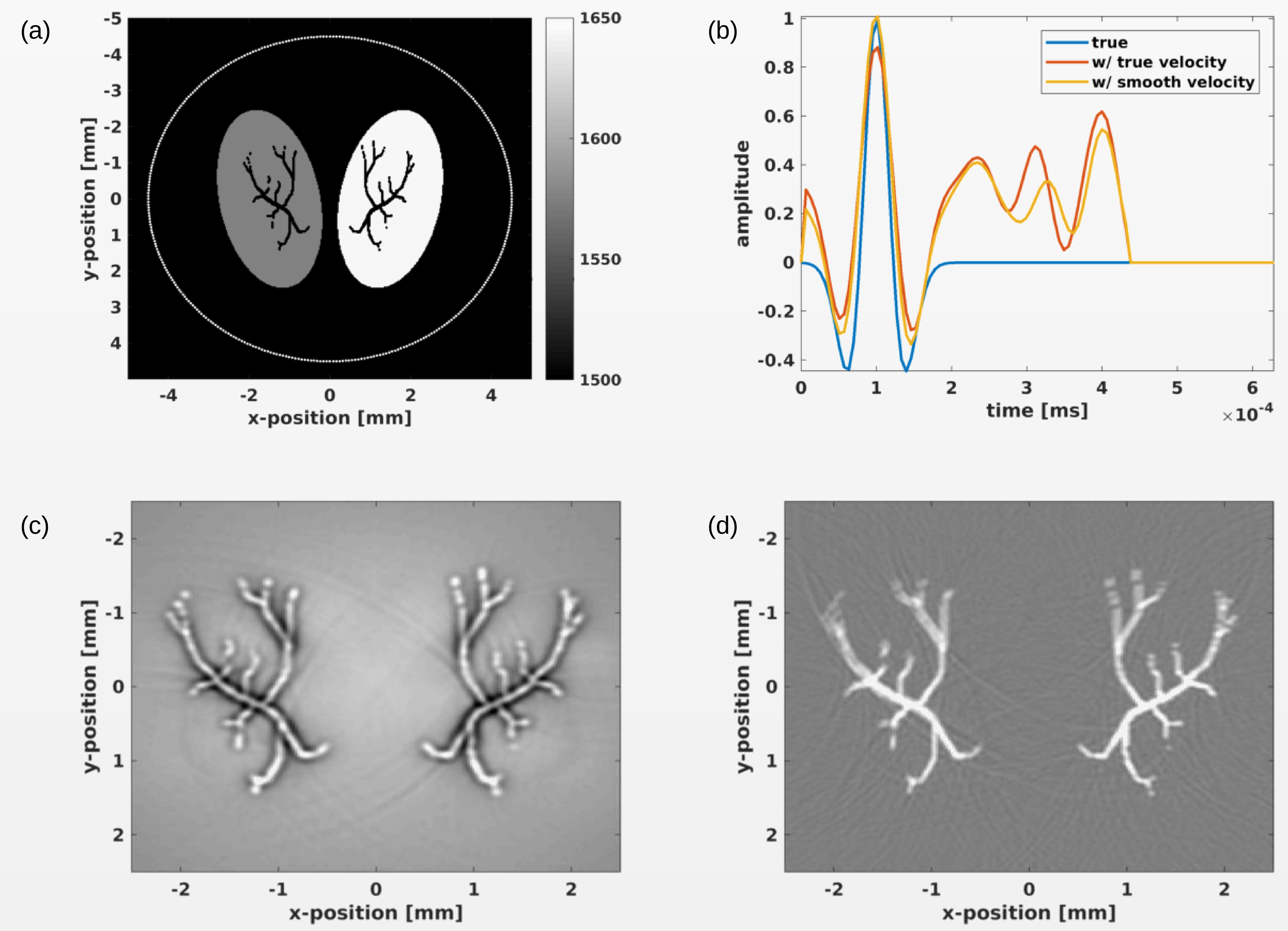

Fig 4. (a) Heterogeneous background speed of sound phantom. (b) Source-time functions with the true and smoothed velocity reconstruction. Reconstructed photoabsorber image (zoomed) using smooth velocity with (c) proposed method and with (d) k-Wave backprojection.

Discussion

- The proposed method would allow to study the waveforms at the photoabsorber origin.
- A lower number of transducers may be used while still recovering an image. This could be applied in the future for tomographic 3D image reconstruction, potentially reducing acquisition times thus increasing time resolution.
- In comparison with conventional backprojection method, the proposed method showed an improvement when the number of receiving transducers was reduced.
- This method could potentially be explored to distinguish different types and conditions of photoabsorbers, e.g., the degree of aggregation of exogenous agents, under the assumption that these would generate different waveforms at the moment of laser irradiation.

Conclusions and future work

- The full source wave field was recovered without making assumptions on the source-time mechanism for each source pixel.
- Future studies will test the algorithm using tissue mimicking phantoms.
- Additionally, the method will be generalized towards 3D image reconstruction.

References

1. Emelianov, Stanislav Y., Pai-Chi Li, and Matthew O'Donnell. Physics today 62(8), 34. 2009
2. Park, Suhyun, Andrei B. Karpiouk, Salavat R. Aglyamov, and Stanislav Y. Emelianov. IEEE IUS, 2008.
3. Fabio Luporini et. al., Architecture and performance of Devito, a system for automated stencil computation. CoRR, abs/1807.03032, 2018.
4. Shashin Sharan et. al., Fast sparsity-promoting microseismic source inversion. Geophys. J. Int., in press. 2018.
5. Treeby, Bradley E and Cox, Benjamin, International Society for Optics and Photonics, 2010.

Acknowledgments

Seismic Laboratory for Imaging and Modeling

Ultrasound Imaging and Therapeutics RESEARCH LABORATORY