Row-column 3D beamformation

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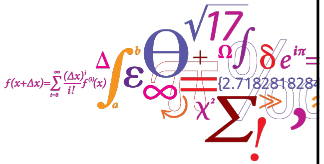

DTU Health Technology

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Outline

- **Introduction**
  - Challenges of 3D imaging
  - 3D Imaging with row-column probes
- **New faster imaging method**
  - Hypothesis
  - Algorithm
- **Results**
  - Image quality comparison
  - Imaging speed

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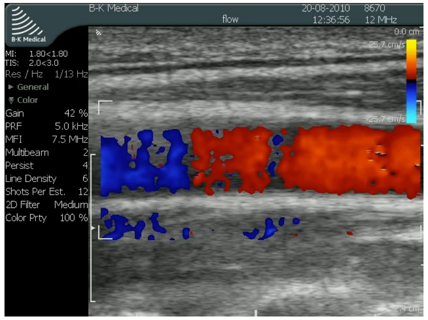
What current scanners offer

- CFM:
  - 1D velocity in a 2D slice
  - Flow perpendicular to the beam cannot be estimated



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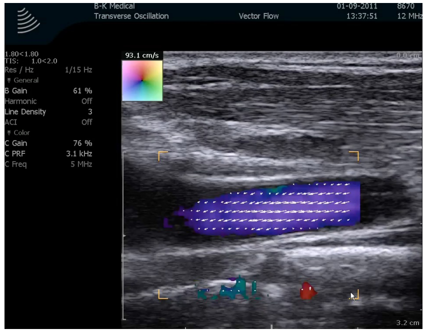
What some scanners offer

- VFI:
  - 2D velocity in a 2D slice
- High level flow analysis is challenging
  - E.g. flow rate estimation requires many assumptions



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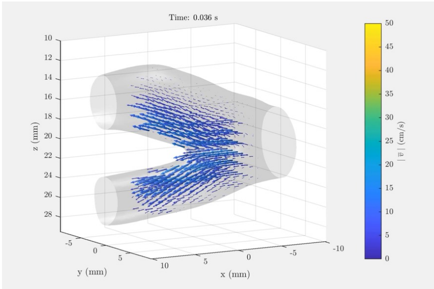
Why 3D?

- Full flow data set
- No ambiguity
- Operator independent
- More capable at deriving any flow metric



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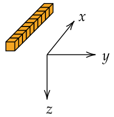
Challenges of 3D imaging

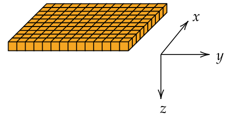
- Resolution in x and y:
  - Increases with aperture width → #elements in x and y
  - Decreases with imaging depth

- **1D array**



  - 2D image quality $\propto$ #elements

- **2D array**



  - 3D image quality $\propto \sqrt{\#\text{elements}}$

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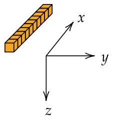
2D array = too many elements

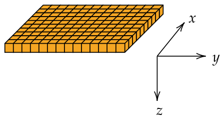
- At 5 cm imaging depth:
  - separating objects >0.25 mm apart requires (approx.):

- **1D array**



  - 200 elements
  - 1x Vantage 256^{TM} research scanner
    - ➢ 236,000 $

- **2D array**



  - 200x200 = 40,000 elements
  - 157x Vantage 256^{TM} research scanners
    - ➢ 37 mil. $

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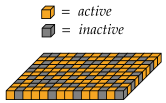
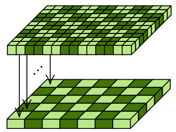
Design solutions

1. Sparse arrays



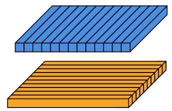
- Side-lobe levels
- 2x~4x fewer elements

2. Micro-beamformation



- Low volume rate
- Complicated circuits

3. Row-column (RC) probes



- Large apertures
- Image quality $\propto$ #elements

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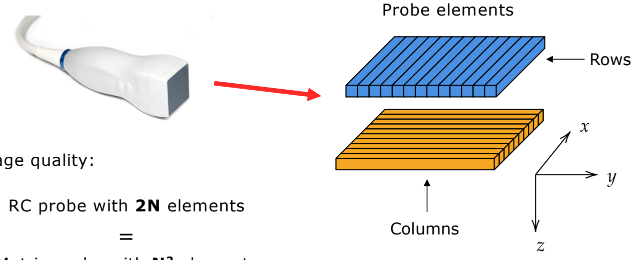
3D imaging with row-column probes

- Row-column (RC) probe



- Image quality:

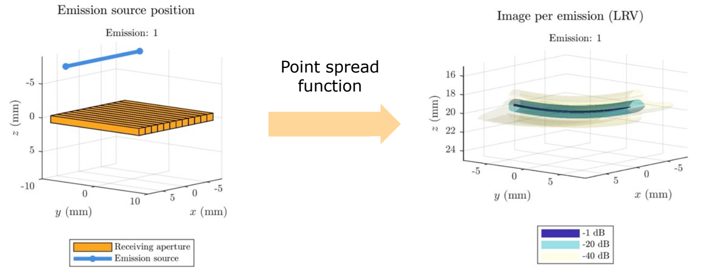
RC probe with **2N** elements

=

Matrix probe with **N²** elements

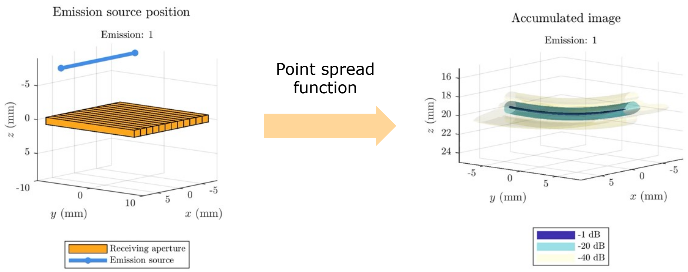
RC imaging (low-res volume)

- Each emission produces a low-res volume (LRV)



RC imaging (high-res volume)

- Combining the low-res volumes yields a high-res volume



RC delay-and-sum (DAS) beamformation

- Similar to conventional 2D DAS beamformation.

2D beamformation:

$$t_{ToF} = \frac{z_v \pm \sqrt{(x-x_v)^2 + (z-z_v)^2} + \sqrt{(x-x_e)^2 + (z-z_e)^2}}{c}$$

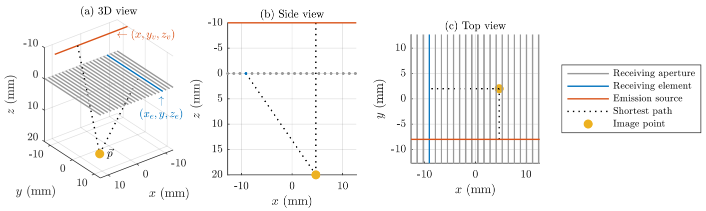
RC 3D beamformation:

$$t_{ToF} = \frac{z_v \pm \sqrt{(y-y_v)^2 + (z-z_v)^2} + \sqrt{(x-x_e)^2 + (z-z_e)^2}}{c}$$

Point source's center: (x_v, z_v)
Line source's center: (y_v, y_v)
Element's center: (x_e, z_e)
Speed of sound : c
Time-of-flight: t_{ToF}

Time-of-flight geometry

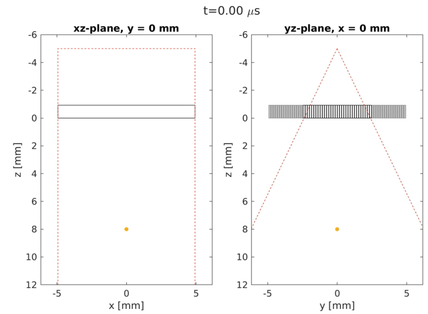
- Distance from **source** to **image-point** calculated using (x,z)-coordinates(*)
- Distance from **image-point** to **element** calculated using (y,z)-coordinates(*)



(*) Vice-versa when columns transmit and rows receive

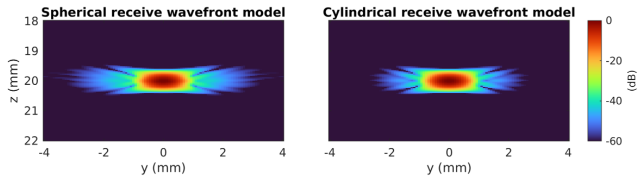
RC transmit wavefront

- Cylindrical transmit wavefront:
  - xz-plane: plane wave
  - yz-plane: circular



Wave propagation model

- The wavefront is modelled as cylindrical in transmit and receive.
- **NB!** Actual receive wavefront is spherical (seemingly no benefit to model this)

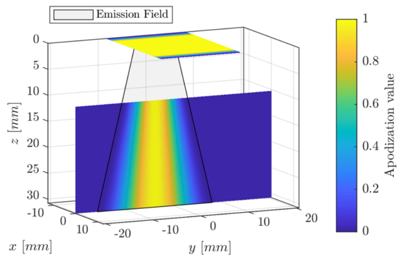


Apodization

- Effective RC imaging requires many layers of apodization
- **Post-processing apodization:**
  - Fixed or dynamic receive apodization
  - Weighting each LRV before summation (highly recommended!)
  - Weighting each LRV's image-points before summation
- **Pre-processing apodization:**
  - Transmit apodization
  - Built-in edge apodization

LRV image-point apodization

- Weighting each LRV's image-points before summation
- Each LRV image-point are weighted based on distance to emitted field's center
- Creates constant FWHM in the transmitting plane (yz-plane)



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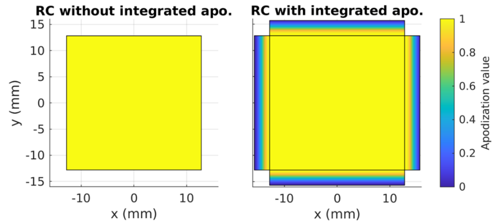
Edge apodization

- Must be built into to aperture (easy to simulate, hard to manufacture)
- Needed to reduce "ghost echoes", i.e. the signal from edge waves



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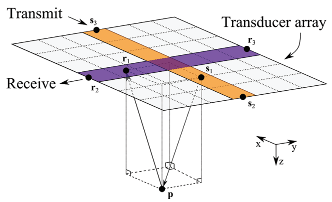
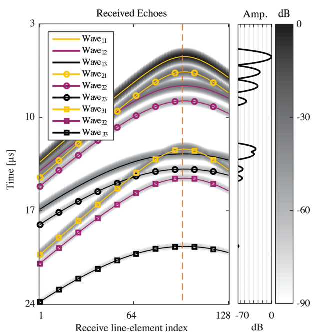
Ghost echoes

- Line elements transmits 3x waves and receives at 3x positions
- Scatter-signal thus received 9x





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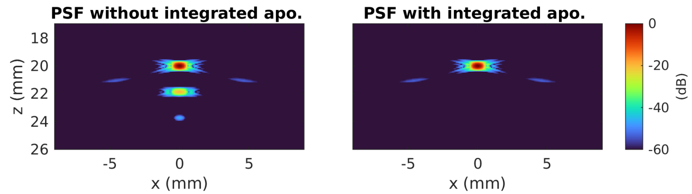
Edge apodization

- Reduces "ghost echoes" created by edge waves



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Motion artifacts and Correction

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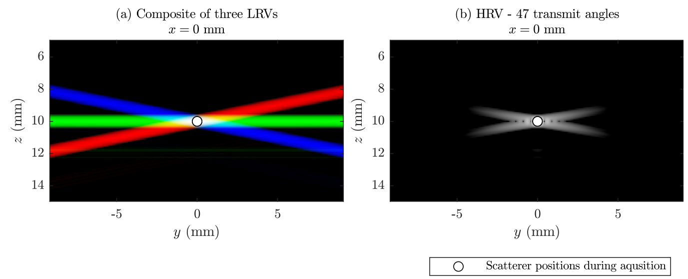
No motion = great imaging



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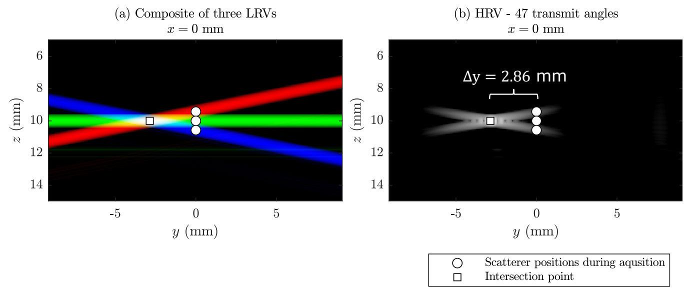
Motion = reduced accuracy



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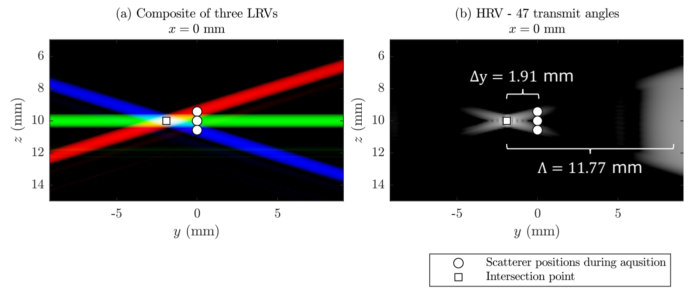
Motion artifacts vs grating lobes

- Improving accuracy can cause grating lobes



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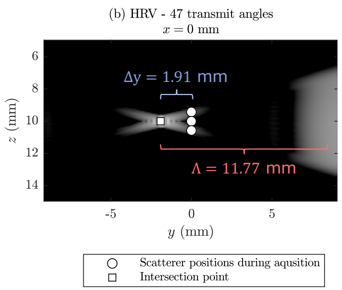
Motion artifacts vs grating lobes

- Goal: Δy small as possible, Λ large as possible



$$\Delta y = \frac{v_z \Delta t}{\sin(\Delta\phi/2)}$$

$$\Lambda = \frac{\lambda}{2\sin(\Delta\phi/2)}$$

Axial velocity: v_z
Time step: Δt
Angle step: $\Delta\phi$
Wave length: λ

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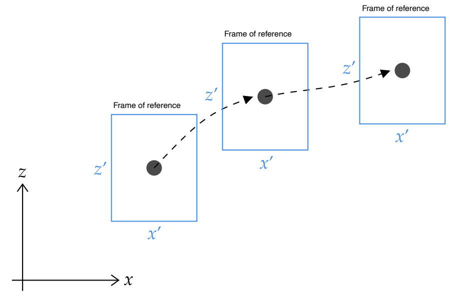
Motion correction

- No motion in a moving frame of reference



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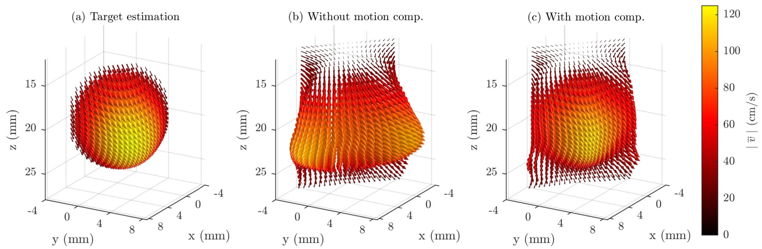
Motion correction improves accuracy



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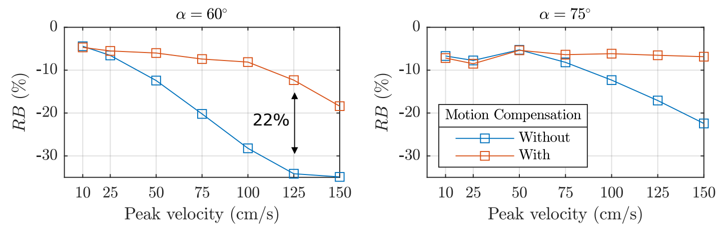
Bias reduction from motion correction



Relativ bias: RB
Beam-to-flow angle: α

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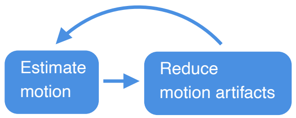
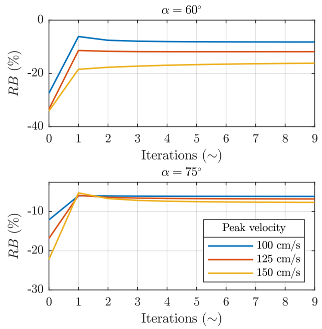
Recursive process





Relativ bias: RB
Beam-to-flow angle: α

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<u>After break:</u>
Real-time full volumetric imaging

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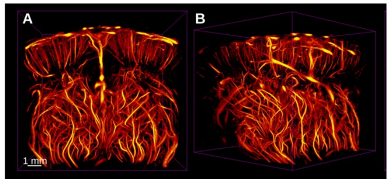
3D imaging is computationally demanding

Example from Jacob R. McCall, et al. (2023) [1]

- Measurement: **3 min 20 s**
- B-mode imaging: **8 hours**

- Needed to be **144x** faster for real-time imaging



Matrix probe: 32x32 elements
Image size: ~ 95x90x100
Volume rate: 3.5 Hz
GPU: 4 x NVIDIA RTX 3090 Ti

[1] Jacob McCall, et al., *Non-invasive transcranial volumetric ultrasound localization microscopy of the rat brain with continuous, high volume-rate acquisition*, Theranostics, 2023.

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Is RC imaging fast?

- Yes! Few elements → fast imaging:

#Operations
=
#Receiving elements
x
#Image points
x
#Emissions

- <u>However</u> must be 10-100 x faster for real-time 3D imaging

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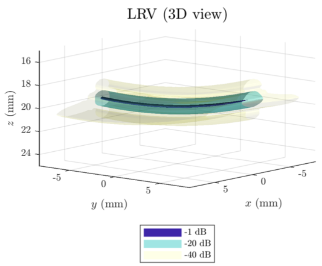
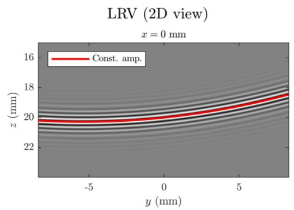
Center for Fast Ultrasound Imaging

Redundant image calculations?

- Constant image values in low-res volumes (LRV)





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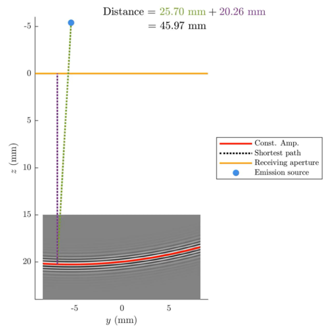
Center for Fast Ultrasound Imaging

Positions with constant amplitude

- Determined by constant time of flight to aperture surface



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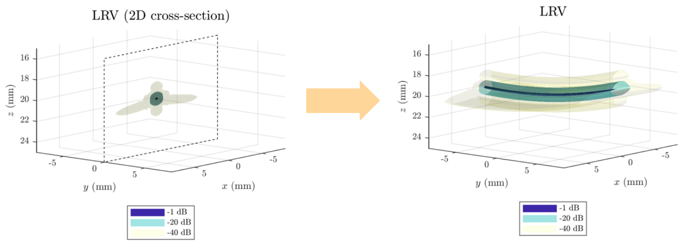
Center for Fast Ultrasound Imaging

Hypothesis

- The 3D LRV can be reconstructed from a single 2D cross-section



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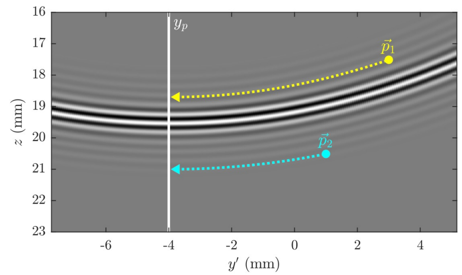
Center for Fast Ultrasound Imaging

Mapping (2D view)



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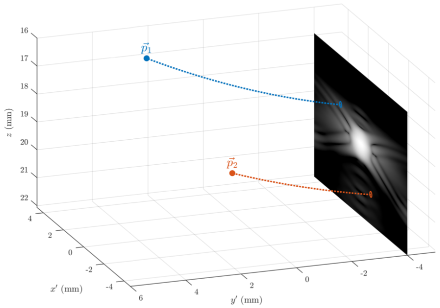
Mapping (3D view)



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Mapping function

- Maps any 3D coordinate onto a xz −plane at $y = y_p$:

$$(x, y, z) \mapsto \left(x, y_p, f(y_p, y, z)\right)$$

- Focused emissions:

$$f(y_p, y, z) = z + \frac{(y - y_p)(2y_v - y - y_p)}{2\left(z_v - z \pm \sqrt{(y + y_v)^2 + (z - z_v)^2}\right)}$$

- Plane waves:

$$f(y_p, y, z) = z + \tan(\phi/2)(y - y_p)$$

Emission source pos.: $(x, y) = (x_v, y_v)$

Transmit angle: ϕ

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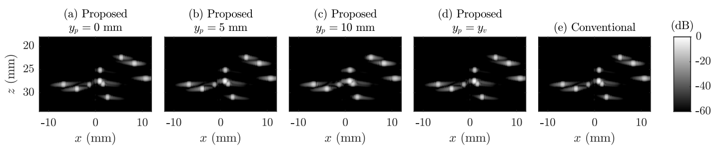
Mapping function

- Maps any 3D coordinate onto a xz −plane at $y = y_p$:

$$(x, y, z) \mapsto \left(x, y_p, f(y_p, y, z)\right)$$

- It's recommended to set $y_p = y_v$



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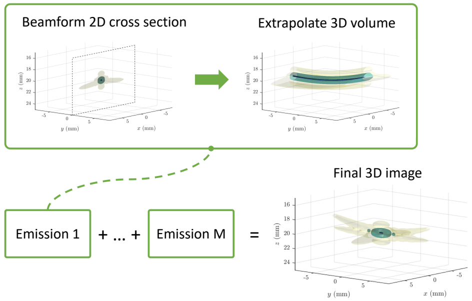
Proposed imaging algorithm



Operations per emission

Conventional method

$NN_W N_H N_H$

Proposed method:

$(SN + N_W) N_W N_H$

N: #Receiving elements
N_H: Image points in height
N_W: Image points in width
S: Decimation factor (≤8)

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Axial sampling

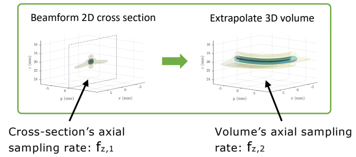
- Accurate extrapolation requires:

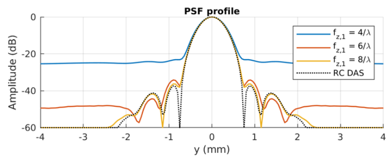
$$f_{z,1} \geq \frac{8}{\lambda}$$

- Decimation factor:

$$S = \frac{f_{z,2}}{f_{z,1}}$$

Imaging type	Decimation
B-mode	4-8
Functional	<1-2





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Reduction in operations

3D imaging method	#Receiving elements	Operations
Matrix array	128x128	8796.1×10^9
Row-column (Conventional)	128	68.7×10^9
Row-column (Proposed)	128	2.7×10^9

3D image size: 128x128x1024, #Emissions: 32, Decimation: 4

2D imaging method	#Receiving elements	Operations
1D array	128	0.5×10^9

2D image size: 128x1024, #Emissions: 32

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Results: Output comparison

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Setup

Vermon 128+128 RC probe

Vantage 256™ scanner

NVIDIA RTX 2080Ti (*)

Implementation (*)

CUDA

(*) Differs from paper

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Cyst phantom image

36x fewer operations

Image size: 200x200x650

Decimation: 4

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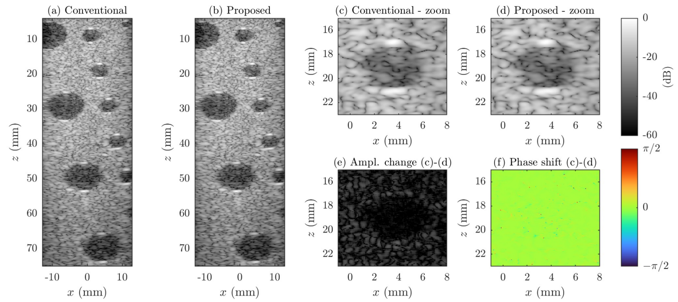
Cyst phantom image



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Rat kidney image

56x fewer operations

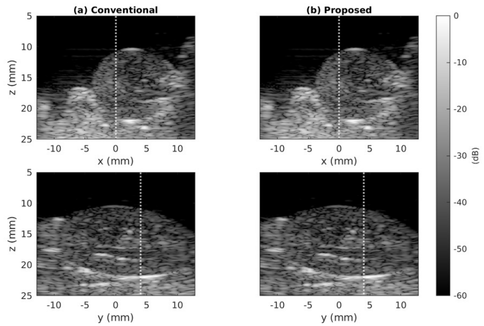

Image size: 200x200x300

Decimation: 2

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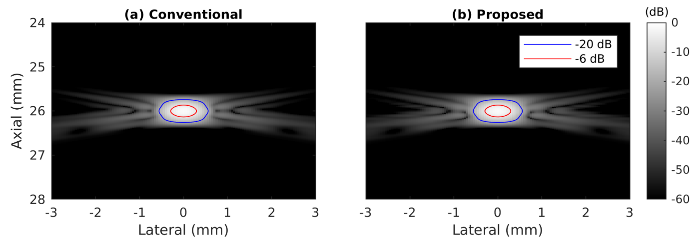
Point spread function

Width increase: **1.2%** (-20 dB) & **0.6%** (-6 dB)



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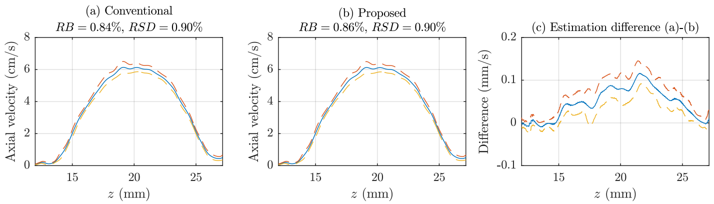
Velocity estimation

Negligible difference in estimator performance and simulated parabolic flow



Relative bias: RB
Relative standard deviation: RSD

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Results: Imaging speed

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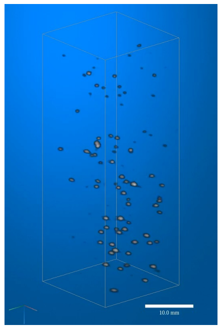
Moving particles in water

Volume rate:
22 Hz (13x faster)

Max pulse repetition frequency:
1.08 kHz



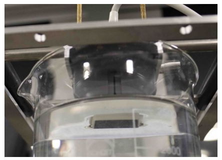


Image size:
100x100x250

Decimation: 8

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Carotid artery phantom

Volume rate:
51 Hz (11x faster)

Max pulse repetition frequency:
2.44 kHz

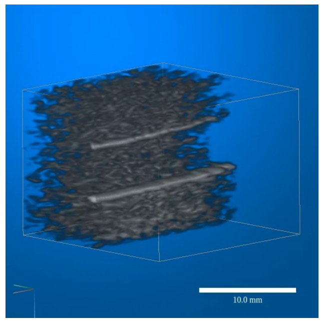

Image size:
100x100x200

Decimation: 2

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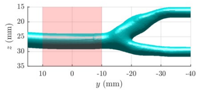
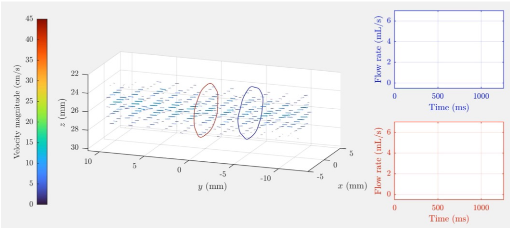
Volumetric imaging enables 3D velocity estimation

DTU Center for Fast Ultrasound Imaging





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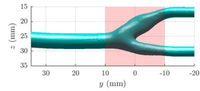

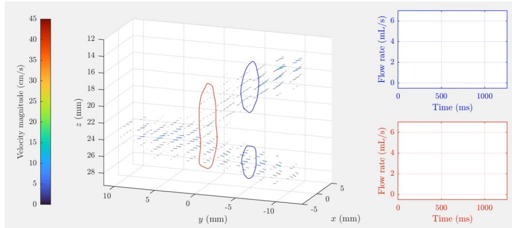

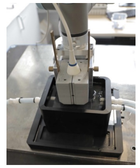

Conclusion

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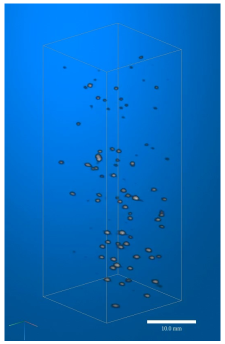
- New RC imaging method enables real-time 3D imaging
- What was demonstrated:
  - **11-13x** faster than conventional method
  - **51 Hz**, 100x100x200 imaging on a 2080Ti NVIDIA RTX GPU
  - Real-time volumetric imaging possible with pulse repetition frequency of **2.44 kHz**



Course exercise

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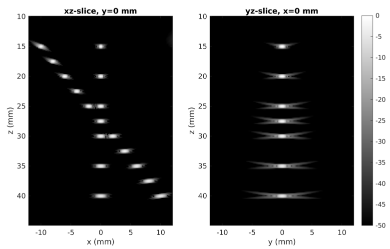
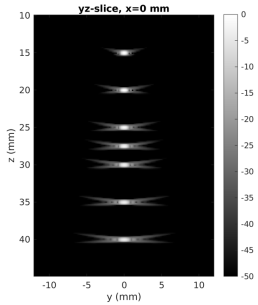
- Implement the conventional RC beamformer, presented by Rasmussen et al.
- Beamform an xz- and yz-cross-section.
- You should obtain the output seen on the right
- The output was obtained by using fixed receive apodization by weighting each low-res volume before summation.



Project

- Implement the new RC beamformation method presented by Jørgensen et. al.
- Extrapolate a yz-image plane from lines beamformed with conventional beamformer.
- Compare both beamformer’s output
- Determine the number of interpolation operations used by both methods.



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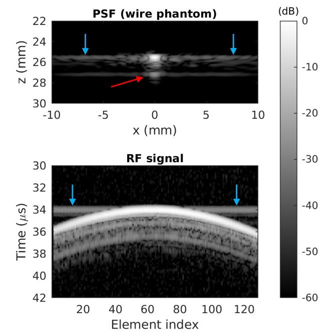
Measurement limitations

Vermon 128+128 RC probe

- No edge apodization ☹
- Electrical cross-talk ☹



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Thank you for your attention

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