Poster presentation | Poster session
Poster Session
Thu. Jul 18, 2024 4:30 PM - 6:30 PM Room P

[PO-09] Detection of Bubble Size and Location using Ultrasound Simulation with Machine Learning

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Keywords: Ultrasound imaging, Multiphase flow, Bubbly flow, Machine learning, Deep Neural Networks

Ultrasound Imaging Using Machine Learning

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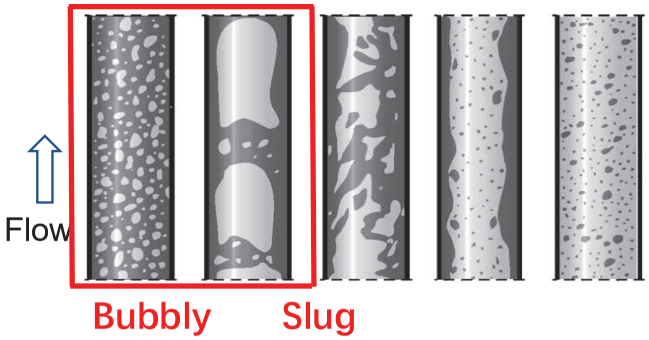
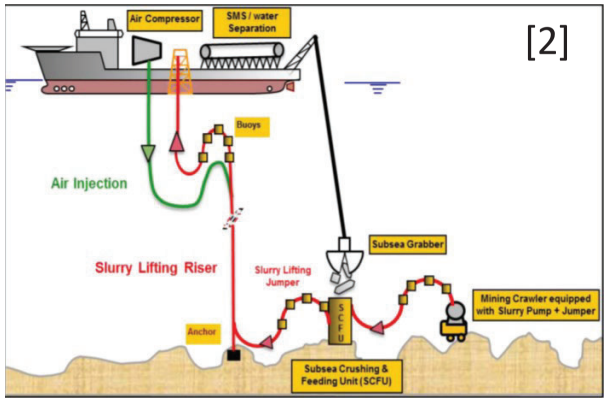
2024.7.3

Research Background –Ultrasound Imaging

Bubble imaging in airlift pumps

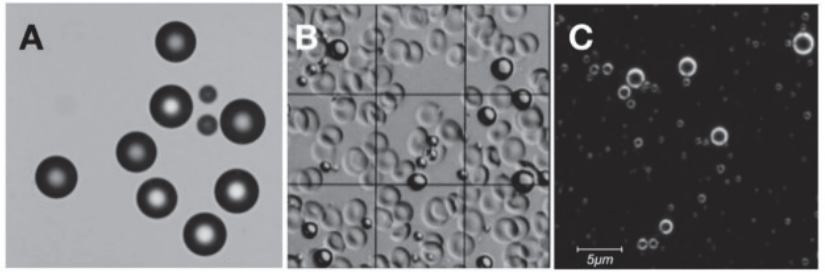


[1]



[2]

Red blood cell (RBC) imaging



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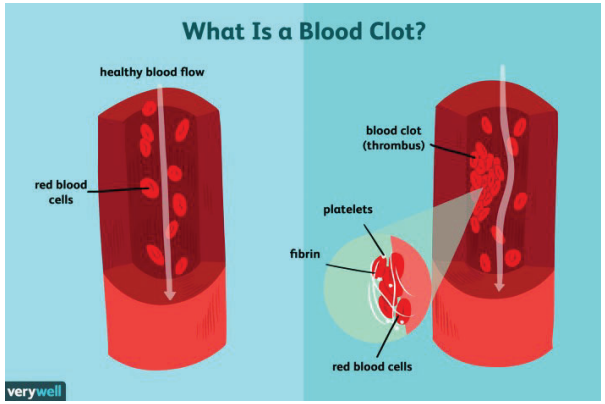
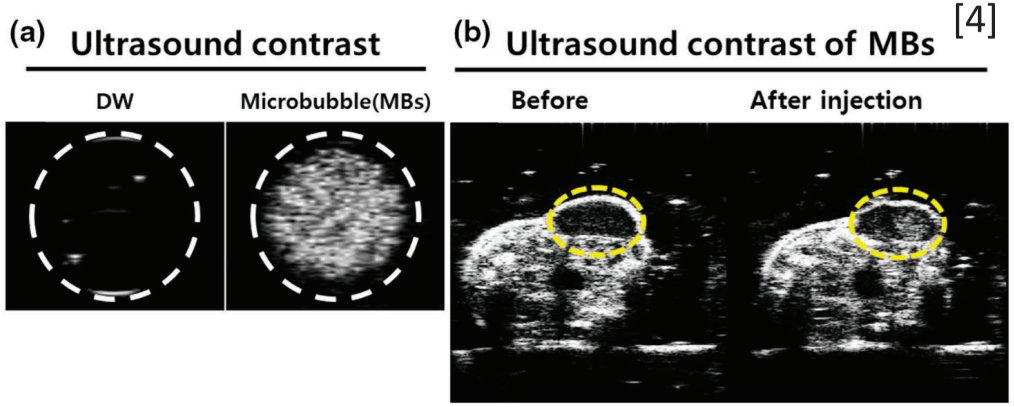


Microbubble(MB) Imaging



[4]

[1] Dziubinski, K, et al., Flow Meas Instrum, Vol.30, 2004.
[2] Saito, T.et.al., In: Proceedings OCEANS, (1989), No.592812
[3] Versluis, et al., Ultrasound in medicine & biology, 2020.
[4] R. Ajit et al., The American journal of cardiology 90.10 (2002): 3-7.

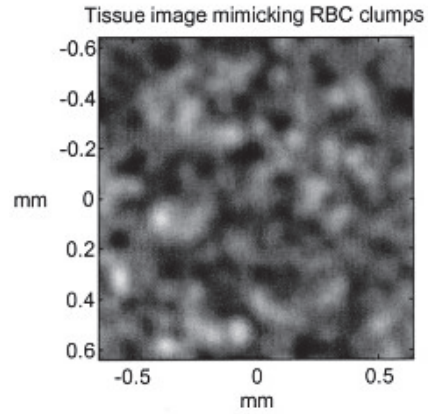
Research Background – RBC imaging

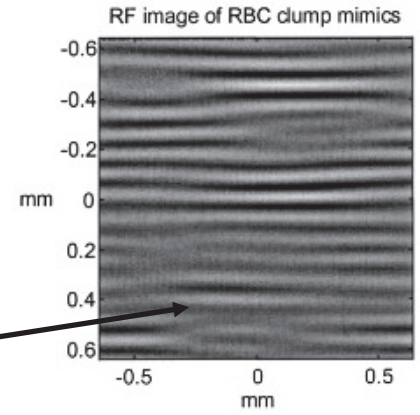
RBC imaging difficulty

- Size:
  - RBC size: 6-8 micrometers;
  - Ultrasound wavelength: 0.5 millimeters of 3MHz.
- Movement:
  - RBCs are moving in blood flow;
  - May cause blurring and distortion.
- Low contrast:
  - Acoustic properties are similar with surroundings.

Complexed interpretation

[5]



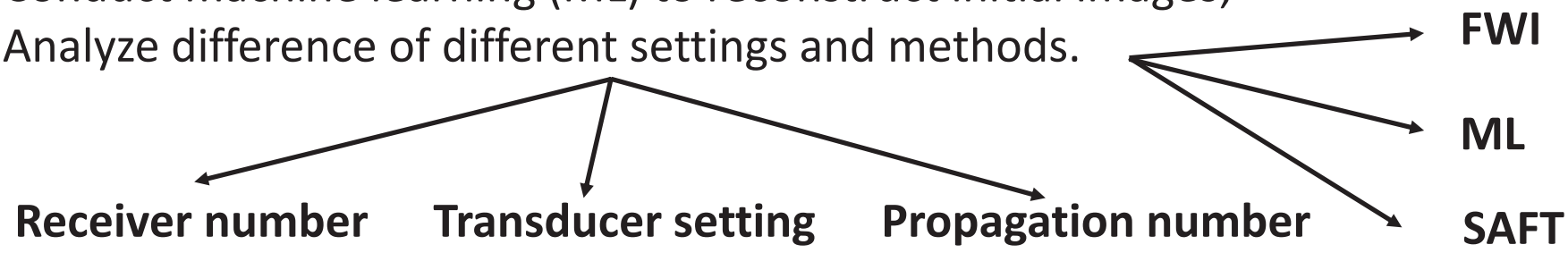


[5] Paeng D G, et al., Journal of Visualization, 2009, 12(4): 295-306.

Research Objectives and Methods

- Objectives:
  - To model the ultrasound propagation in biological environments and blood flows;
  - To apply algorithm to translate Radio Frequency (RF) data into images.

- Methods:
  - Conduct the process on bubbles, MBs, micro droplets and RBCs sequentially;
  - Use Full Wave Inversion (FWI) for speed of sound reconstruction;
  - Conduct machine learning (ML) to reconstruct initial images;
  - Analyze difference of different settings and methods.

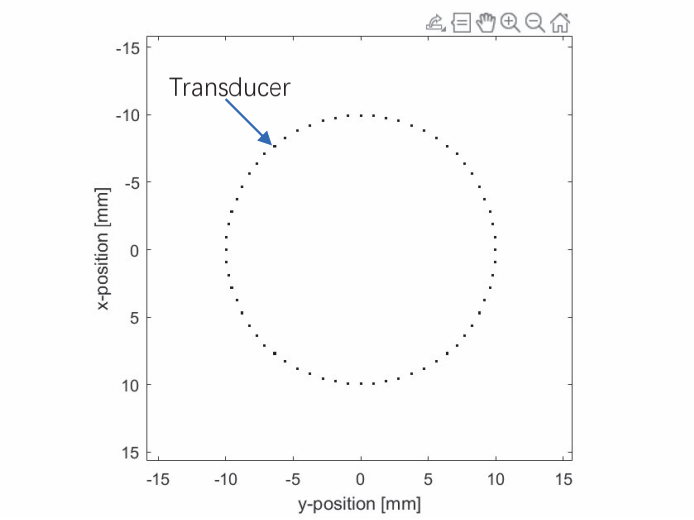


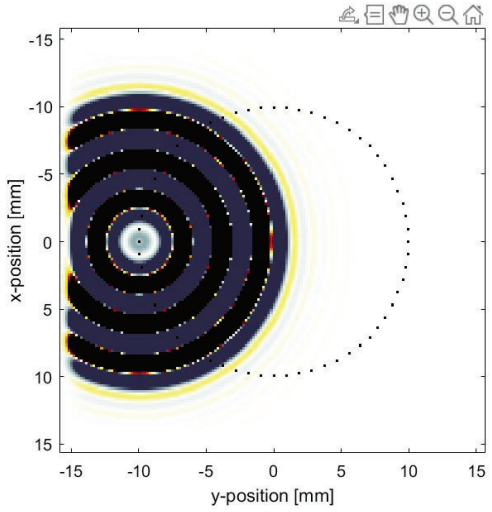
Ultrasound simulation

K-wave simulation

K-wave package is designed specially for time domain acoustic and ultrasound simulations in complex media.

Bubble phase is assigned by configuration and ultrasound propagation equations are solved.





Ultrasound simulation

Governing equations

$$\frac{\partial \mathbf{u}}{\partial t} = -\frac{1}{\rho_0}\nabla p \qquad \text{(momentum conservation)}$$

$$\frac{\partial \rho}{\partial t} = -\left(2\rho + \rho_0\right)\nabla \cdot \mathbf{u} - \mathbf{u} \cdot \nabla \rho_0 \qquad \text{(mass conservation)}$$

$$p = c_0^2\left(\rho + \mathbf{d} \cdot \nabla \rho_0 + \frac{B}{2A}\frac{\rho^2}{\rho_0} - \mathrm{L}\rho\right) \qquad \text{(pressure-density relation)}$$

Absorption follows a frequency power law $\alpha = \alpha_0 \omega^y$

$$L = \tau \frac{\partial}{\partial t}(-\nabla^2)^{\frac{y}{2}-1} + \eta(-\nabla^2)^{\frac{y+1}{2}-1}$$

Dispersion

$$\tau = -2\alpha_0 c_0^{y-1}, \qquad \eta = 2\alpha_0 c_0^y \tan\left(\pi y/2\right),$$

B mode imaging

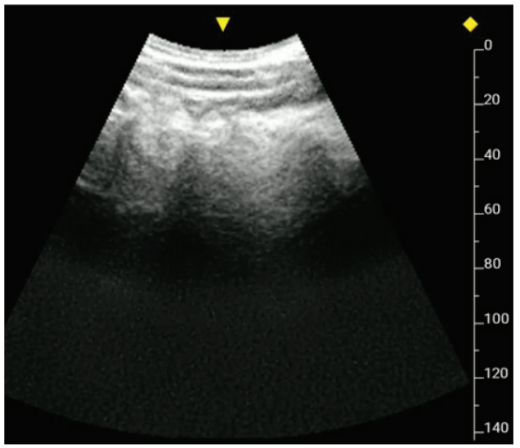
Advantages and disadvantages

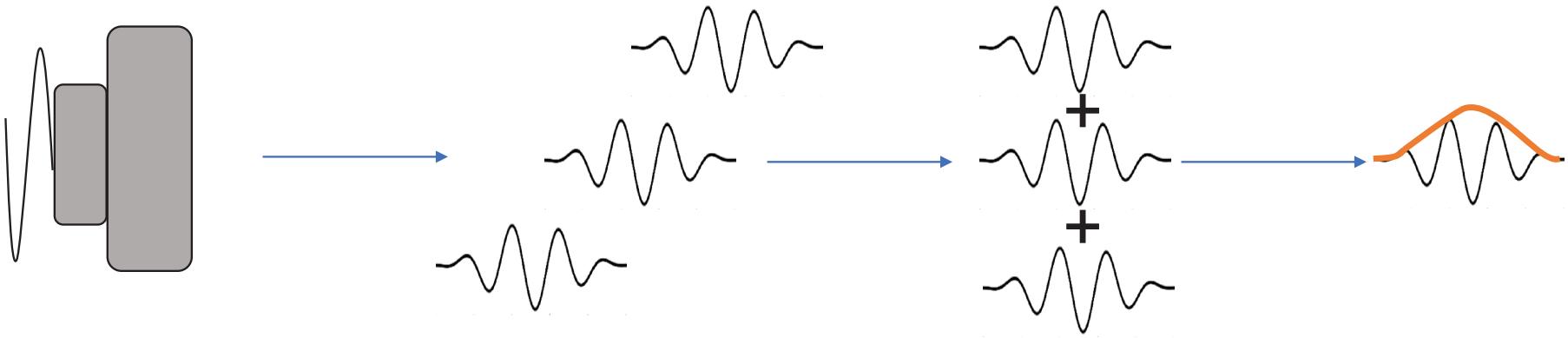
Advantage: Convenience, Low cost, Easy to carry;

Disadvantages: Rely on skills, Image quality low.

↓ Why?

Imaging technique using the nature of wave interference.





Does not consider speed of sound difference and attenuation.

Full Wave Inversion algorithms

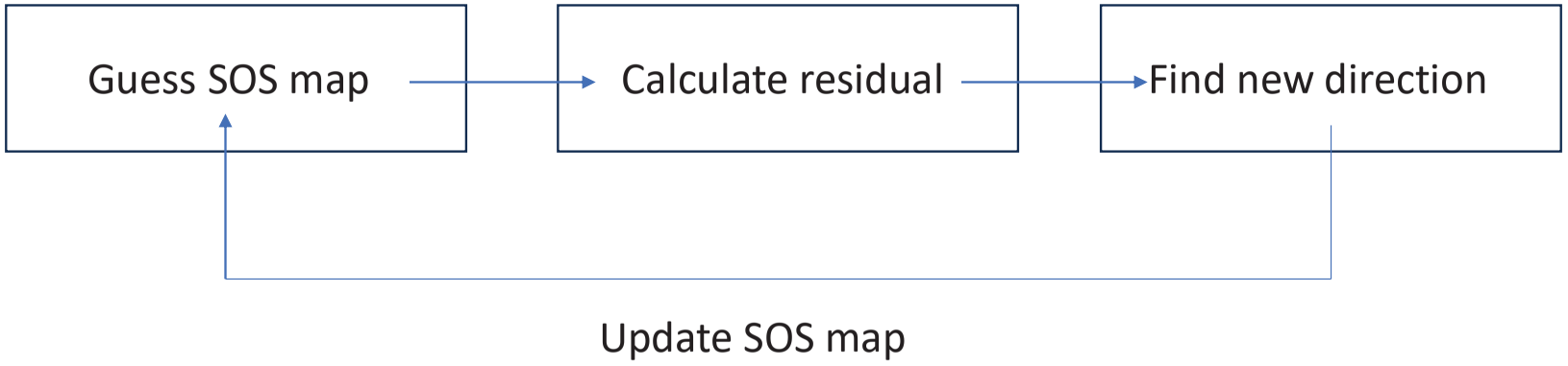
Conjugate gradient (CG) algorithm:

Assume during the k-th loop of the inversion, we could let:

$$\Delta \boldsymbol{p} = \frac{\partial \boldsymbol{p}}{\partial \boldsymbol{s}} \boldsymbol{d}_k$$

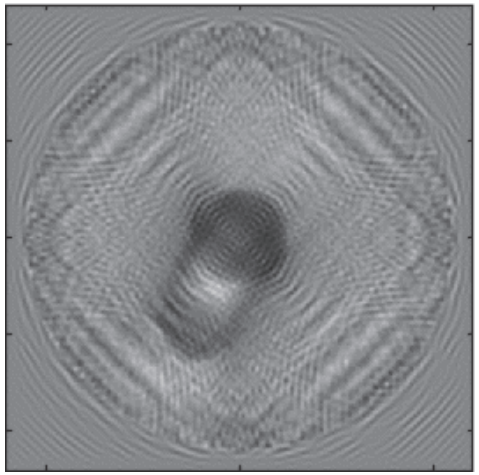
(Since $\Delta \boldsymbol{p}$ is the negative gradient of F at $\boldsymbol{s}_k$ and gradient descent method)

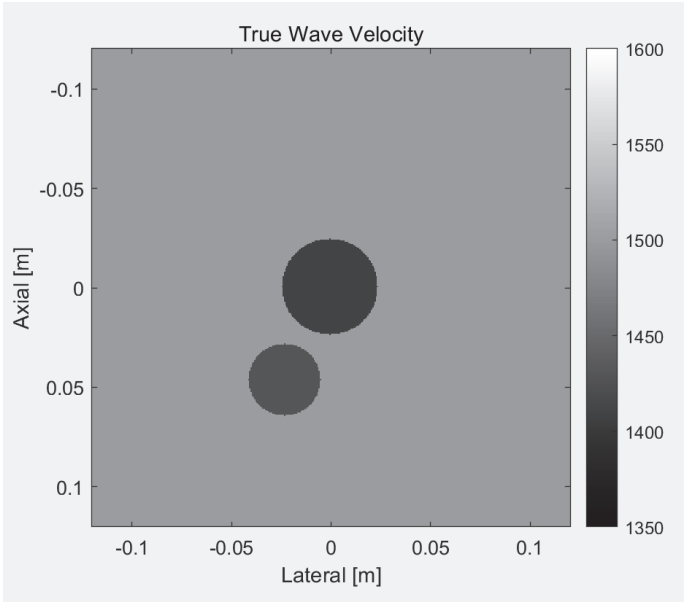
However we insist different $\boldsymbol{d}_k$ to be conjugate to each other.
So Successive iterations of CG update the search direction and SOS guess.

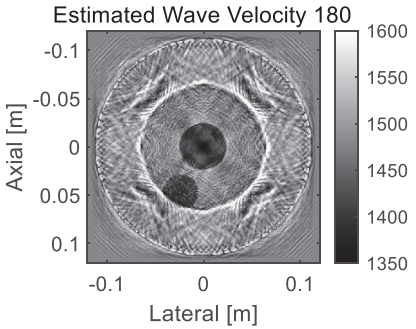


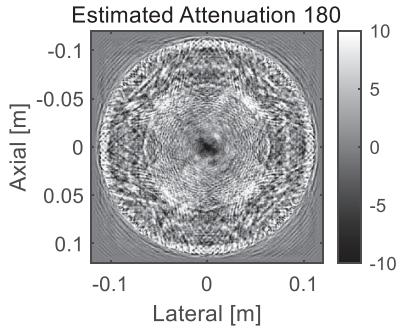
Full Wave Inversion results

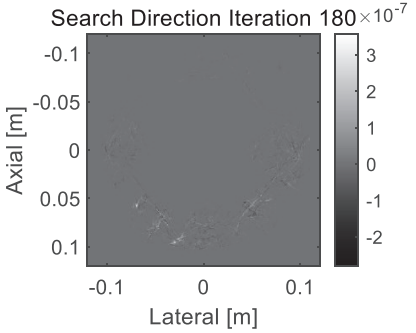
Based on Rehman Ali et al., use latest method of solving Block LU, Microdrop results are:

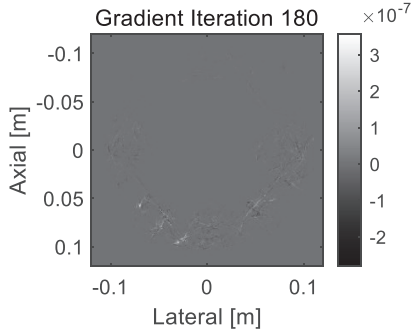




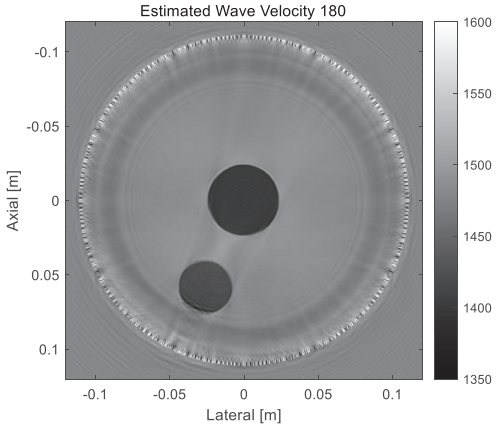




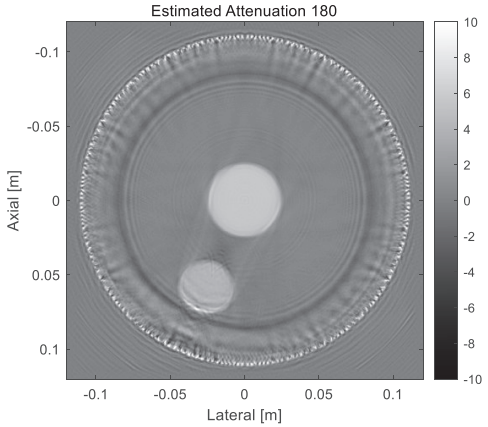




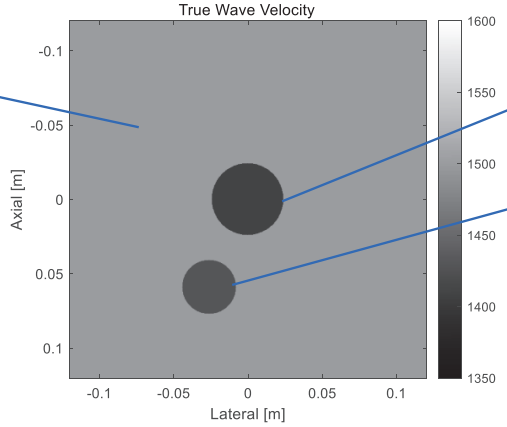
FWI results – 512 sensors



Grid size:
800*800
Sensor number:
512

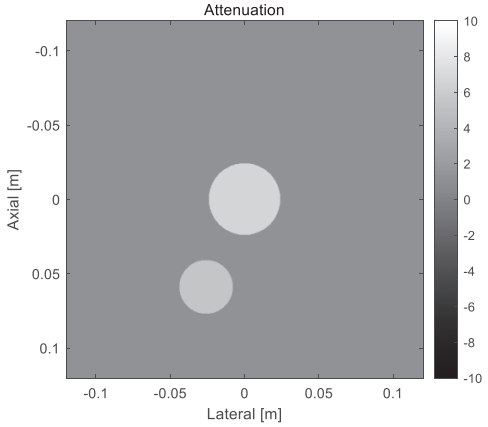


C=1500m/s

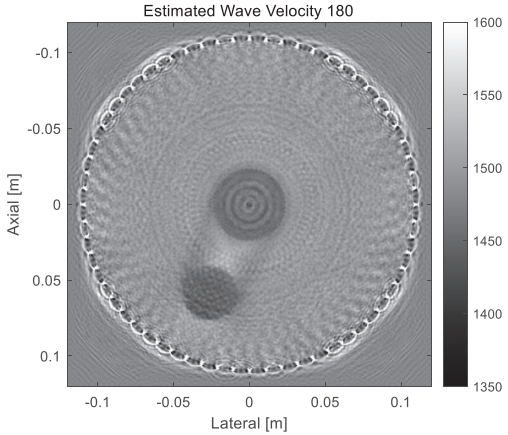


C=1410m/s

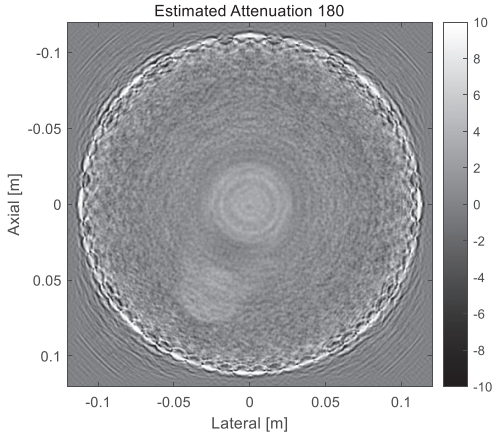
C=1430m/s

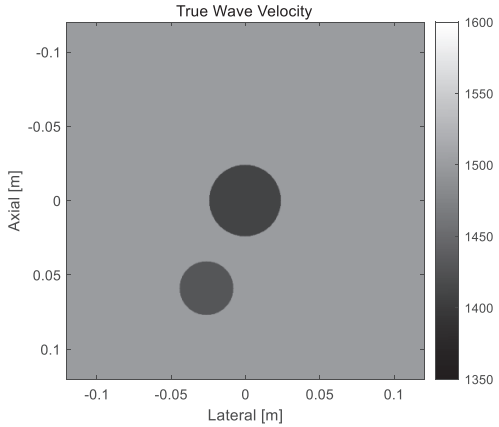


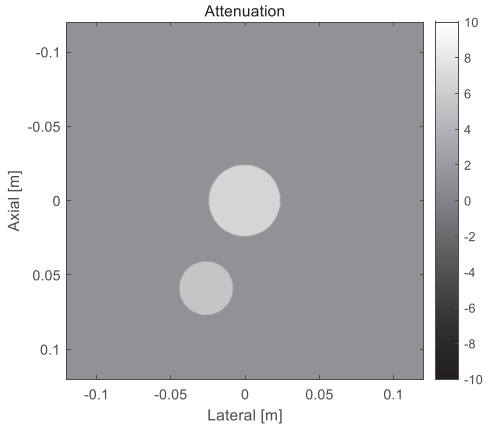
FWI results – 64 sensors



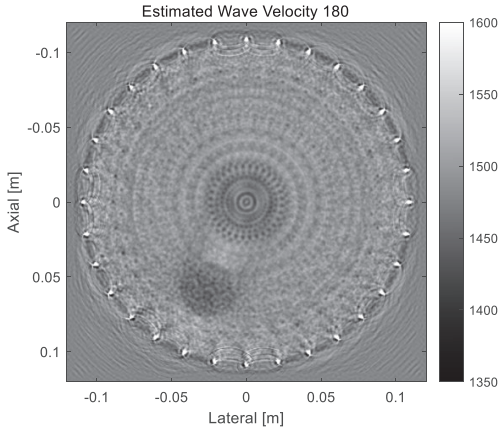
Grid size:
800*800
Sensor number:
64



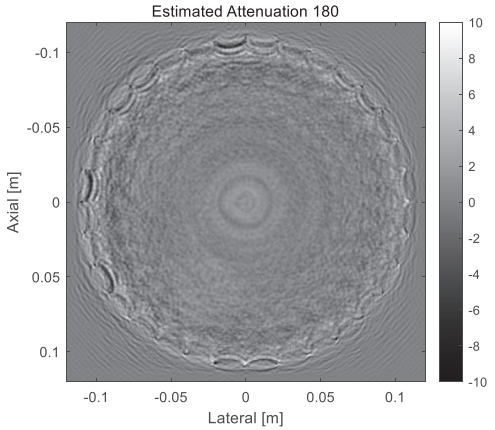


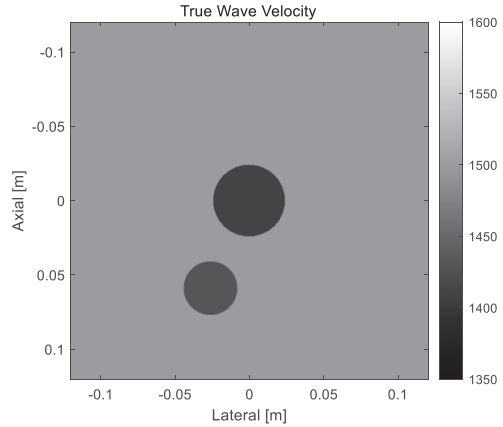


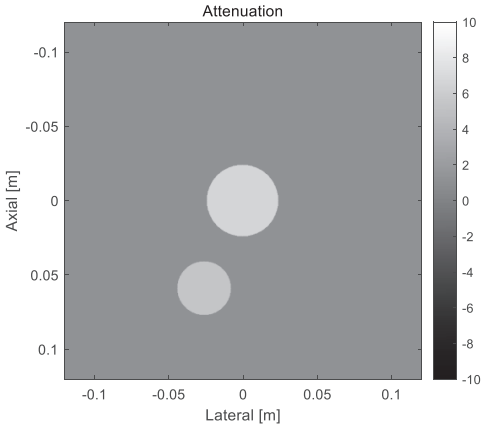
FWI results – 32 sensors



Grid size:
800*800
Sensor number:
32





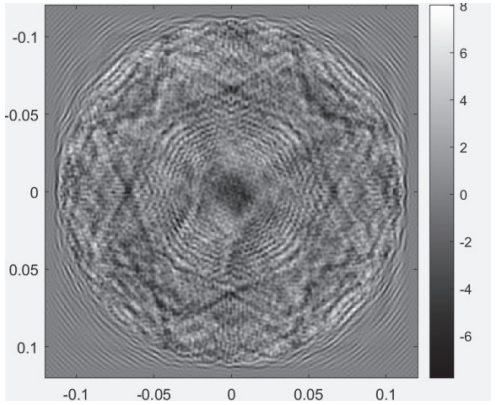


Full Wave Inversion drawbacks

Although nice results are got from previous simulations,
FWI have 2 major drawbacks regarding simulation.

1. High computational cost:

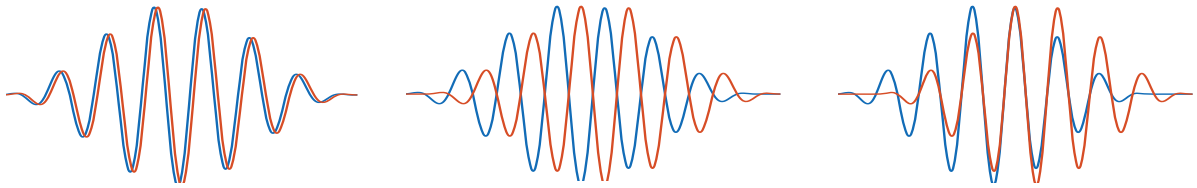
The calculation time/memory requirement for algorithm could be extremely overdemanding.
Previous examples cost 2&1 hours for SOS reconstruction respectively.
However biological tissues require 1024 transducers and microdrop requires 256 transducers.
If transducer number is small, see results:



Full Wave Inversion drawbacks

2. Ill-posed problem and initial guess:

An infinite number of models matches the data.

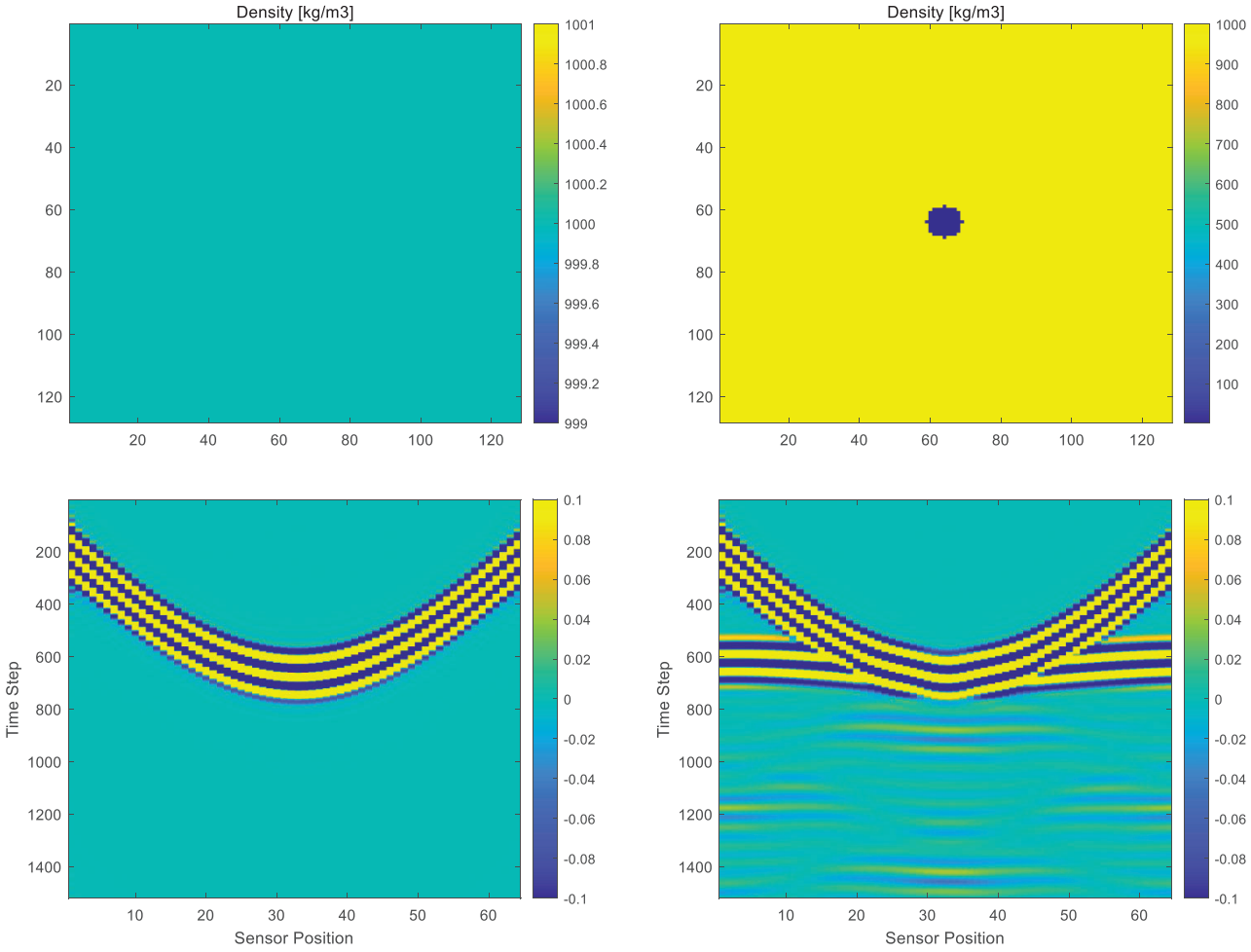


Some regularizations need to be conventionally applied to the inversion to make it better posed.

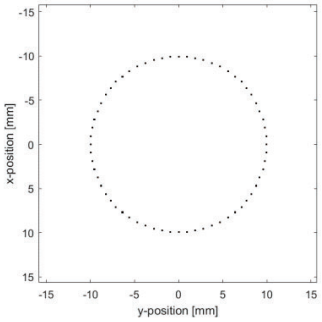
Also initial guess would affect the accuracy largely.

Ultrasound simulation results

Results explanation



Left case: No bubble
Right case: 1 bubble



Topmost V-shape represents the initial ultrasound propagation and lower V-shape represents reflection.

Previous Results

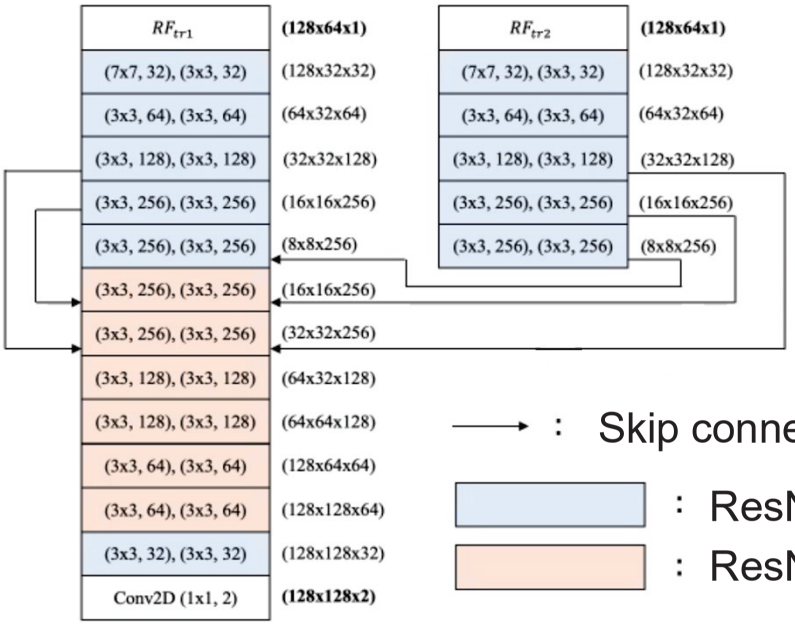
Accuracy for 8 transducers input training

Bubble numbers	Location accuracy	Modified location accuracy	Size accuracy	Modified size accuracy
2 bubbles	96.3%	96.3%→99.9%(3.6)	87.0%	87.0%→99.9%(12.9)
3 bubbles	90.8%	90.8%→96.1%(5.3)	77.0%	77.0%→95.7%(18.7)
4 bubbles	88.7%	88.7%→92.7%(4.0)	81.6%	81.6%→89.4%(7.8)
5 bubbles	78.1%	78.1%→86.2%(8.1)	74.3%	74.3%→80.3%(7.0)

- After postprocessing, prediction accuracy for 5 bubbles cases could reach 80% above.
- Improvement for location is not as high as size, because location determination is easier and more accurate for machine learning only.
- Improvement for size gets lower for more bubble cases, because the deviation for size is more likely to go beyond the preset range as bubbles increase.

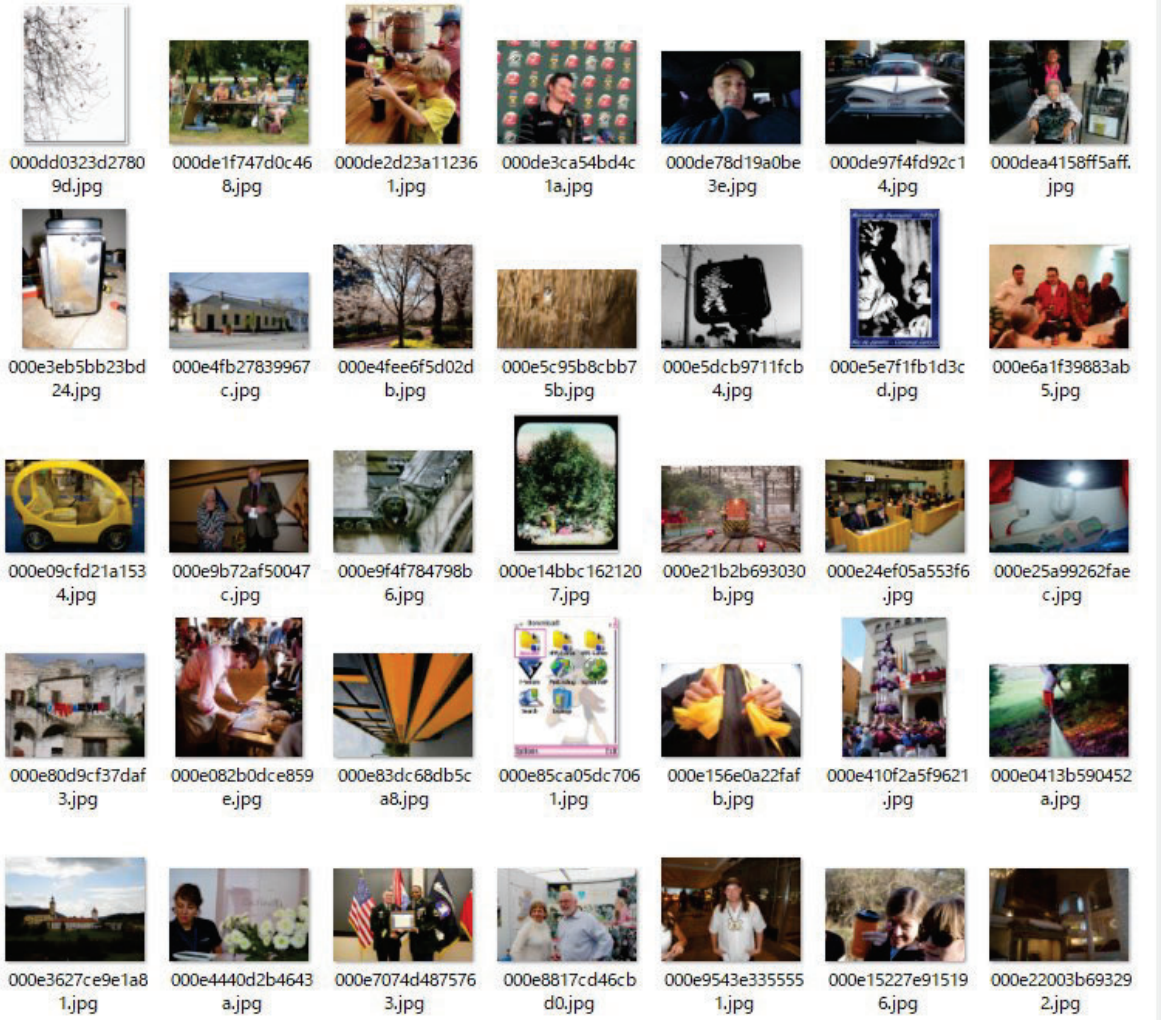
Further discussion

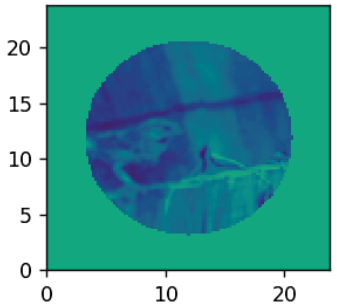
- Based on Y. Watanabe's methods, natural images dataset may be used to reconstruct speed of sound (SOS) map.
- Applying on bubble imaging, conduct training.



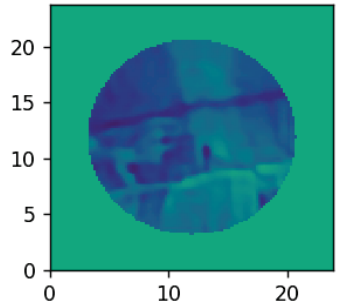
Training parameters:
Epoch: 90
Batch size: 2
Learning rate: 0.00055
Loss: MAE, MSSIM
Dataset: 30,000 sets

Further discussion



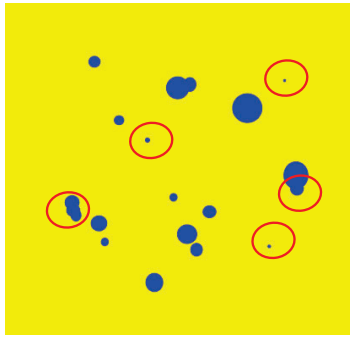


Ground truth

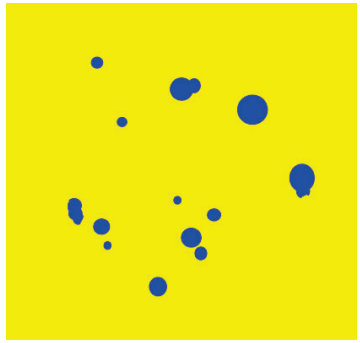


Prediction

Further discussion



Ground truth



Prediction

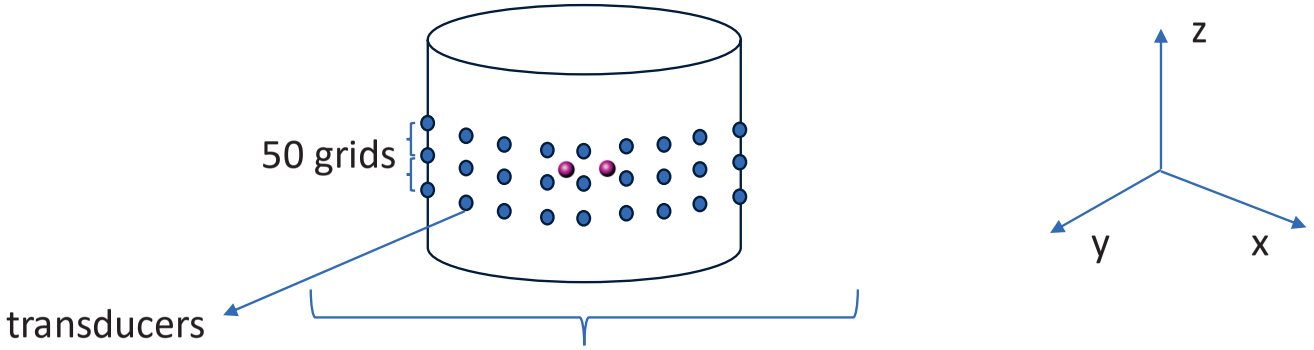
For round bubble:

Bubble numbers	Previous location	Natural image location	Previous size	Natural image size
2 bubbles	99.9%	100%	99.9%	99.9%
3 bubbles	96.1%	97.8%	95.7%	97.8%
4 bubbles	92.7%	98.4%	89.4%	98.4%
5 bubbles	86.2%	97.1%	80.3%	95.5%

For non-uniform shapes:

Dataset types	SOS - MAE	SOS - MSSIM	Density - MAE	Density - MSSIM
Distorted bubbles	5.68±5.78	0.783±0.051	11.34±9.22	0.663±0.059
Natural images	4.85±5.08	0.824±0.050	8.47±8.50	0.812±0.053

Simulation settings



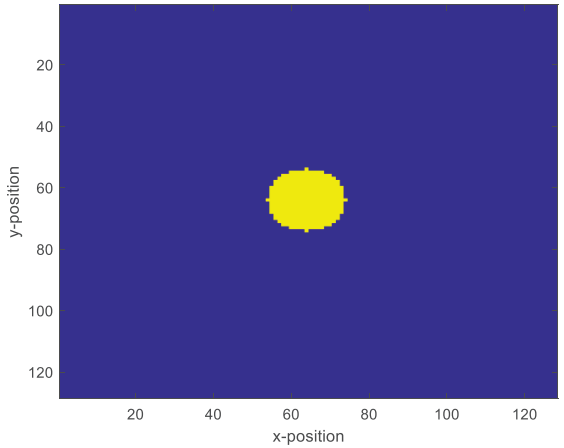
Nx = 400;
Ny = 400;
Nz = 400;
Length_area = 5*10e-4 m
Ring diameter = 4*10e-4 m

SOS(m/s):	Water: 1520	Air: 340	Drop: 1220/1120
Density(kg/m-3):	Water: 1000	Air: 1.34	Drop: 1060

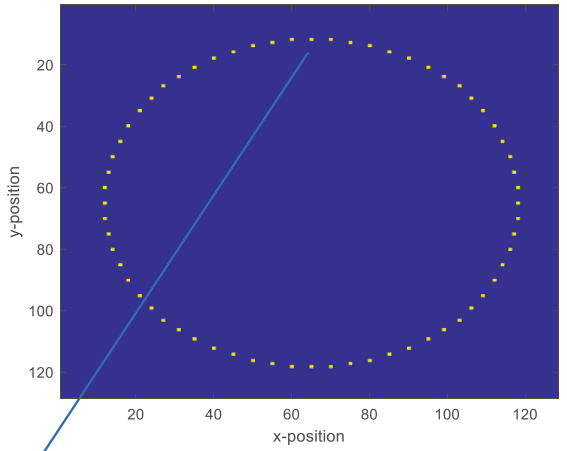
Alpha power: 1.5
Alpha coefficient: 0.0022

Source: sinusoidal, 2 waves, 4MHz, amplitude: 400

Simulation settings



Bubble slice at center

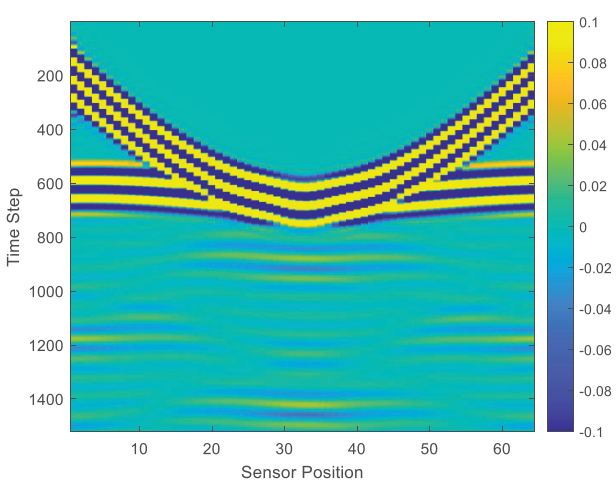


transducer slice at z = 64

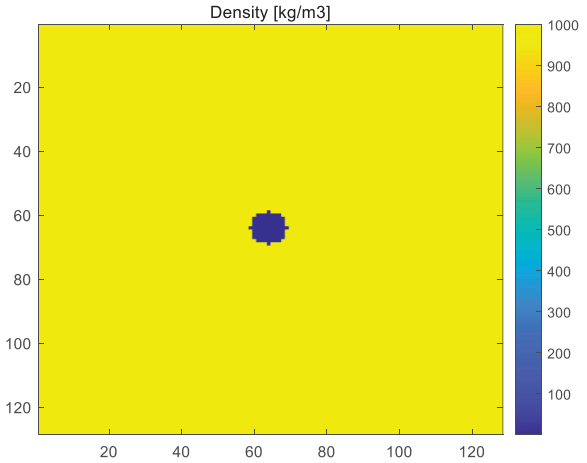
Emitter in simulation

dx = 1.25e-06
CFL = 0.05/0.3

Before training

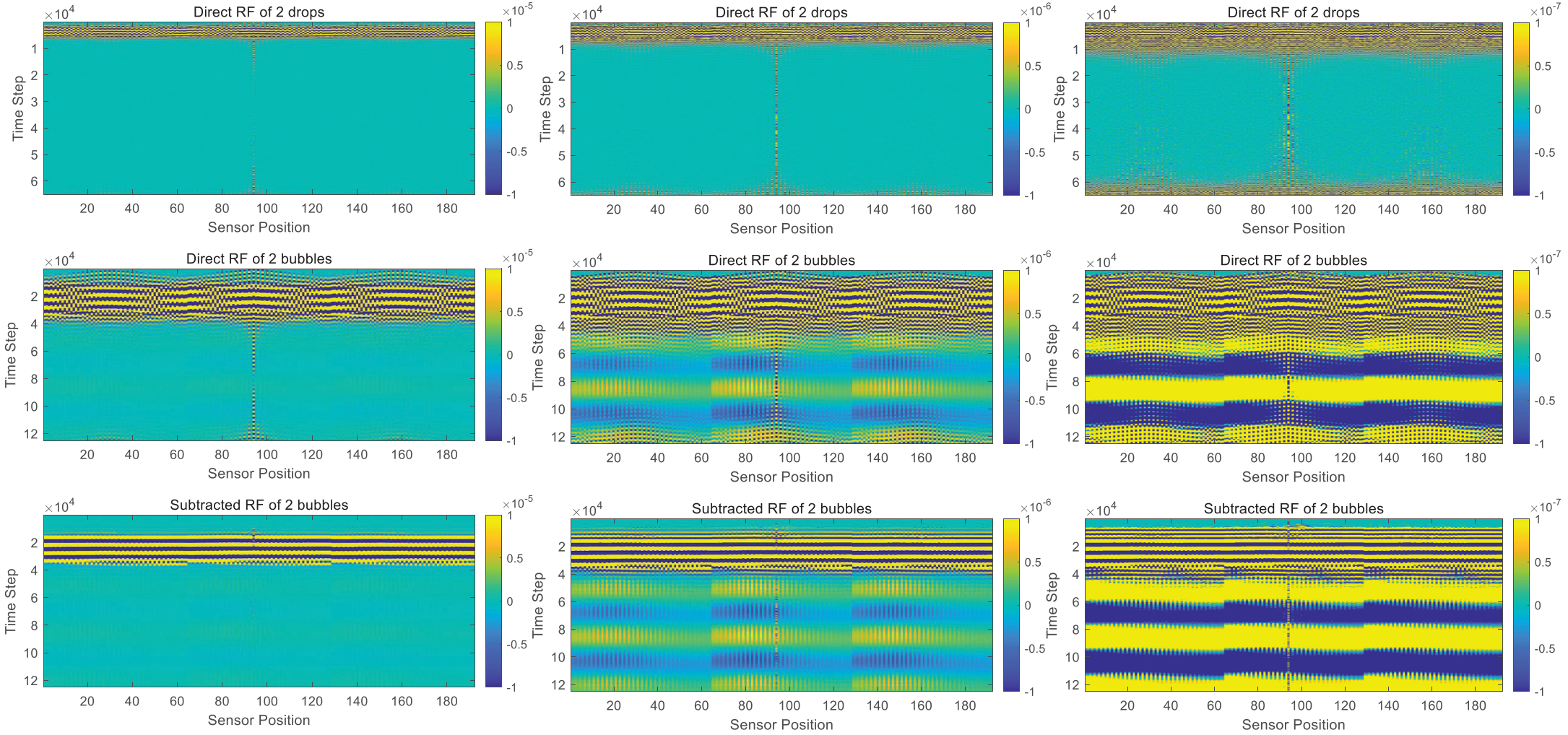


Preprocessing and feature guess

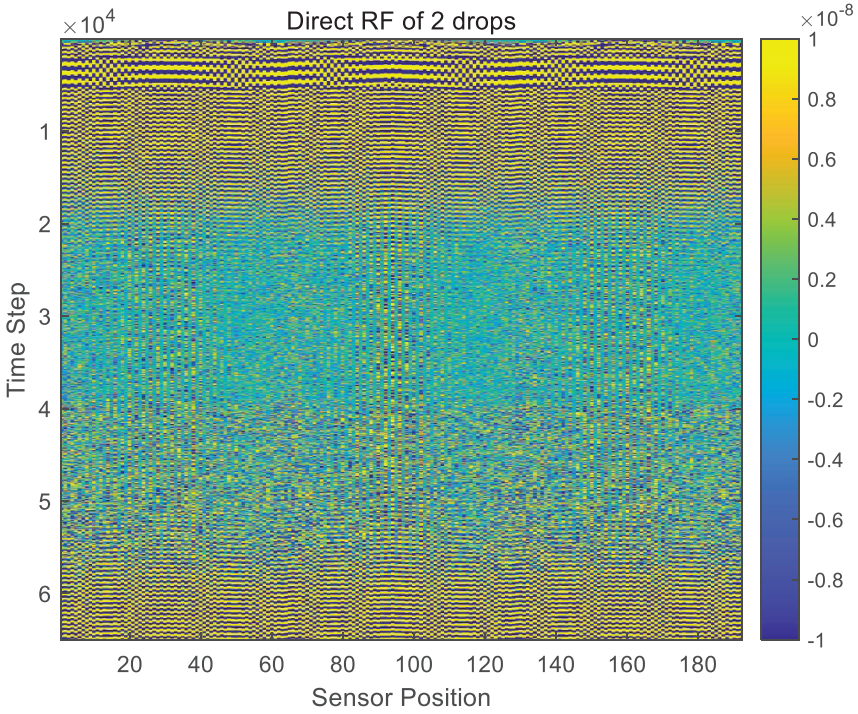


Representation

Preprocessing and feature guess



Preprocessing and feature guess



Summary and Research Plan

- Summary
  - FWI shows good results but still has problems of high computational cost and local solutions.
  - Natural image datasets and algorithm show good generalization performance.
  - 3D MB simulation has been computed but needs further examination.

- Future Work
  - Conduct Algorithm assisted MB simulation in K-wave and compare the results.
  - Conduct 3D images machine learning to reconstruct SOS maps.
  - Eliminate the interference of complexed surroundings.