Array processing for medical ultrasound imaging

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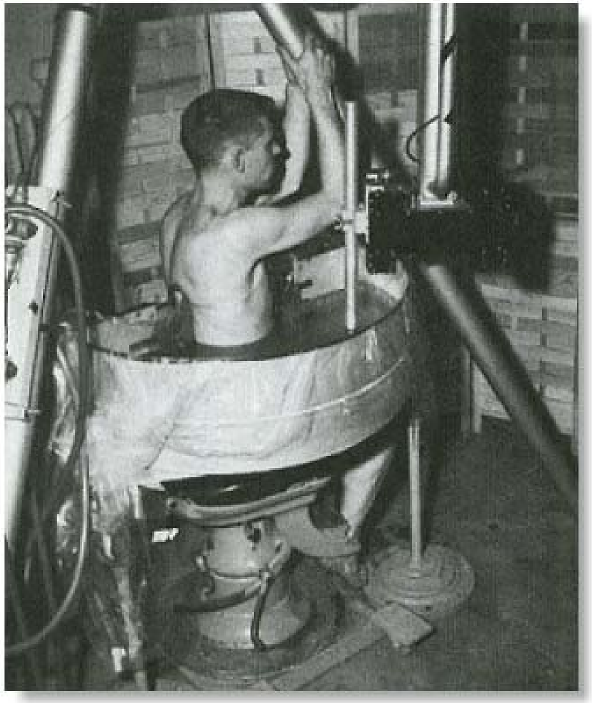
Outline

- Medical ultrasound: Past to Present
- Ultrasound Wave Physics
- Signal Processing examples
- Break
- Image Reconstruction: Beamforming
- Image Reconstruction: Model based
- Medical ultrasound research: compressive imaging and functional ultrasound

Medical ultrasound: Past to Present



1959: Pan-scanner

Now

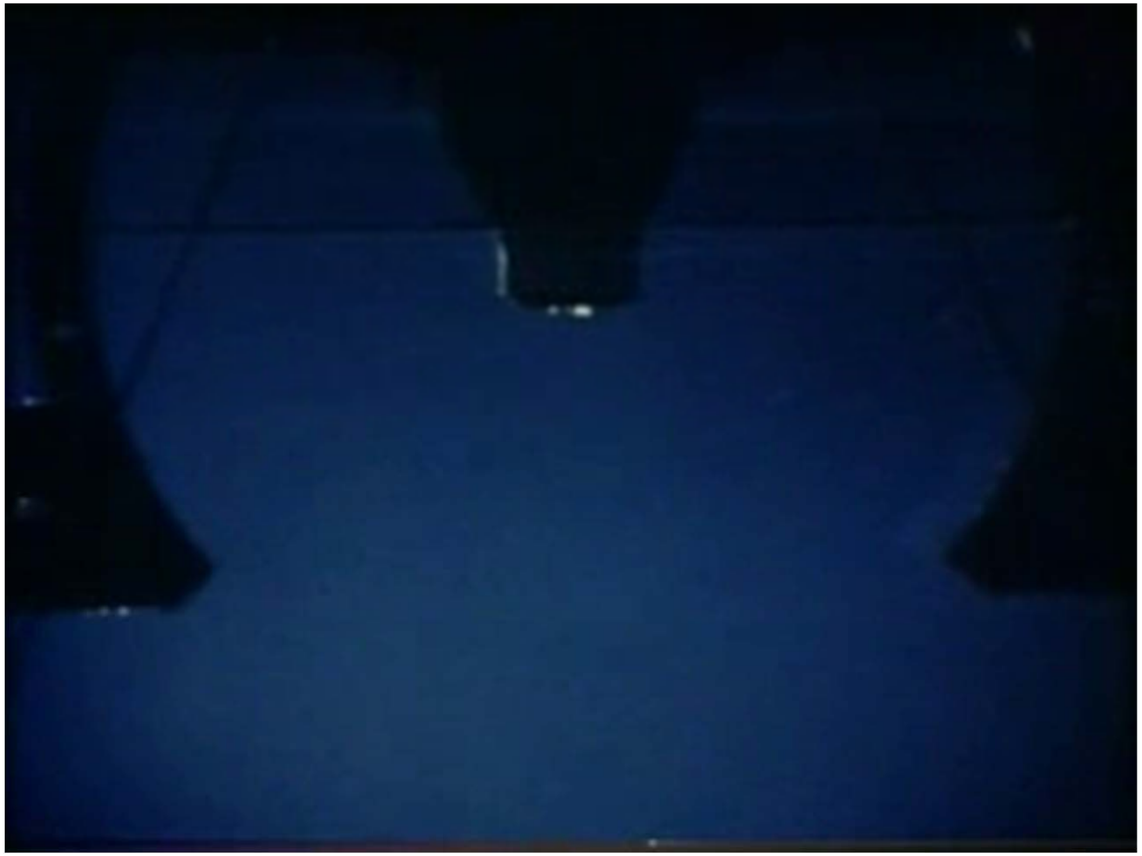
Ultrasound in the 60's

Erasmus MC

In a moving region (heart): M-mode

The revolution in 1970's: real-time imaging

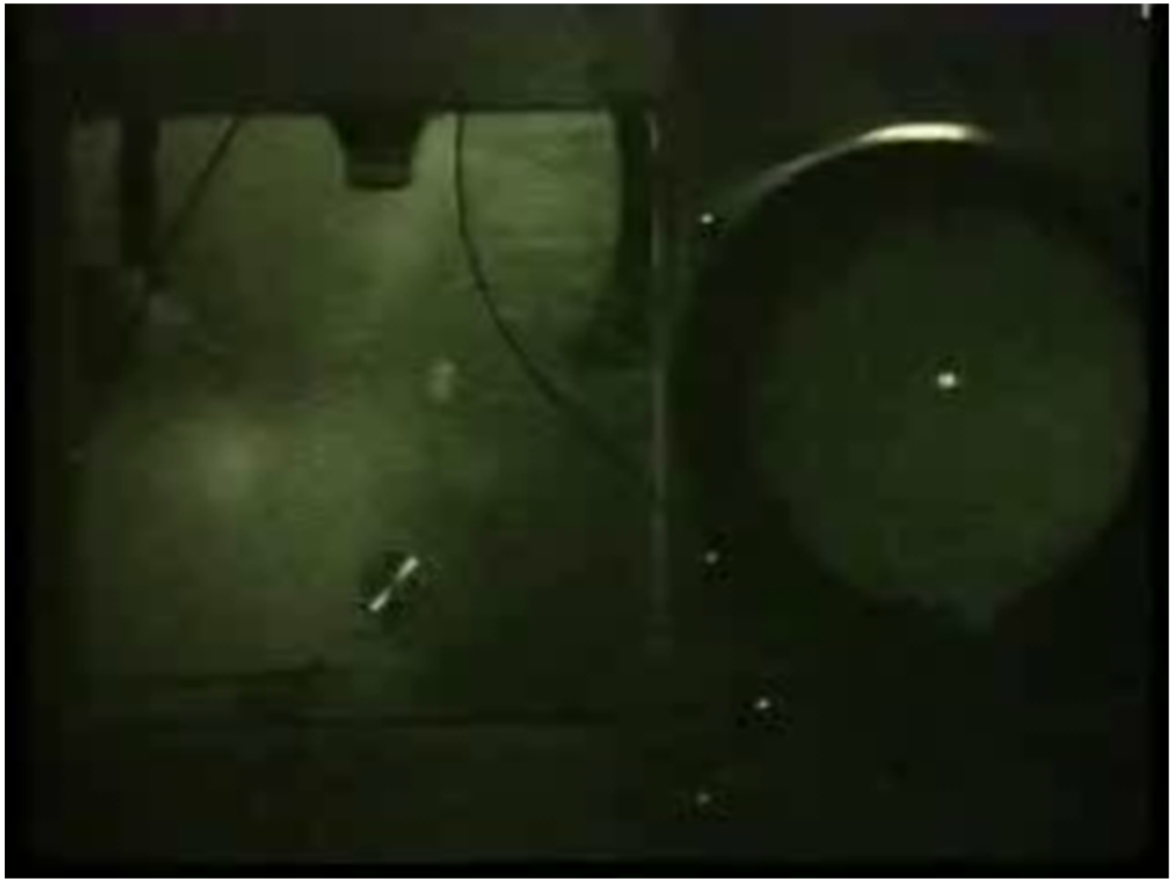
Erasmus MC



First Phased Array in world by
Jan Somer at TNO in Utrecht (1967)

The revolution in 1970's: real-time imaging

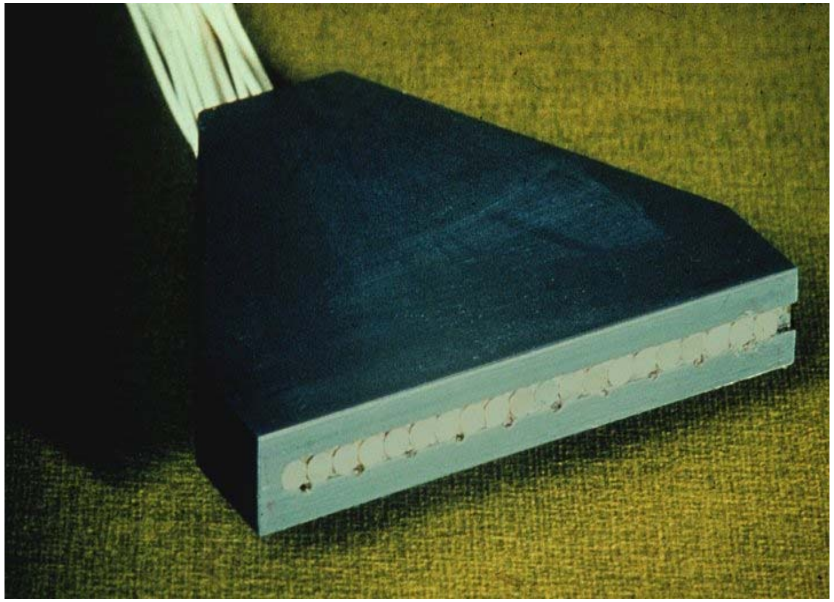
Erasmus MC



First Phased Array in world for imaging the brain
By Jan Somer at TNO in Utrecht (1967)

The revolution in 1970's: real-time imaging

Erasmus MC

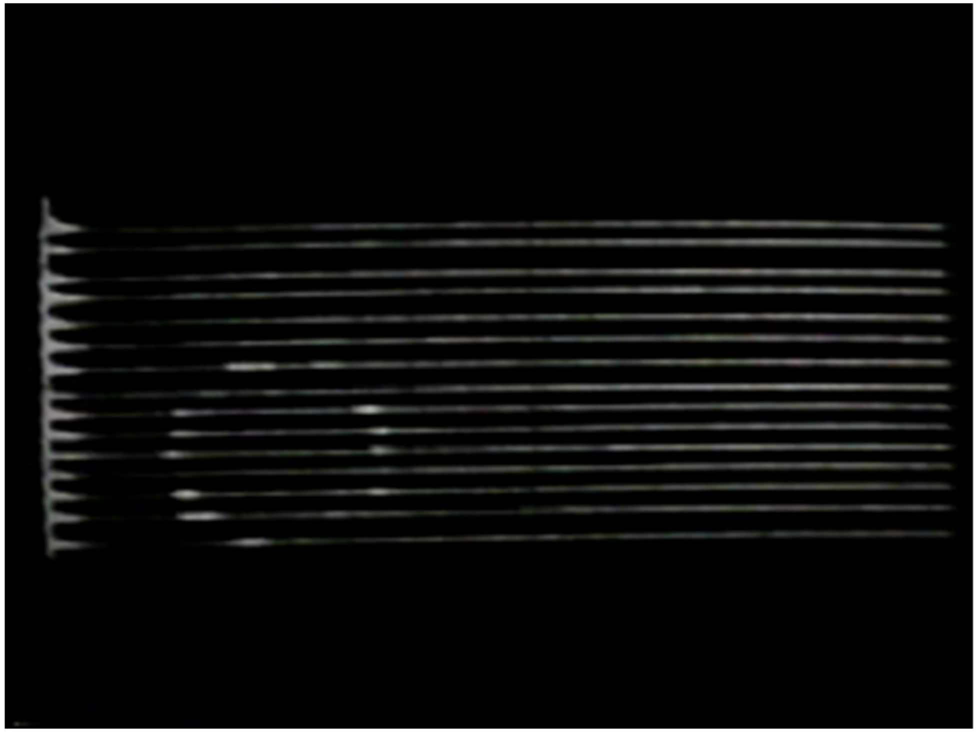


Erasmus MC Rotterdam: first linear array (1970)

First ultrasound images of the moving heart !

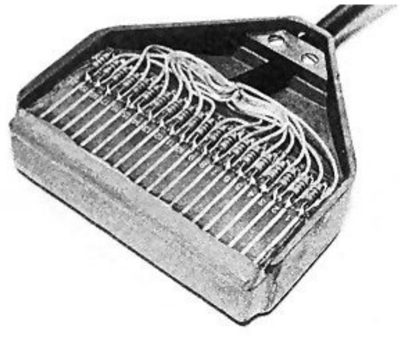
The revolution in 1970's: real-time imaging

Erasmus MC



Klaas Bom & colleagues (The Netherlands)

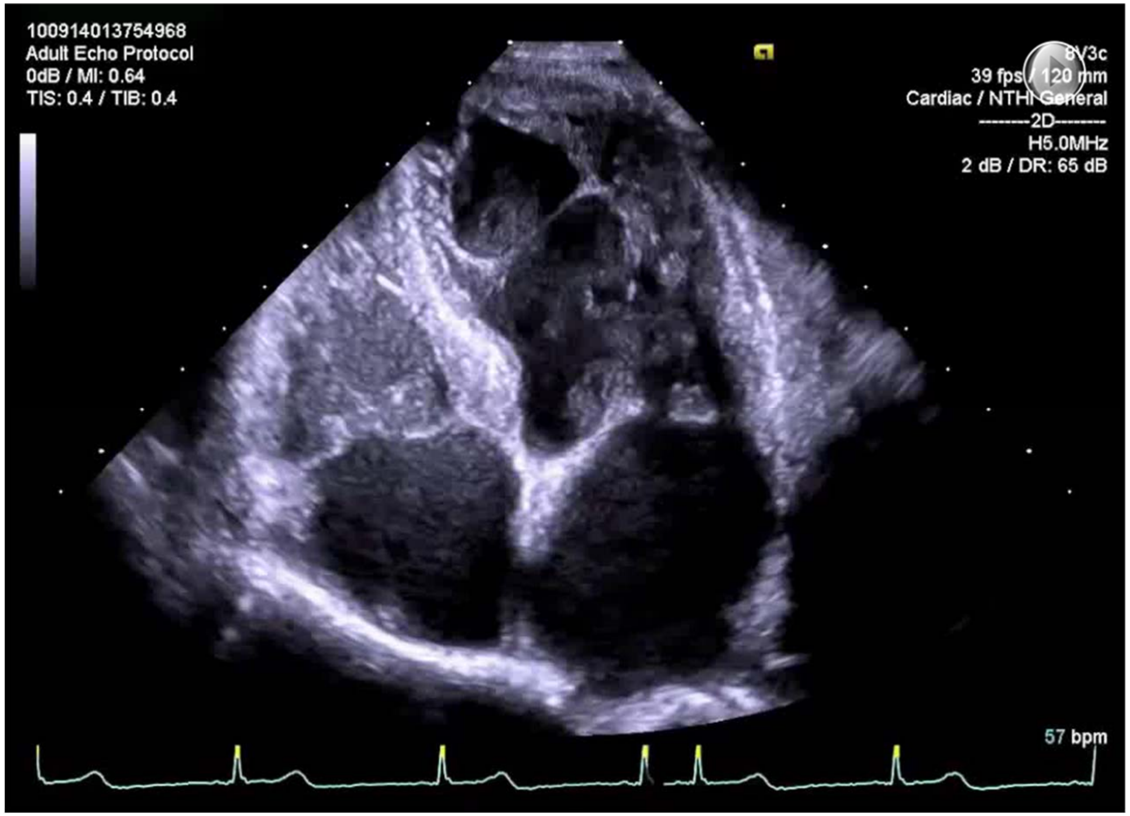
top to bottom transmit an acoustic pulse into the tissues and subsequently switch into the reception mode. Received echoes from the acoustic boundaries (i.e. cardiac structures) are electronically converted to brightness dots (B-mode) and displayed along a horizontal line on the oscilloscope display. Echo positions on the display thus represent the cardiac dimensions in depth along that echo beam. On the vertical axis of the display, each echo line corresponds to the relative position of each crystal in the transducer. On the display, the outline of the cardiac cross-section is represented by brightness dots



"Multiscan" commercialized in 1972 (150 frames per second)

1980s-2010s:

Doppler, image smoothing, expanding clinical usage with specialized probes, DSP, contrast agents, always real-time….



Current state-of-the-art

2010 -> Present

Erasmus MC

Verasonics Research System

Ultrasound Wave Physics

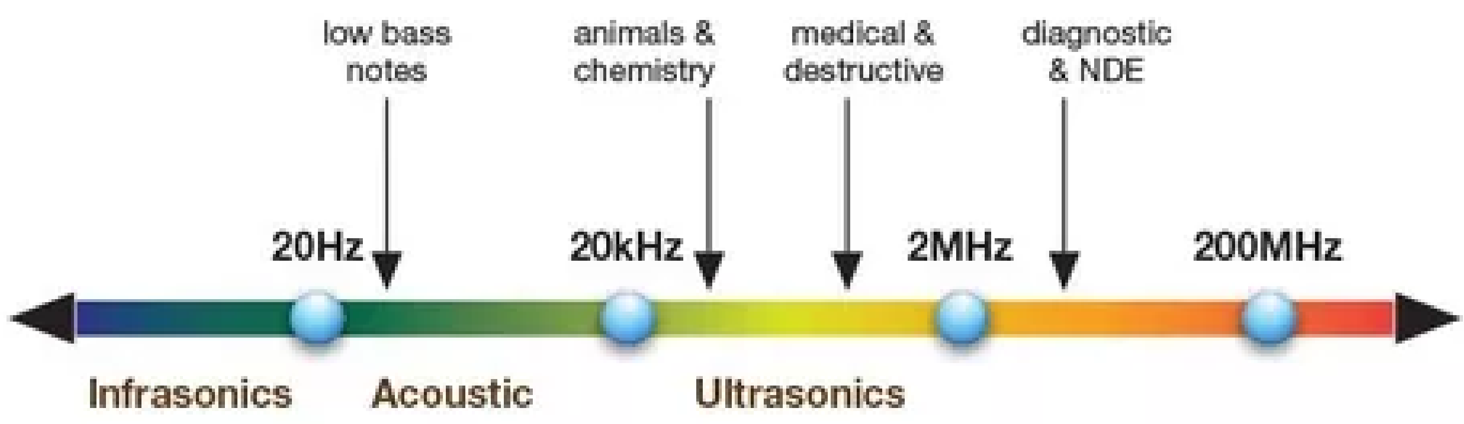
Sound speed in tissue

Erasmus MC

Tissue	c	α	y	ρ	Z	B/A
(units)	M/s	dB/MHz^y – cm		Kg/m^3	megaRayls	
Blood	1584	0.14	1.21	1060	1.679	6
Bone	3198	3.54	0.9[b]	1990	6.364	—
Brain	1562	0.58	1.3	1035	1.617	6.55
Breast	1510	0.75	1.5	1020	1.540	9.63
Fat	1430	0.6	1*	928	1.327	10.3
Heart	1554	0.52	1*	1060	1.647	5.8
Kidney	1560	10	2[b]	1050	1.638	8.98
Liver	1578	0.45	1.05	1050	1.657	6.75
Muscle	1580	0.57	1*	1041	1.645	7.43
Spleen	1567	0.4	1.3	1054	1.652	7.8
Milk	1553c	0.5	1	1030	1.600	—
Honey	2030[s]	—	—	1420[s]	2.89[s]	—
Water @ 20°C	1482.3	2.17e-3	2	1.00	1.482	4.96

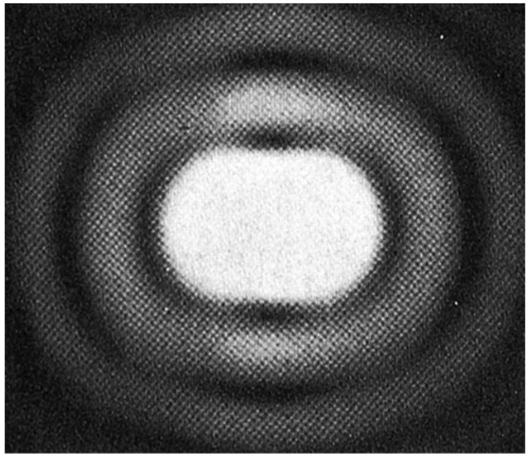
Diagnostic Ultrasound Imaging: Inside Out
Thomas L. Szabo

Ultrasonics Range Diagram

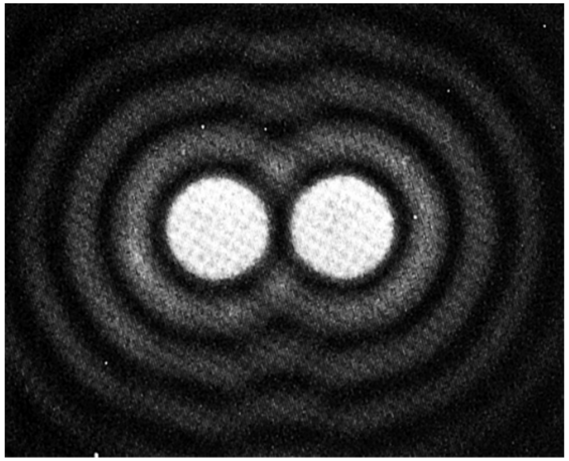


from Wikipedia article on Ultrasound

Resolution



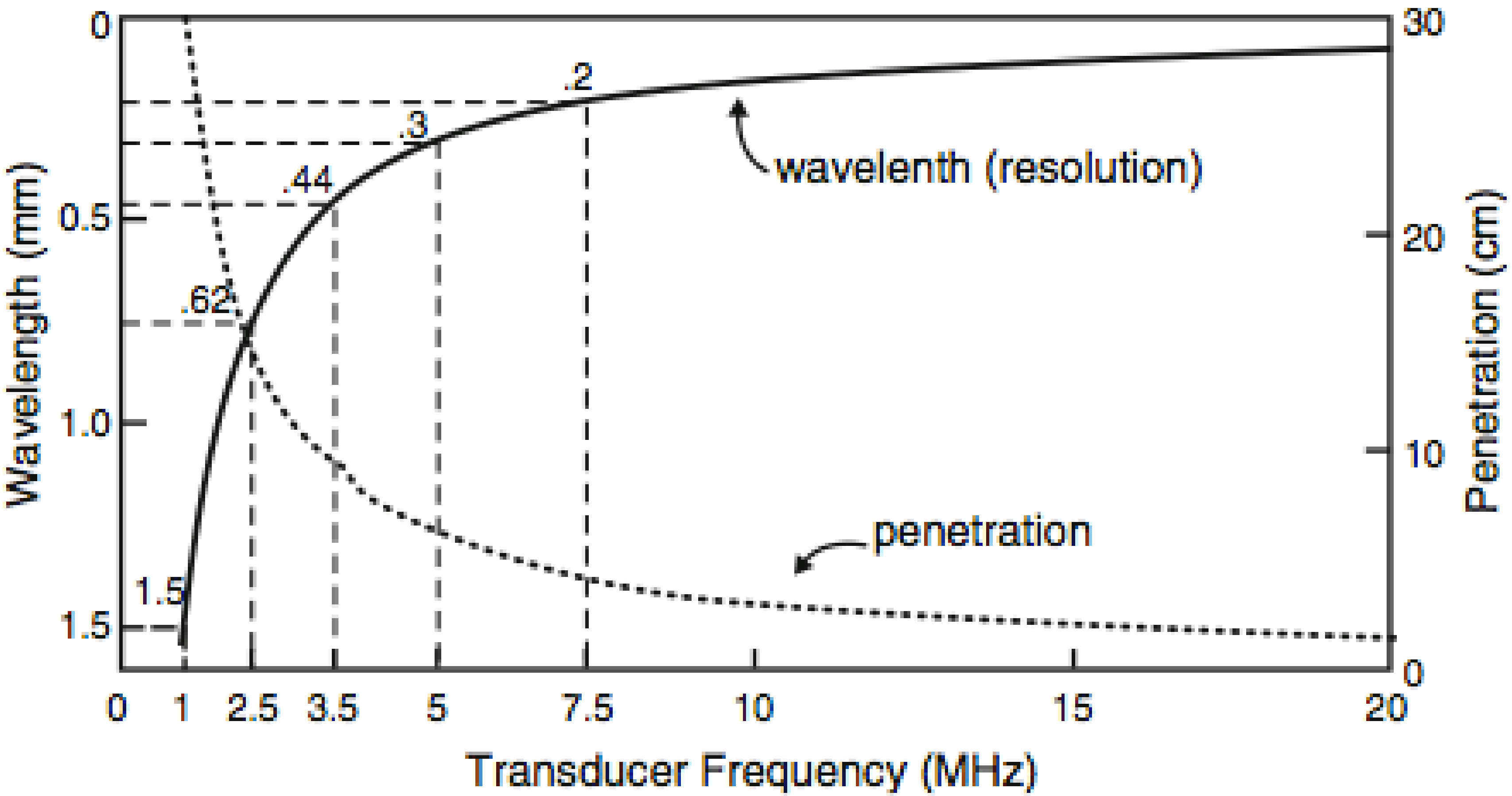
Low frequency =
long wavelength =
low resolution



High frequency =
short wavelength =
high resolution

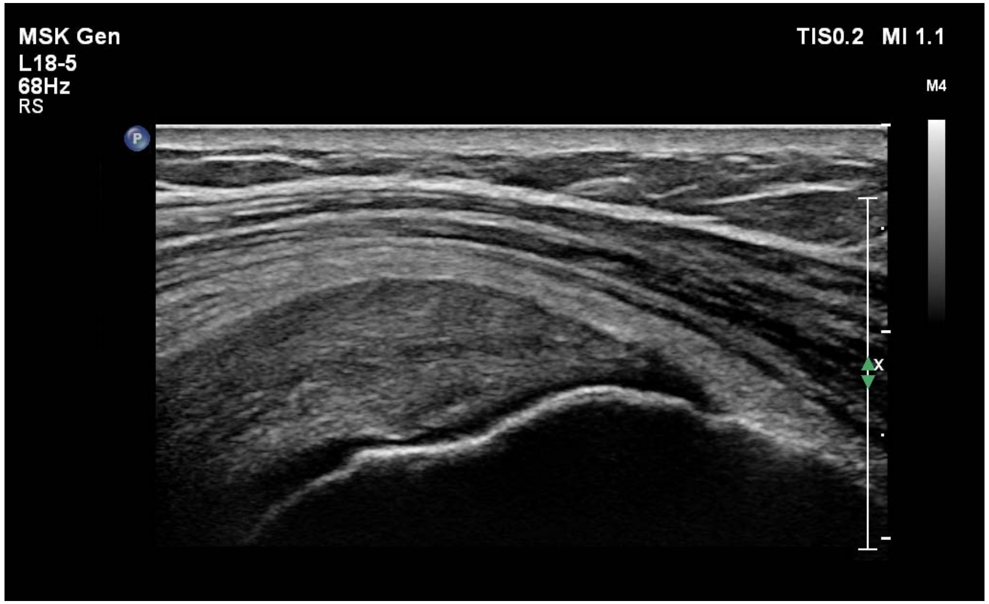
But there is a trade-off

Erasmus MC

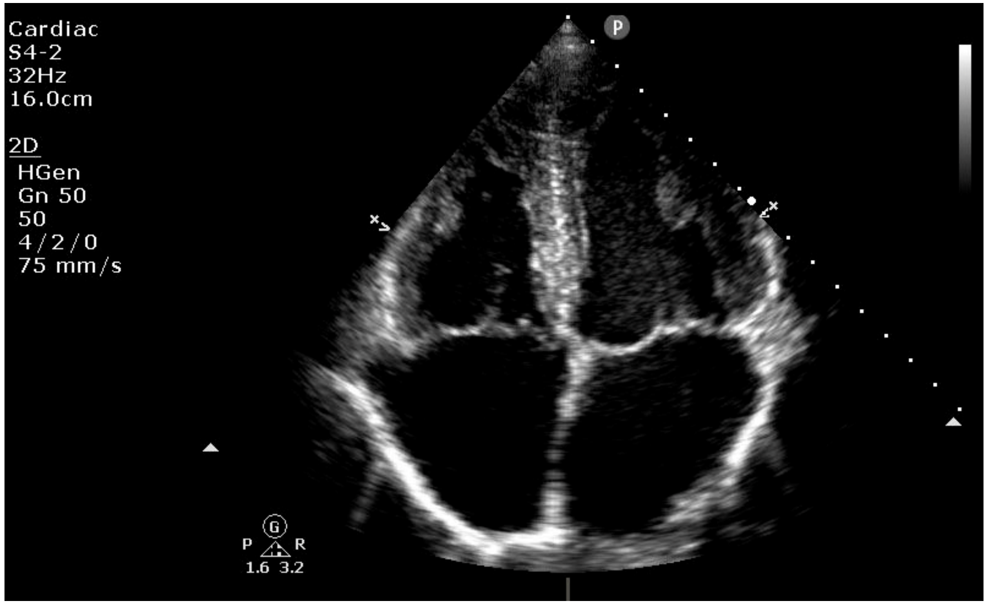


Trade-off between resolution and penetration depth

Superficial muscles
Depth = 1.5 cm
Frequency = 12 MHz



Heart
Depth = 16 cm
Frequency = 3 MHz



Array of piezoelectric elements - resonance

- Thickness resonance frequency of the piezoelectric element determines the operating frequency of the probe

$$2 \times \text{thickness } t = \text{wavelength } \lambda$$

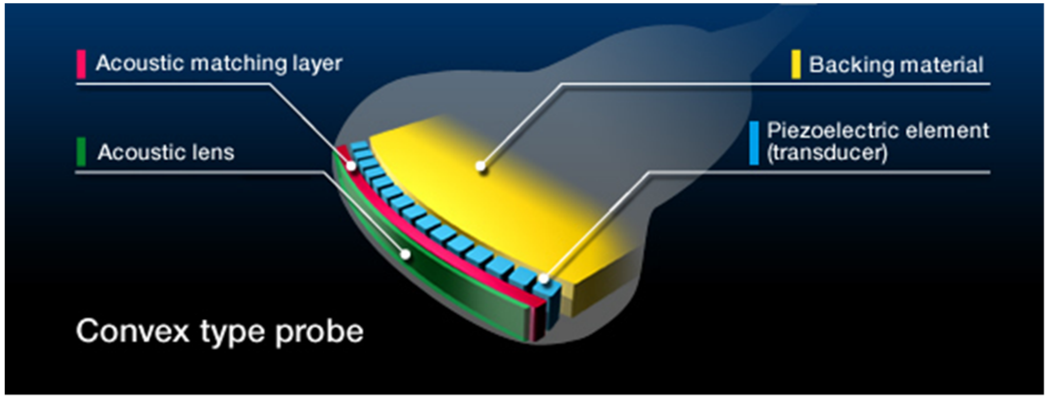
$$f_{resonance} = \frac{c}{\lambda} = \frac{c}{2t}$$

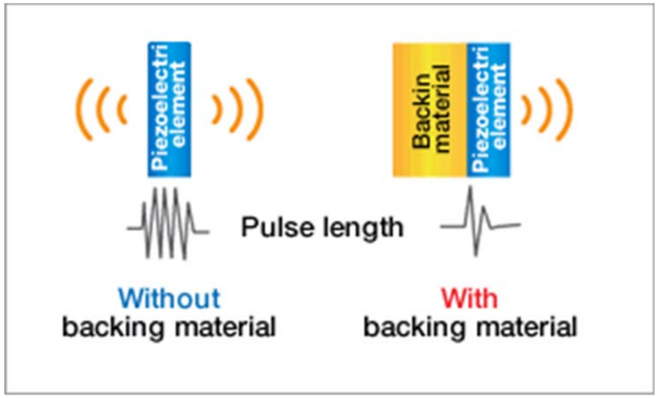
Example: c ~ 4000m/s in piezoelectric material
If f = 4MHz, then t = 0.5mm

- Response of piezoelectric element to an electrical impulse (ring-down or impulse response) must be short (in time) to obtain a good axial resolution

→ Resonance is mechanically damped by backing material (polymer resin)

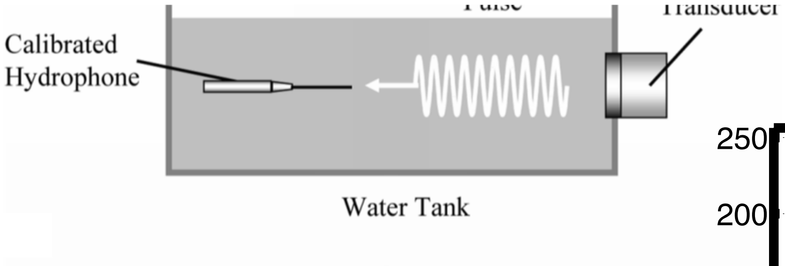
→ Trade-off between sensitivity and axial resolution

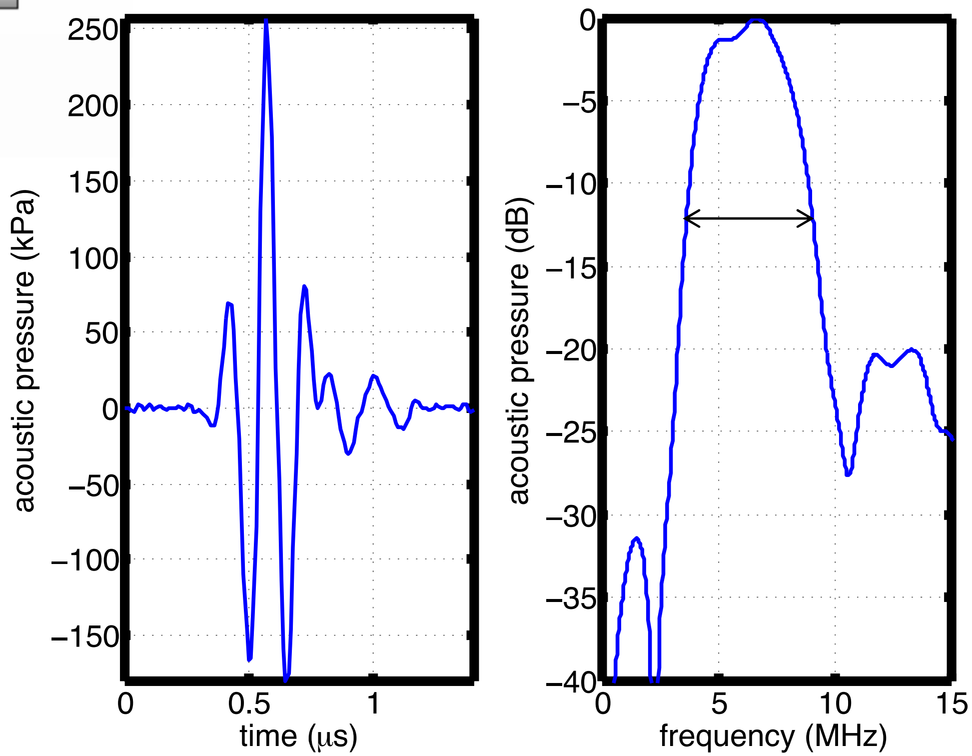




Array of piezoelectric elements - resonance

- Acoustic pulse broadcasted by Philips iU22 equipped with L9-3 probe





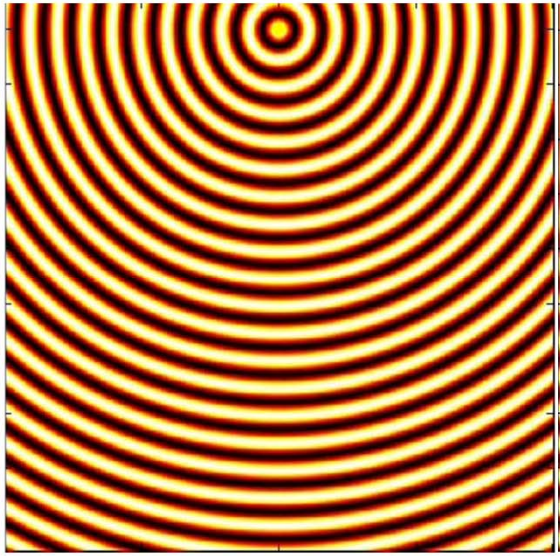
-12 dB frequency bandwidth = [3.7MHz-9.1MHz]

Array of piezoelectric elements – medical probes

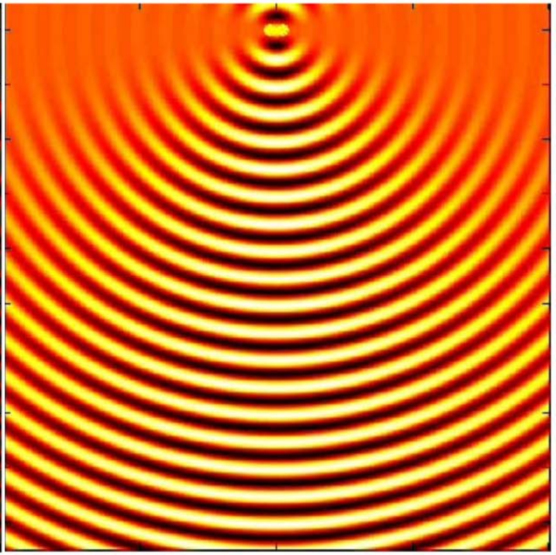
Erasmus MC

Beam anatomy produced by a single element

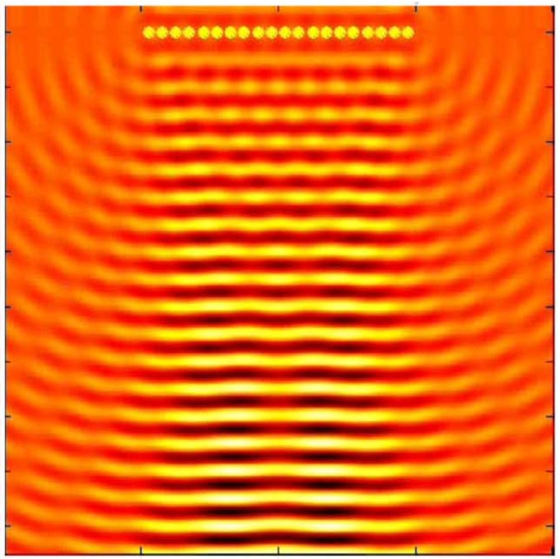
- What is the shape of the ultrasound beam generated by a single crystal of the Multiscan probe?
- → We apply Huygens' principle
- Adding contributions at given locations from many point sources gives an interference pattern → radiation pattern



1 point source



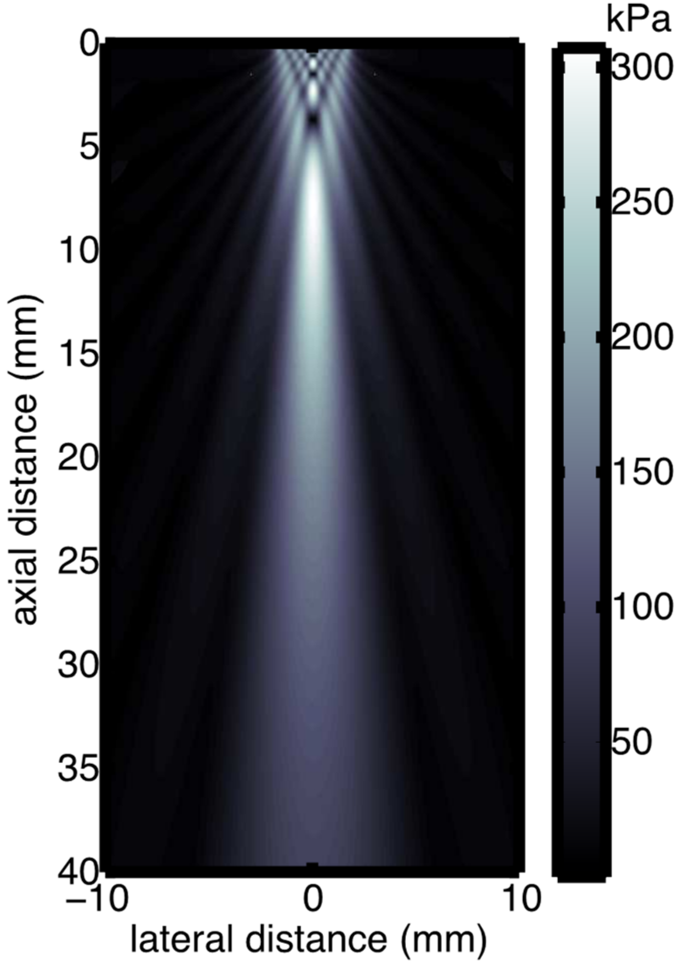
2 point sources



20 point sources

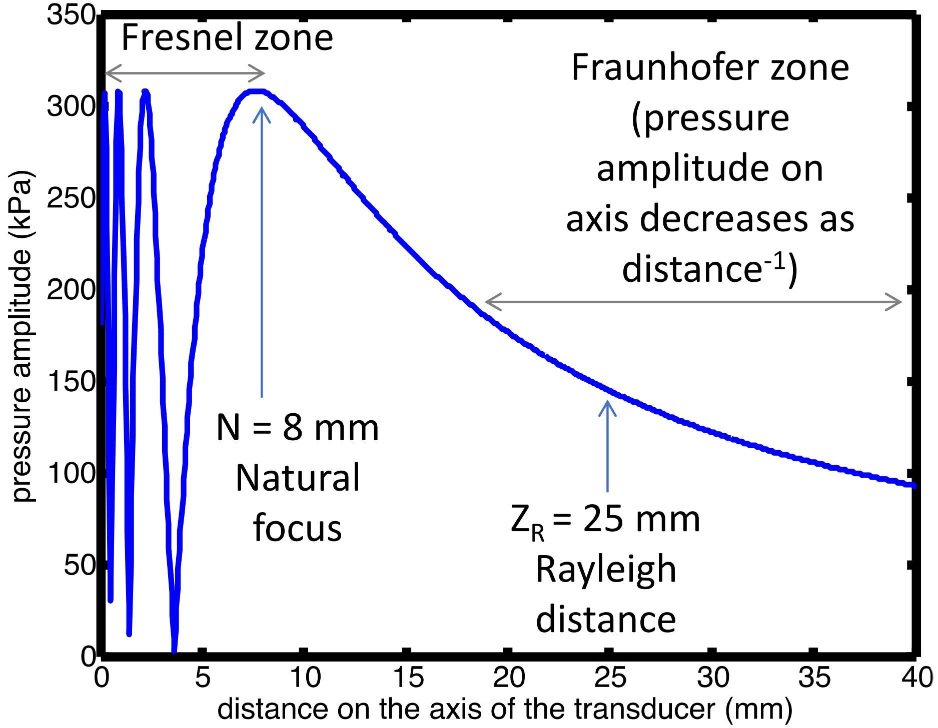
Beam anatomy produced by a single element

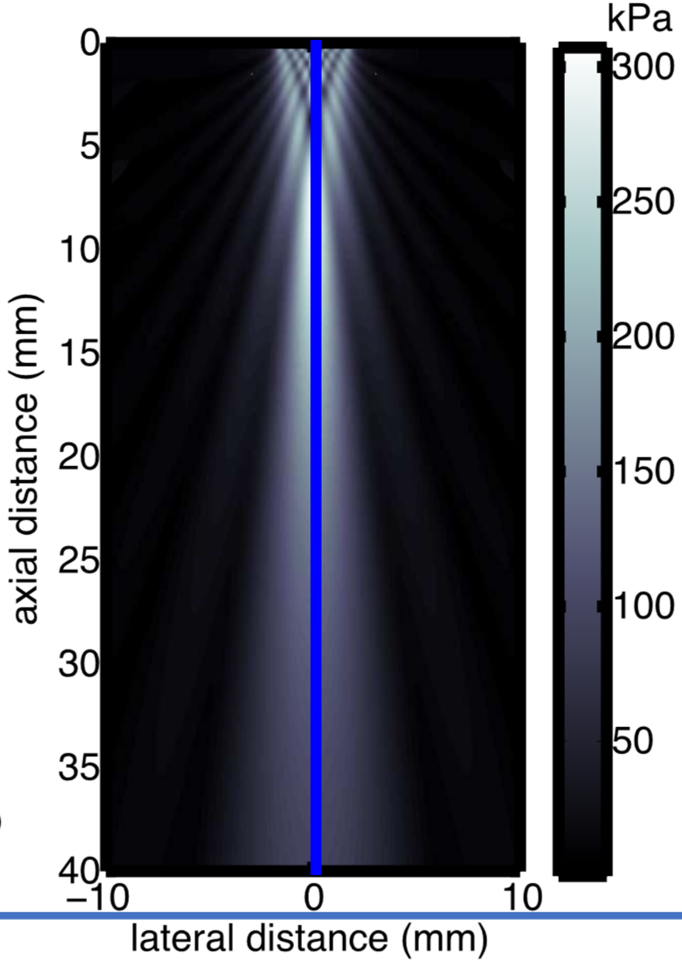
Erasmus MC



Beam anatomy produced by a single element

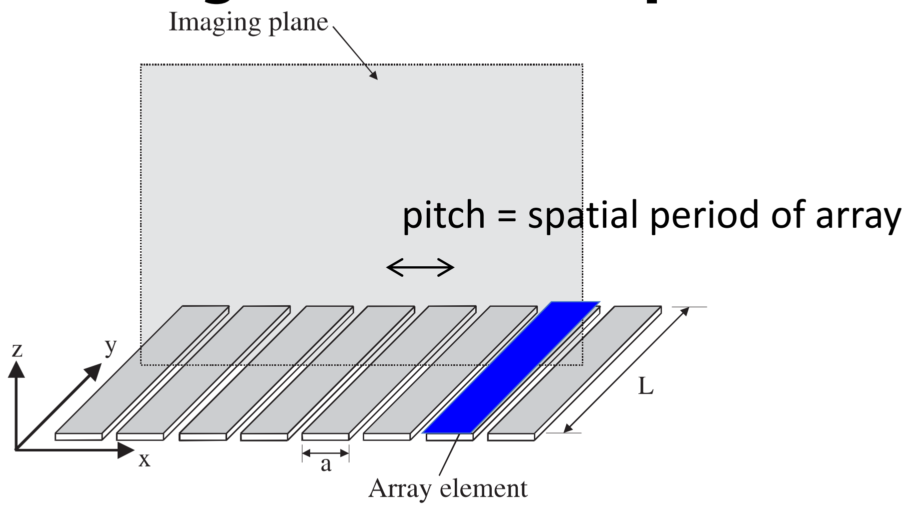
- Axial beam profile



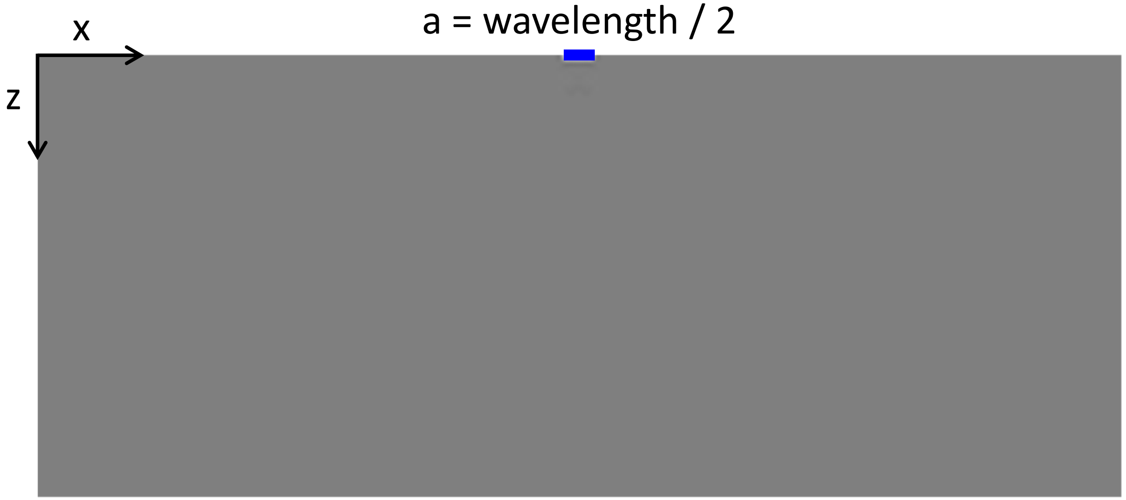


Array of small elements

- **Radiation pattern of a single element (≈ point source)**



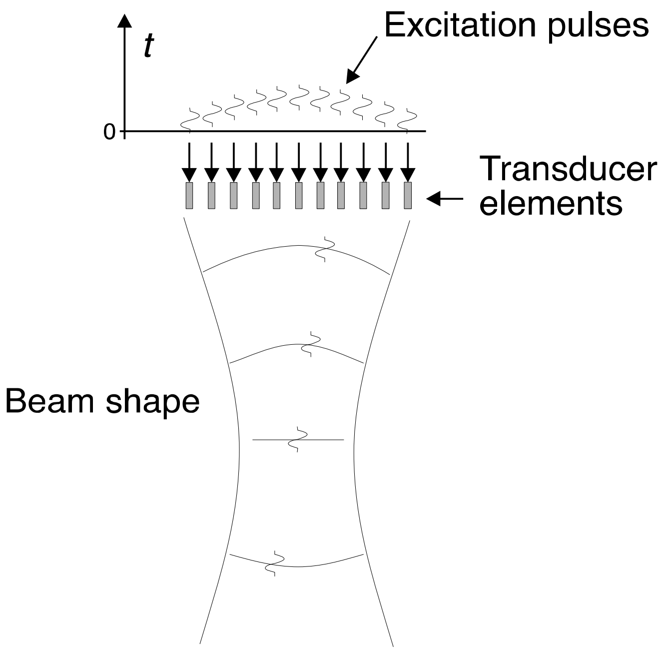
a = wavelength / 2



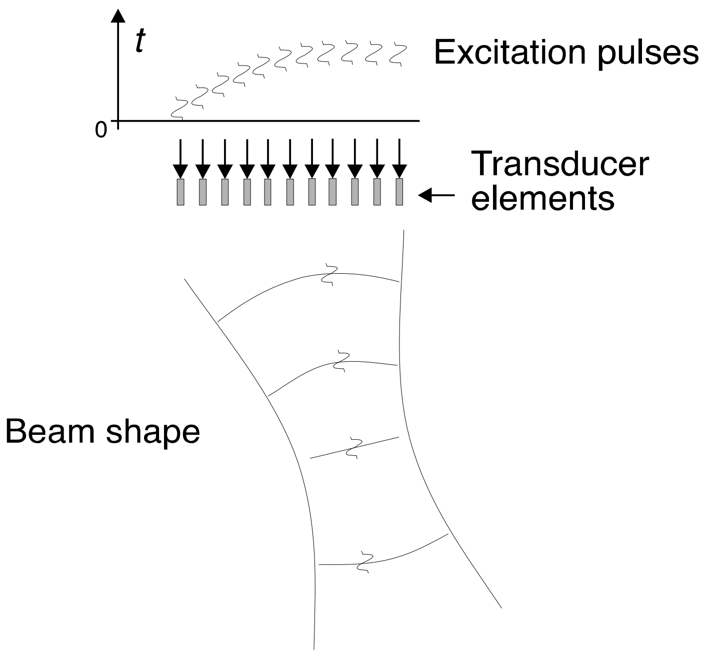
Array of small elements

- Electronic scanning (beam focusing and steering)
- A group of elements is used (= aperture)
- Focusing achieved by delaying the excitation of the individual elements

Electronic focusing



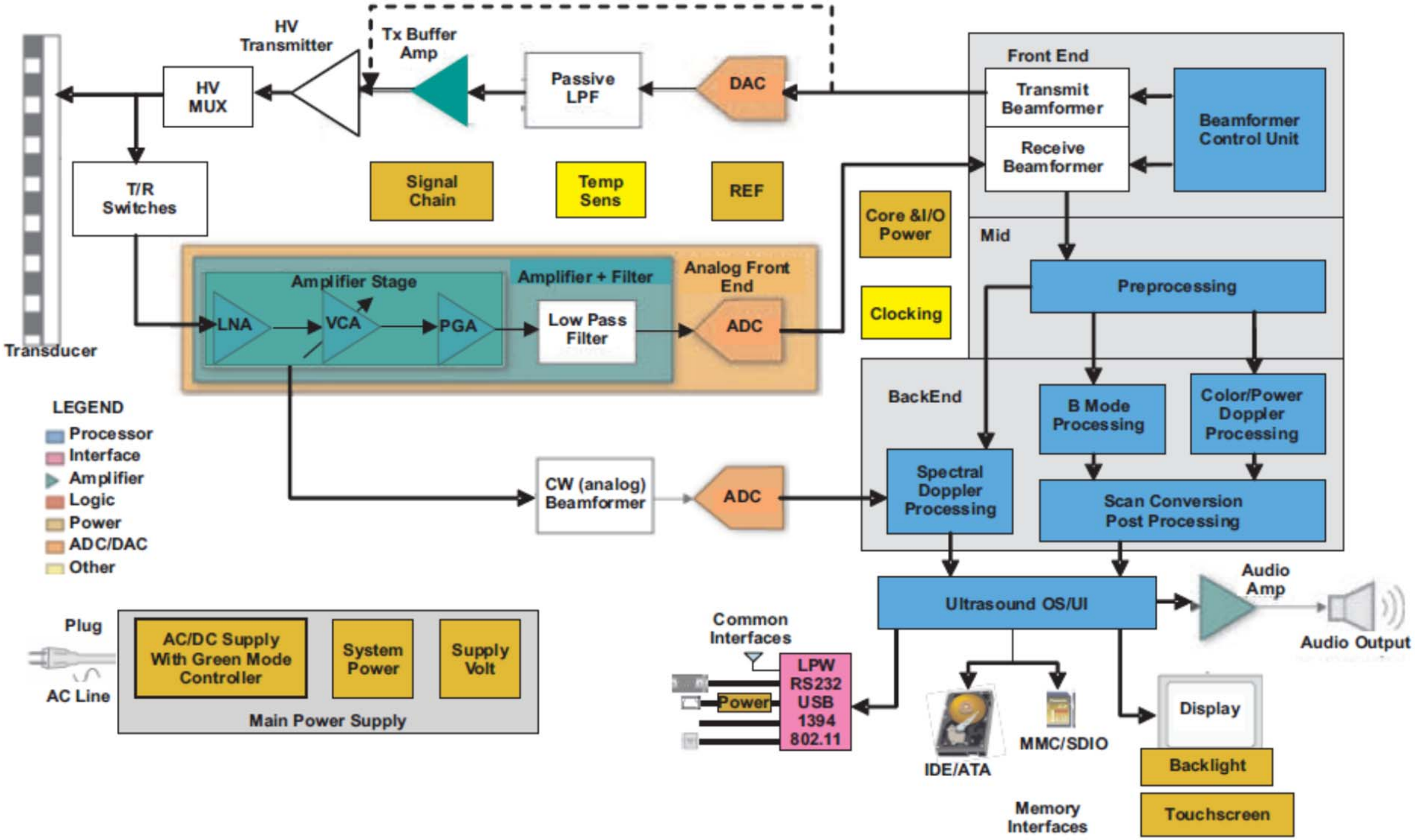
Beam steering and focusing



Signal processing: some examples

Inside an ultrasound system

Erasmus MC



Texas Instruments

Array processing in ultrasound imaging

Capon, mvdr etc… don't work so well as in radar

Radar, telecommunication etc. vs ultrasound imaging

sources = countable
detection

vs

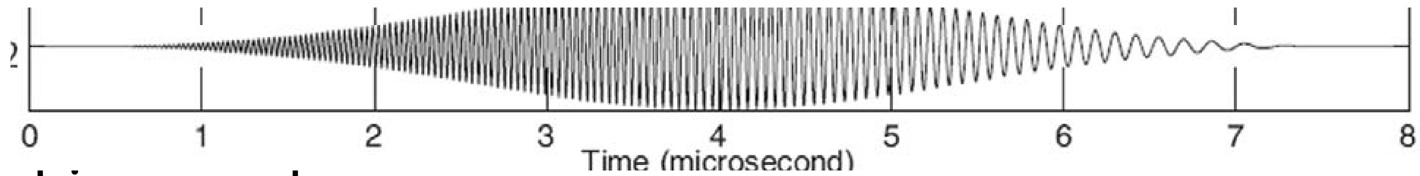
sources = infinite
imaging

Increasing signal-to-noise ratio with coded excitation

- Signal-to-noise ratio (SNR) can be increased by increasing transmit acoustic pressure
- However, to prevent cavitation from happening in soft tissue, there exists a maximum acoustic pressure

- Coded excitations can improve SNR (without increasing amplitude)

- Chirp (frequency-swept signal)



- Golay binary codes

Increasing signal-to-noise ratio with coded excitation

- Theory of coded excitations

- h(t) is the pulse-echo impulse response of the system {ultrasound transducer + imaging medium}
- Transducer excited by a coded waveform e(t) (chirp or Golay)
- Received signal is:

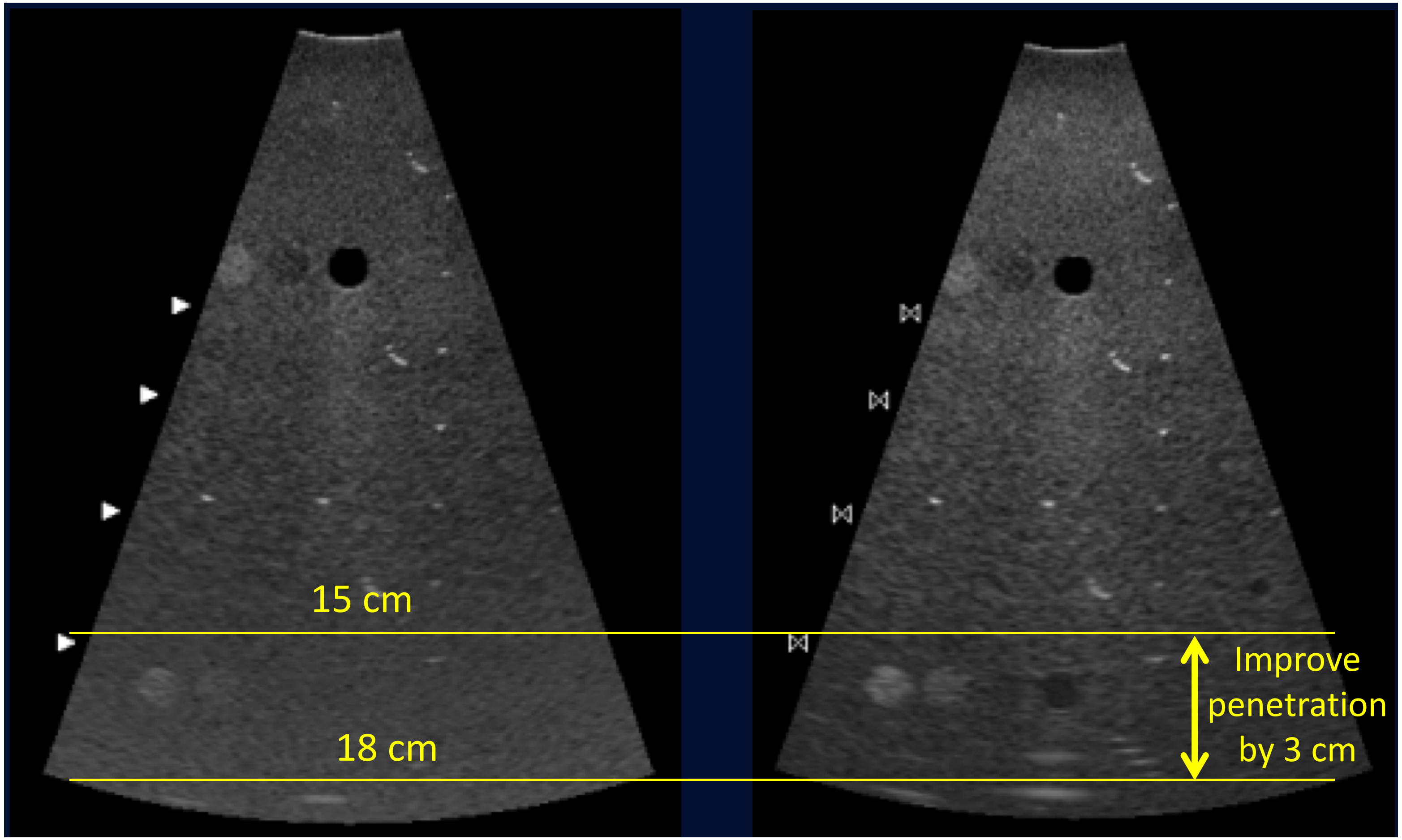
$$s(t) = e(t) * h(t) = \int_{-\infty}^{+\infty} e(t-\tau)h(\tau)d\tau$$

- Received signal is "compressed" by a cross-correlator:

$$s_{\text{compressed}}(t) = e(t) * s(t) = e(t) * [e(t) * h(t)] = R_{ee}(t) * h(t)$$

- R_{ee}(t) is the autocorrelation of the excitation waveform e(t)
- R_{ee}(t) is much shorter than e(t) → axial resolution is recovered

Increasing SNR with coded excitation



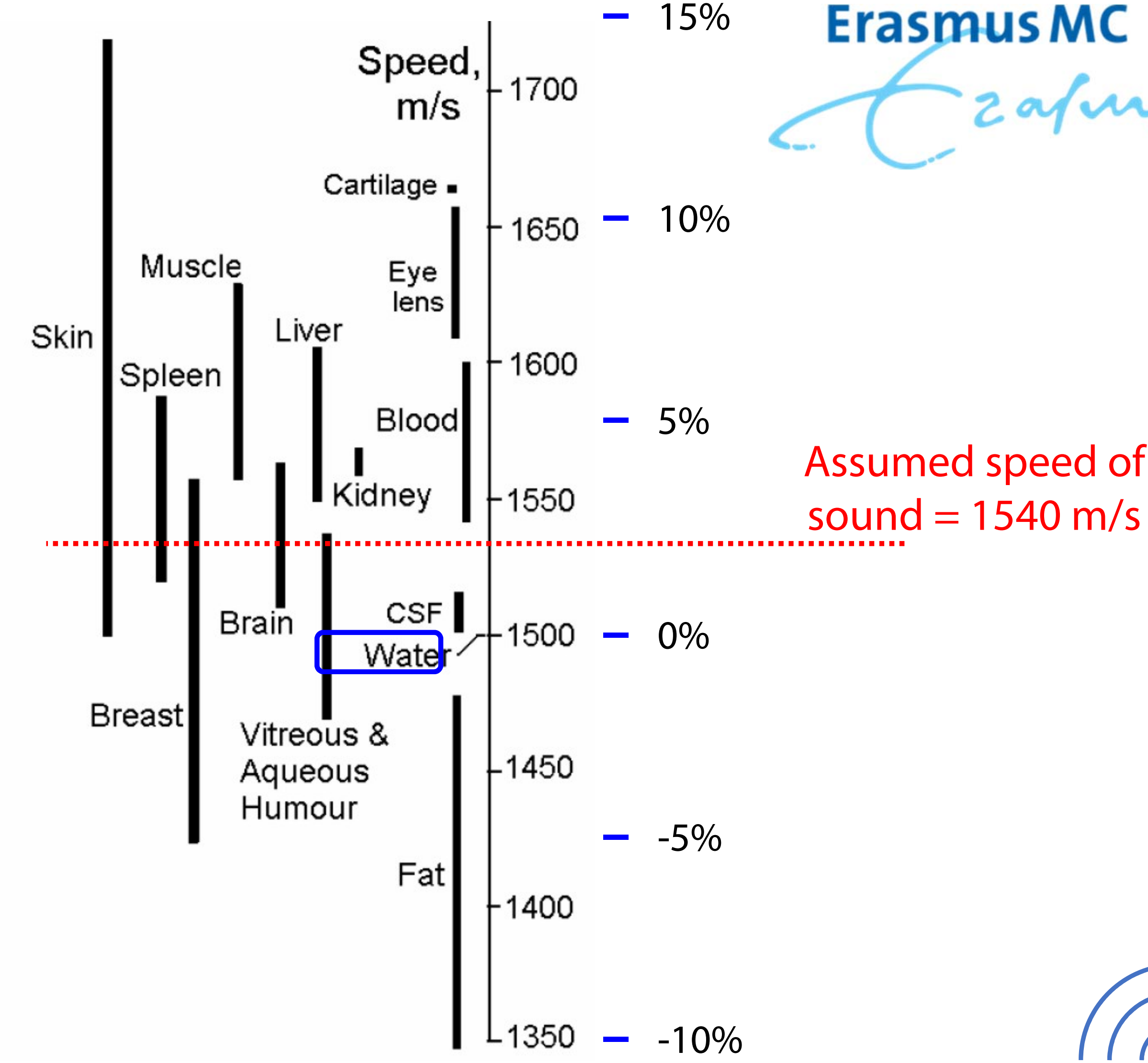
Aberration correction

Ultrasound systems use an assumption of uniform speed of sound, c = 1540 m/s.

Delay laws are calculated with this value for transmit and receive focusing.

However:

- Even in a homogeneous type of tissue (liver), the actual sound speed is unknown
- Medium is heterogeneous, large regional variation of sound speed (fat layer)



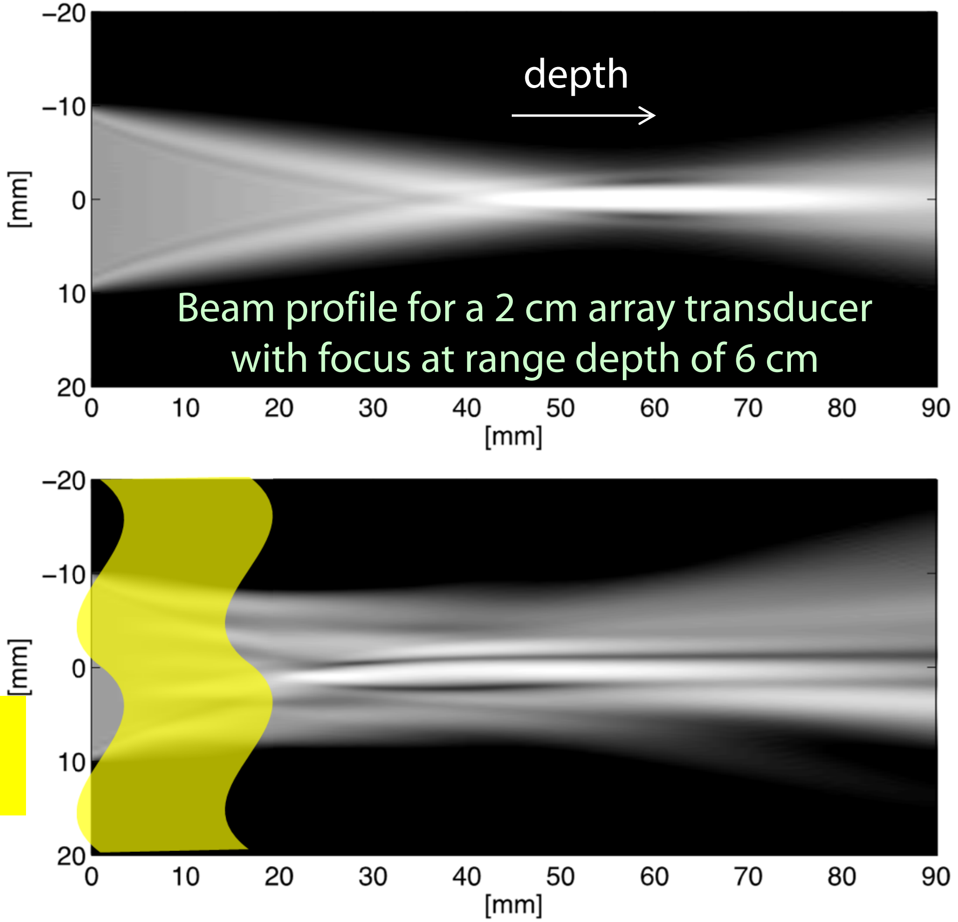
Aberration correction

regional variation of sound speed

In a uniform wavespeed

Effect of 2 cm thick fat layer (1400 m/s) near the probe

Distortion of the transmit ultrasound beam

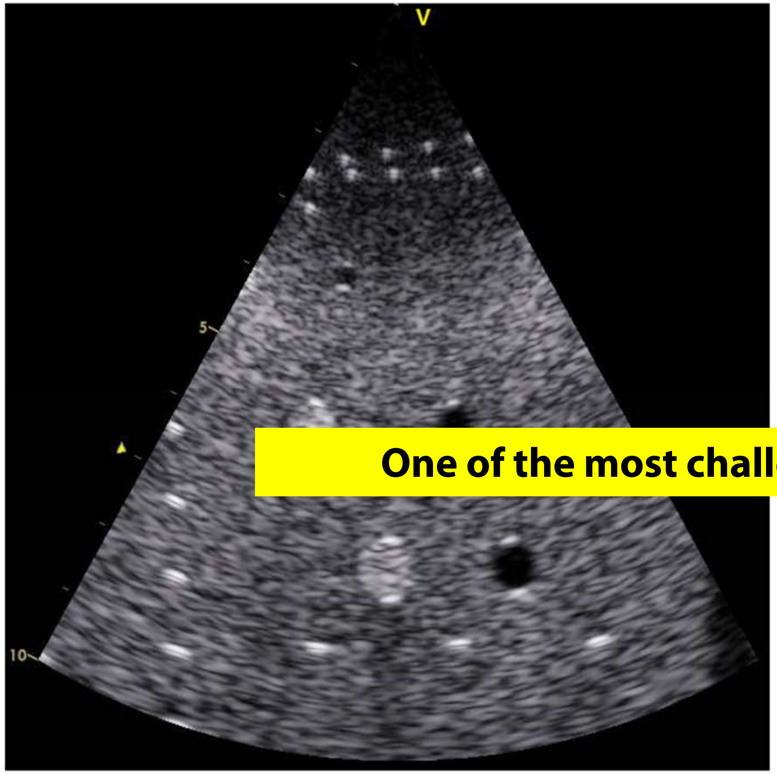


Aberration correction

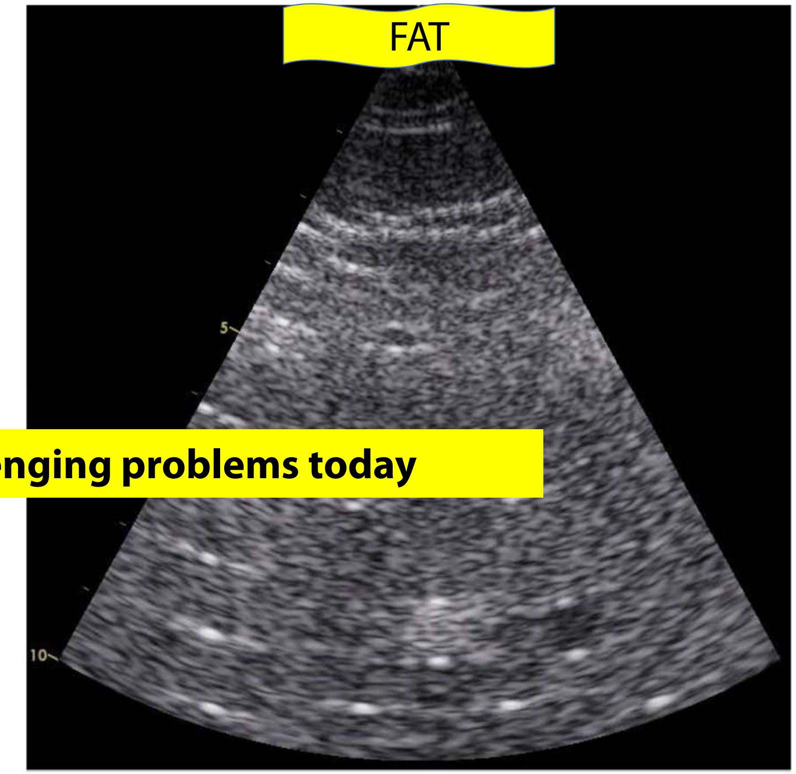
regional variation of sound speed

Erasmus MC

No fat layer



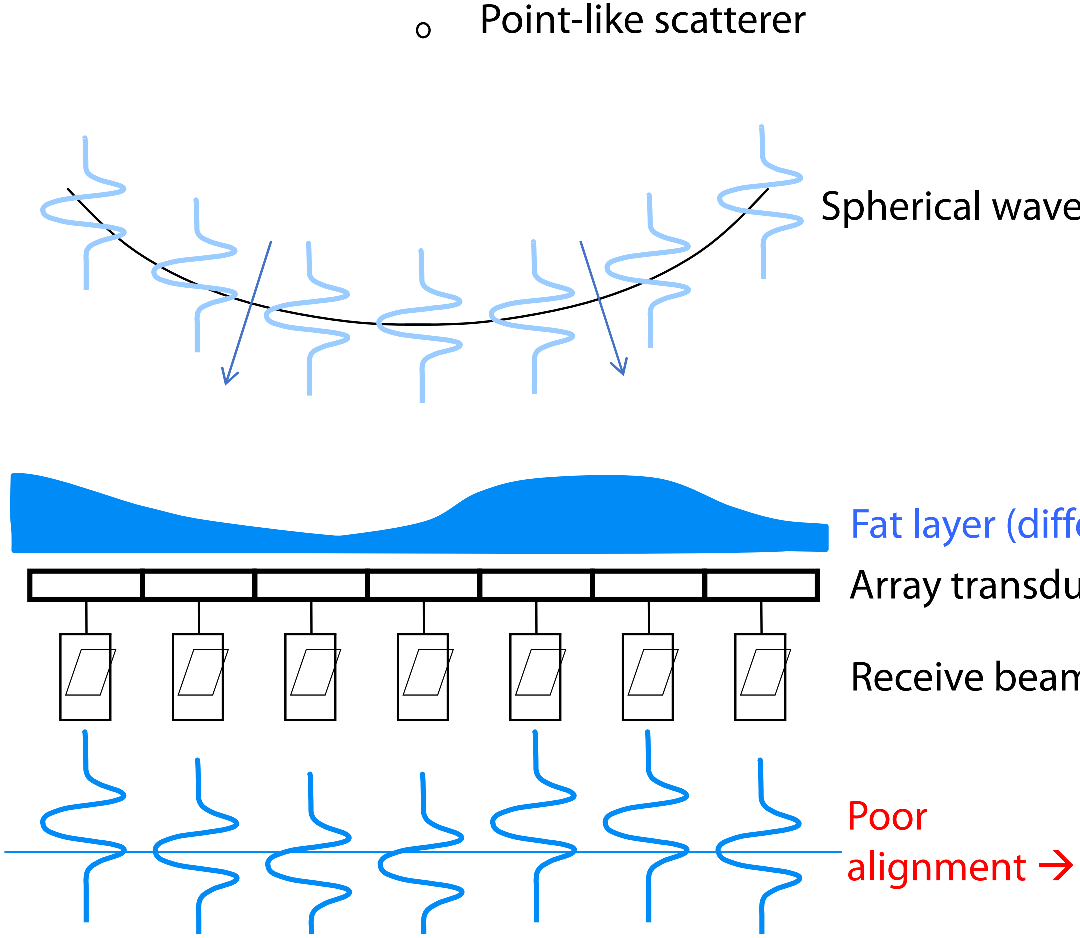
5 mm thick silicon layer in front of the probe to mimic a fat layer



One of the most challenging problems today

Aberration correction

regional variation of sound speed

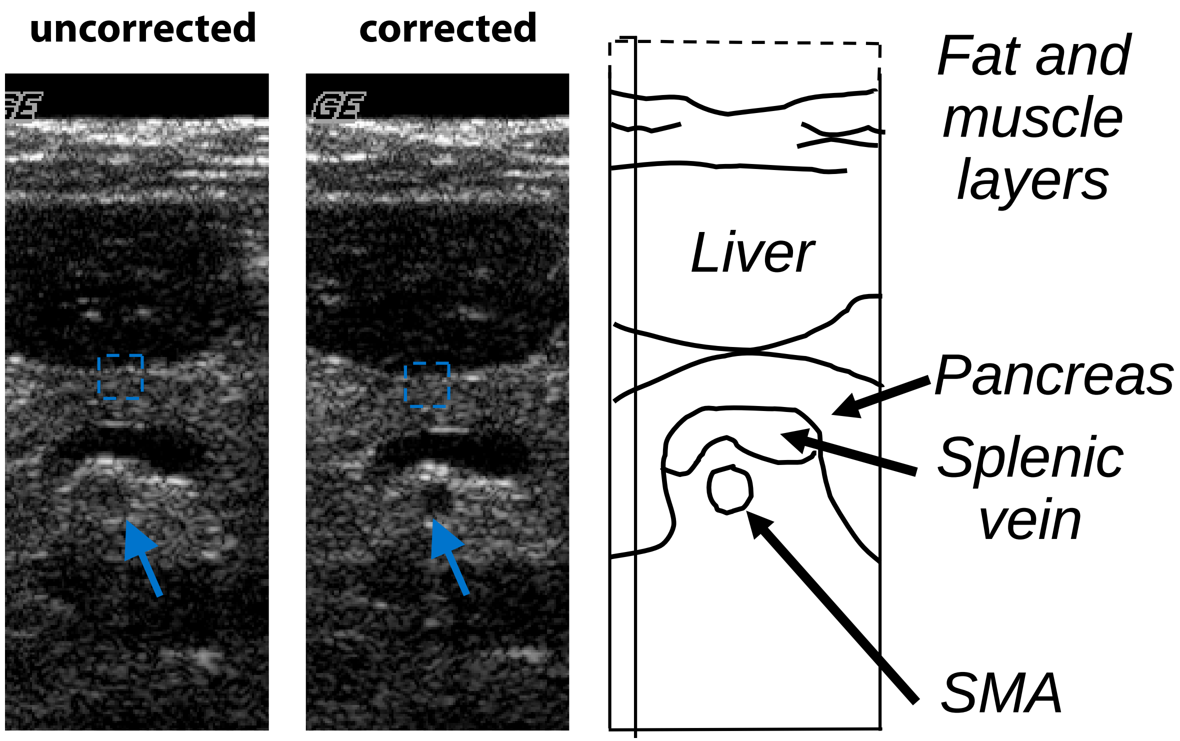


Abberation can be reduced with near-field phase-screen : apply small delays to correct misalignment

Aberration correction

regional variation of sound speed

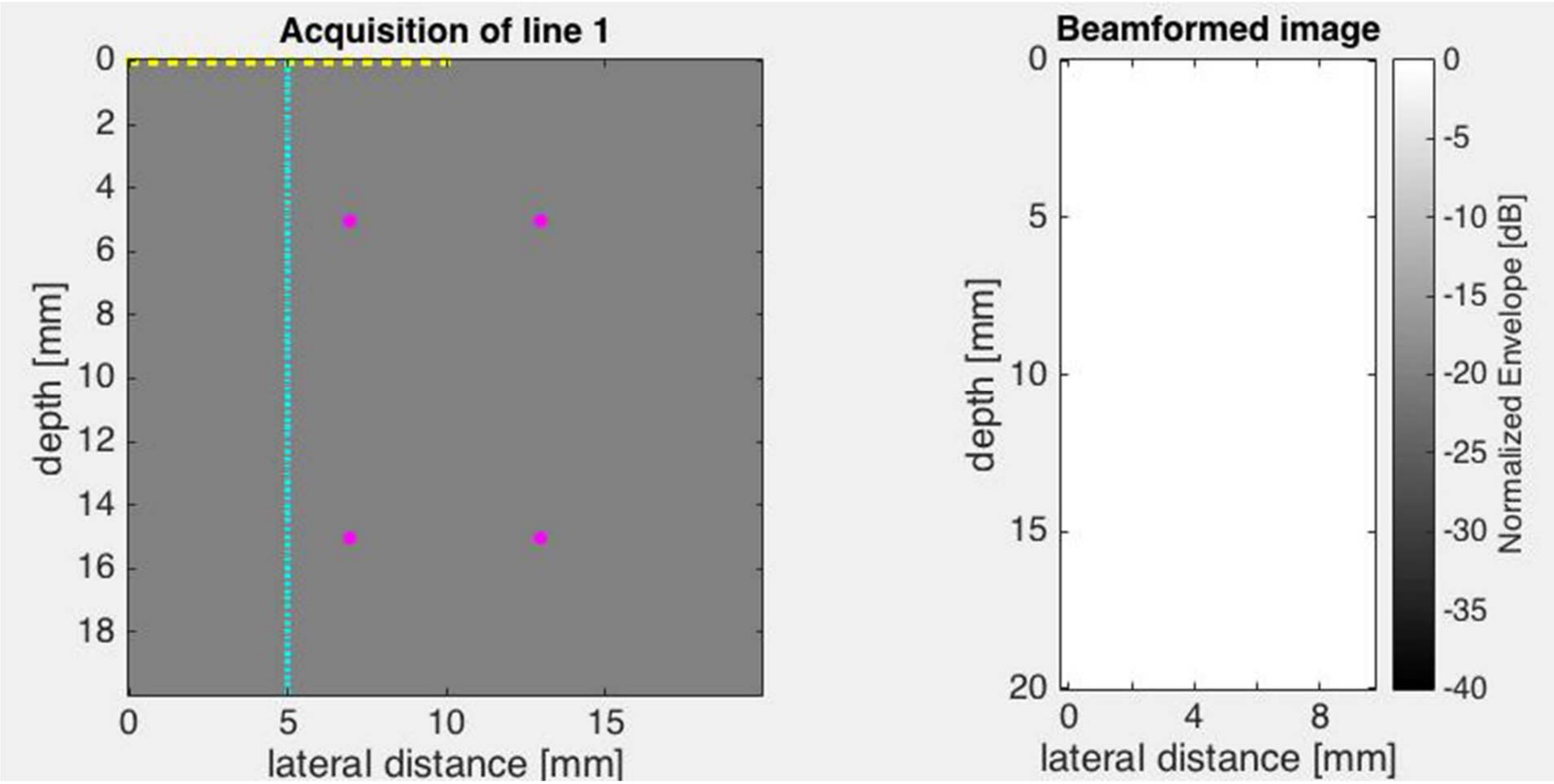
- Aberrating sources near the probe (fat layer)
- Time shifting of echoes (near-field phase-screen models), amount of shift determined by cross-correlation between elements



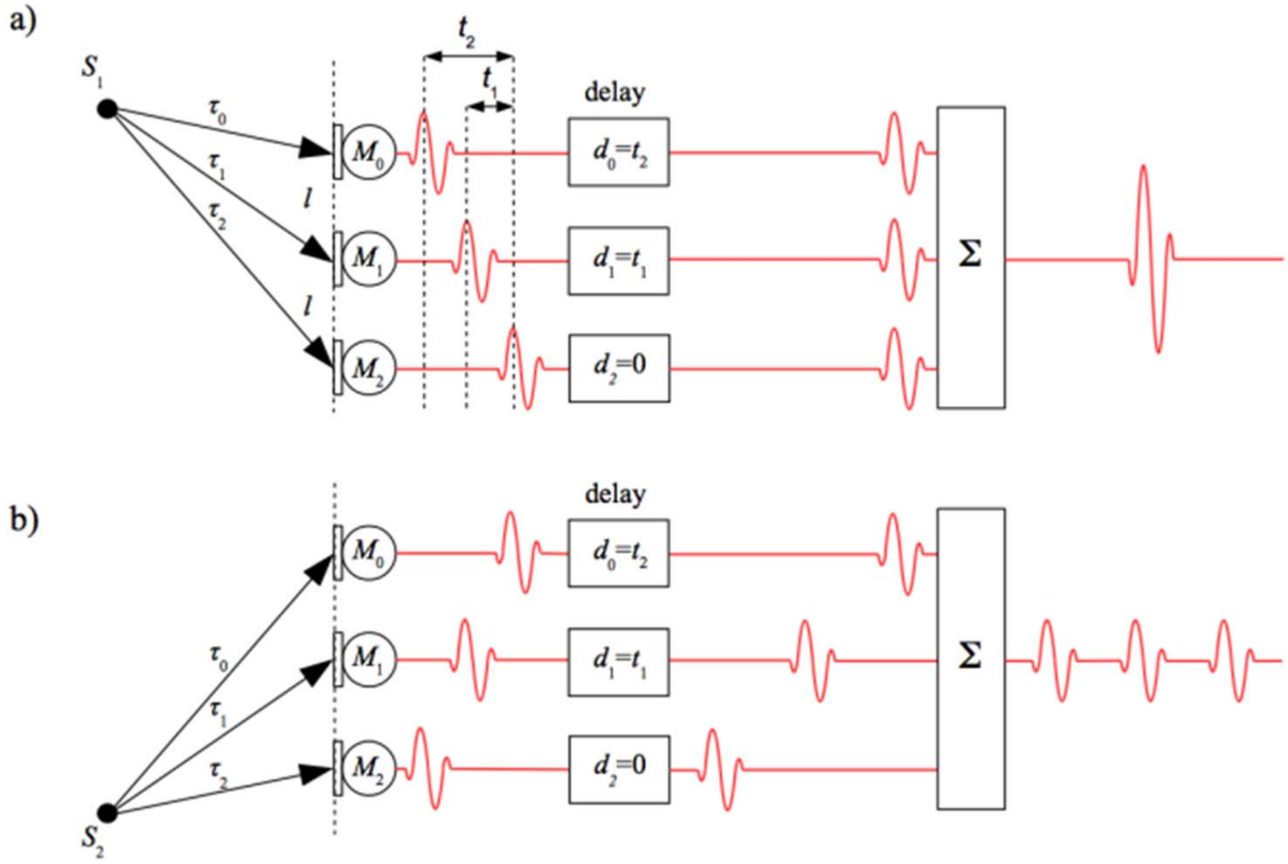
Break

Image Reconstruction: Beamforming

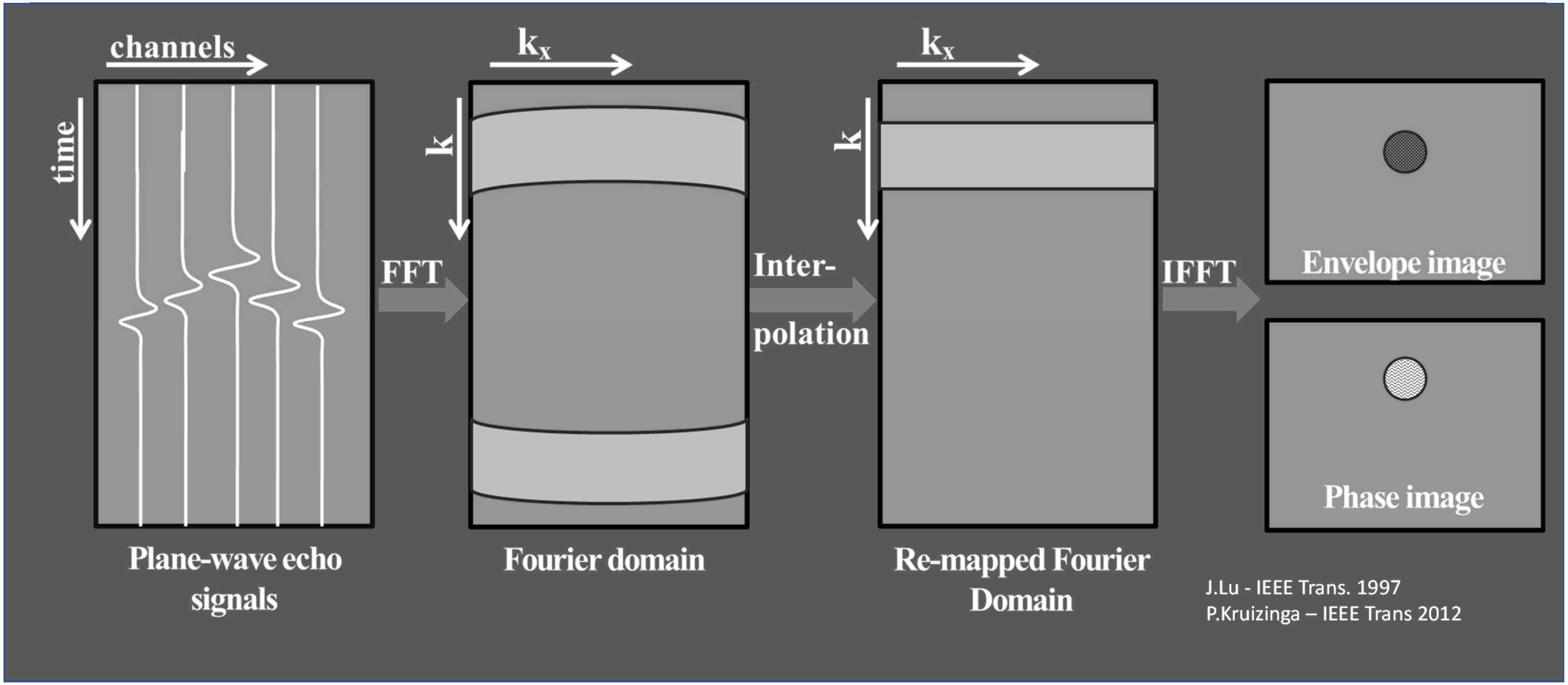
Line-by-line scanning



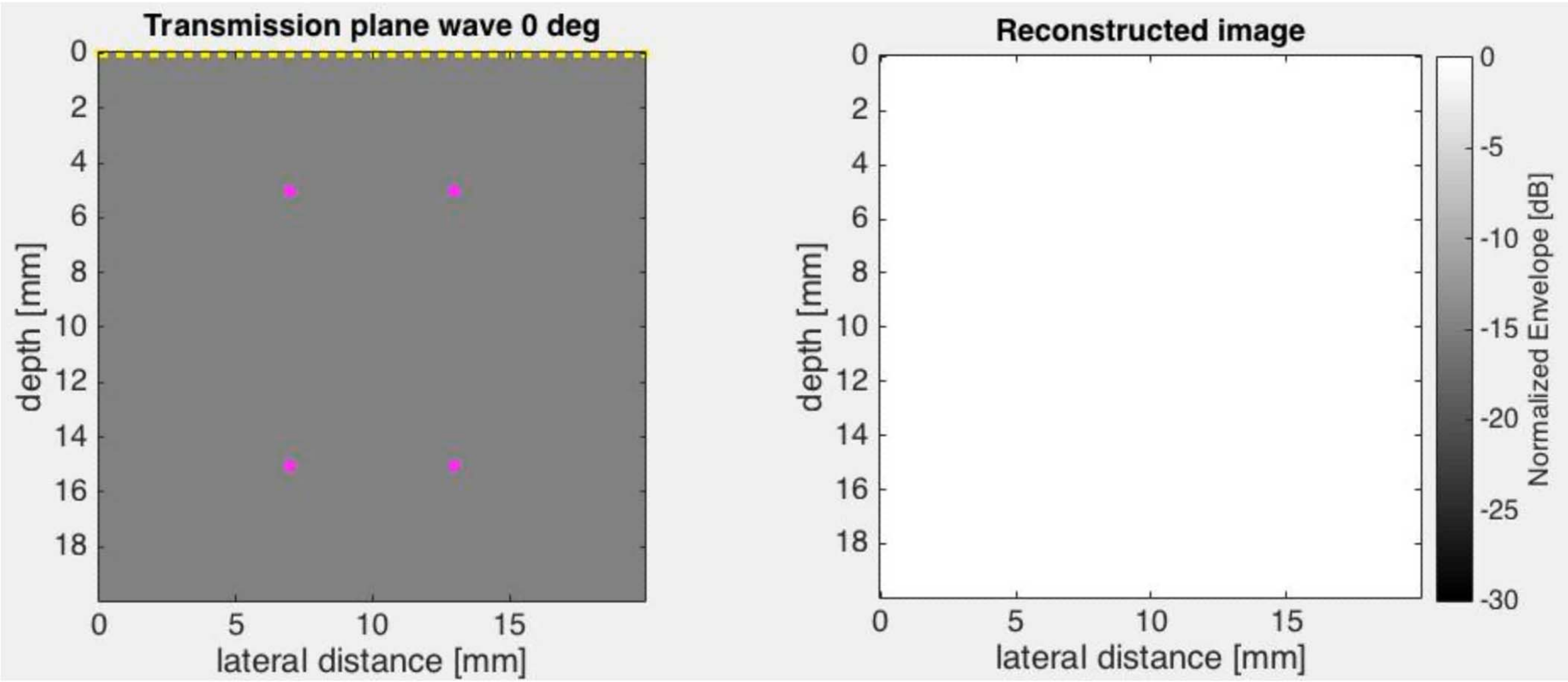
Main image reconstruction technique: Delay-and-sum beamforming



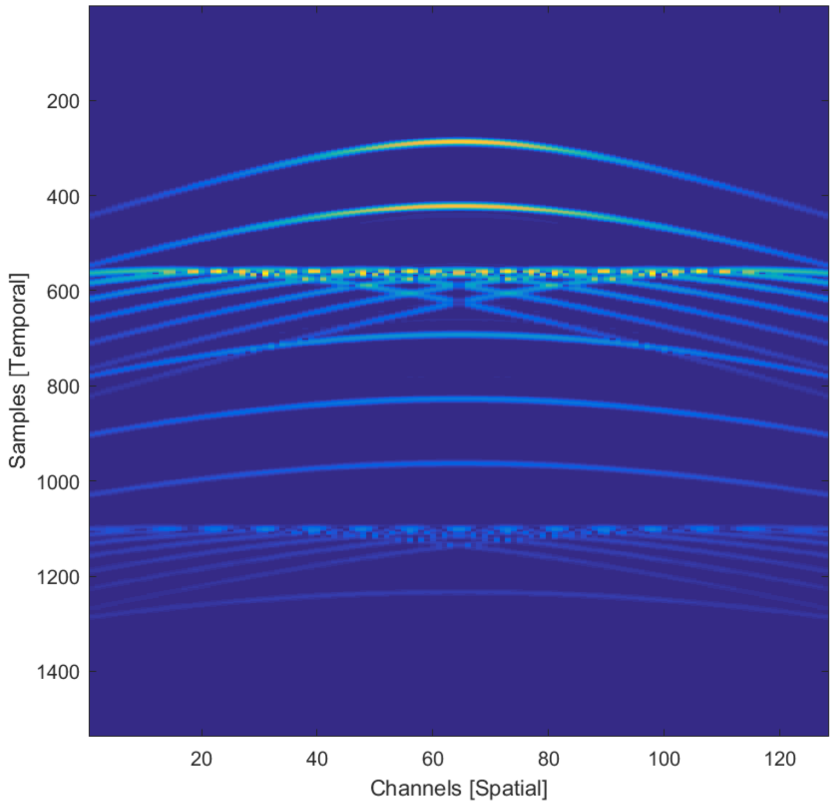
Delay-and-sum beamforming: in the frequency domain (plane wave)

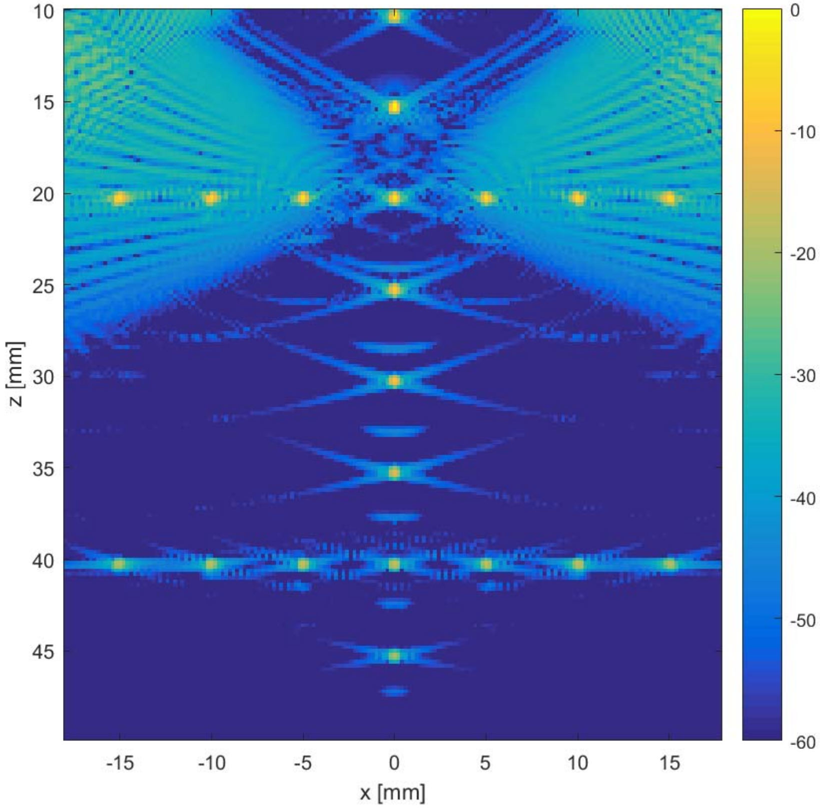


Single plane wave



Data & Image


200
400
600
800
1000
1200
1400
Samples [Temporal]
20
40
60
80
100
120
Channels [Spatial]


10
15
20
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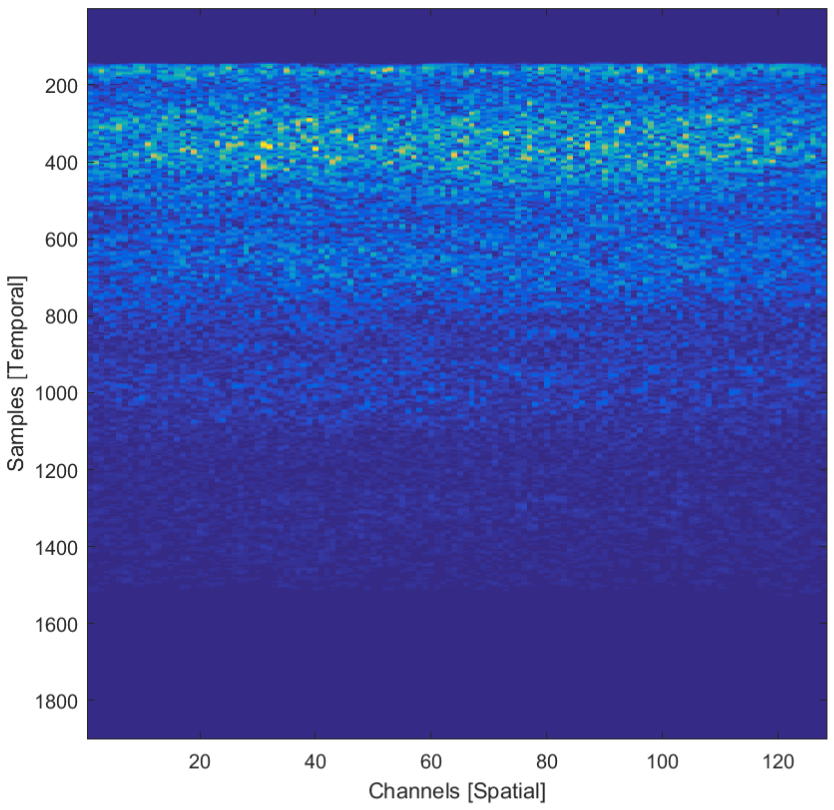
45
z [mm]
-15
-10
-5
0
5
10
15
x [mm]
0
-10
-20
-30
-40
-50
-60

Data & Image



200
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Samples [Temporal]
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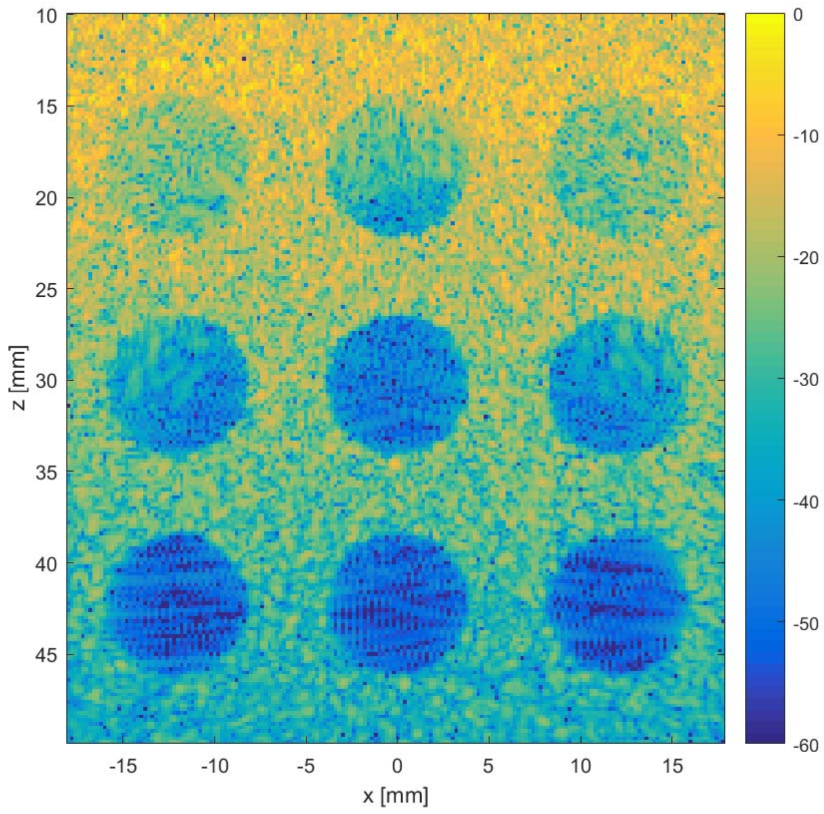
Channels [Spatial]



10
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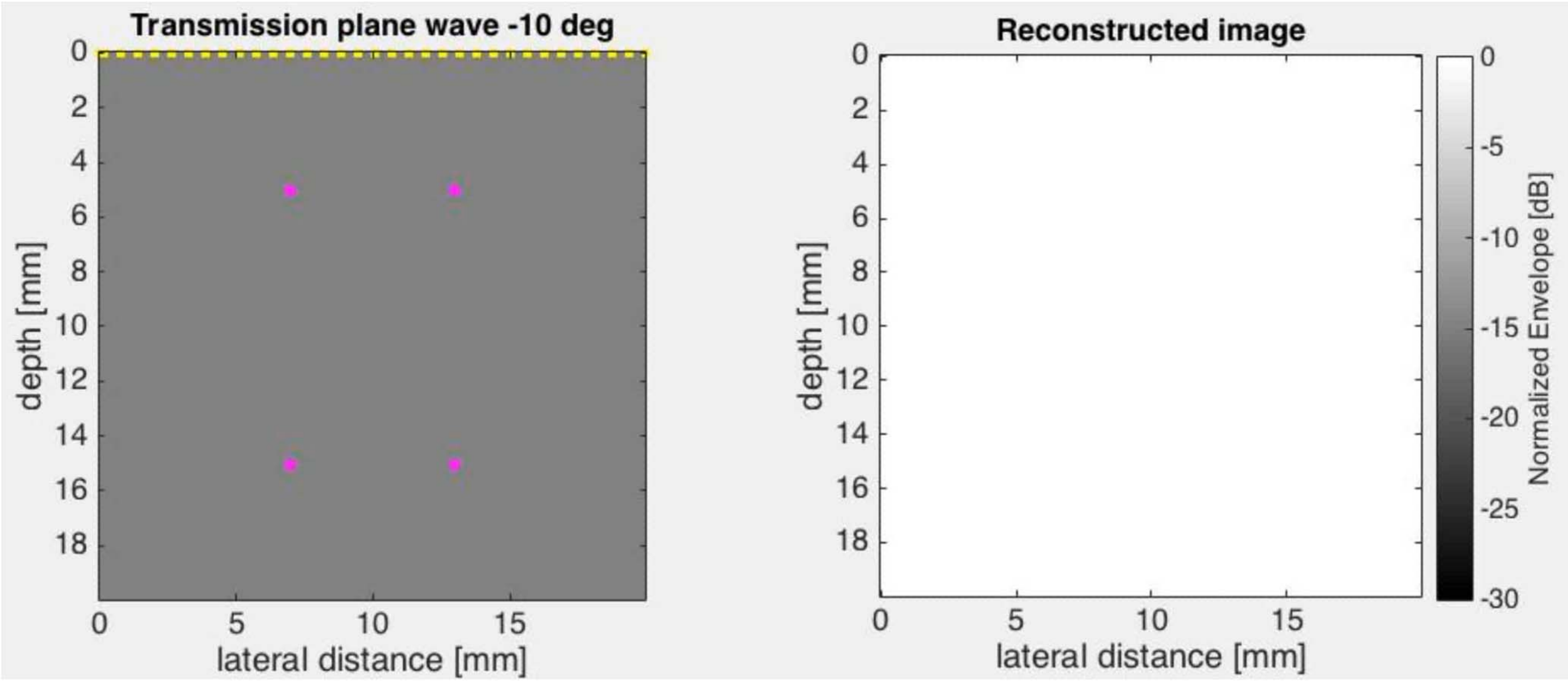
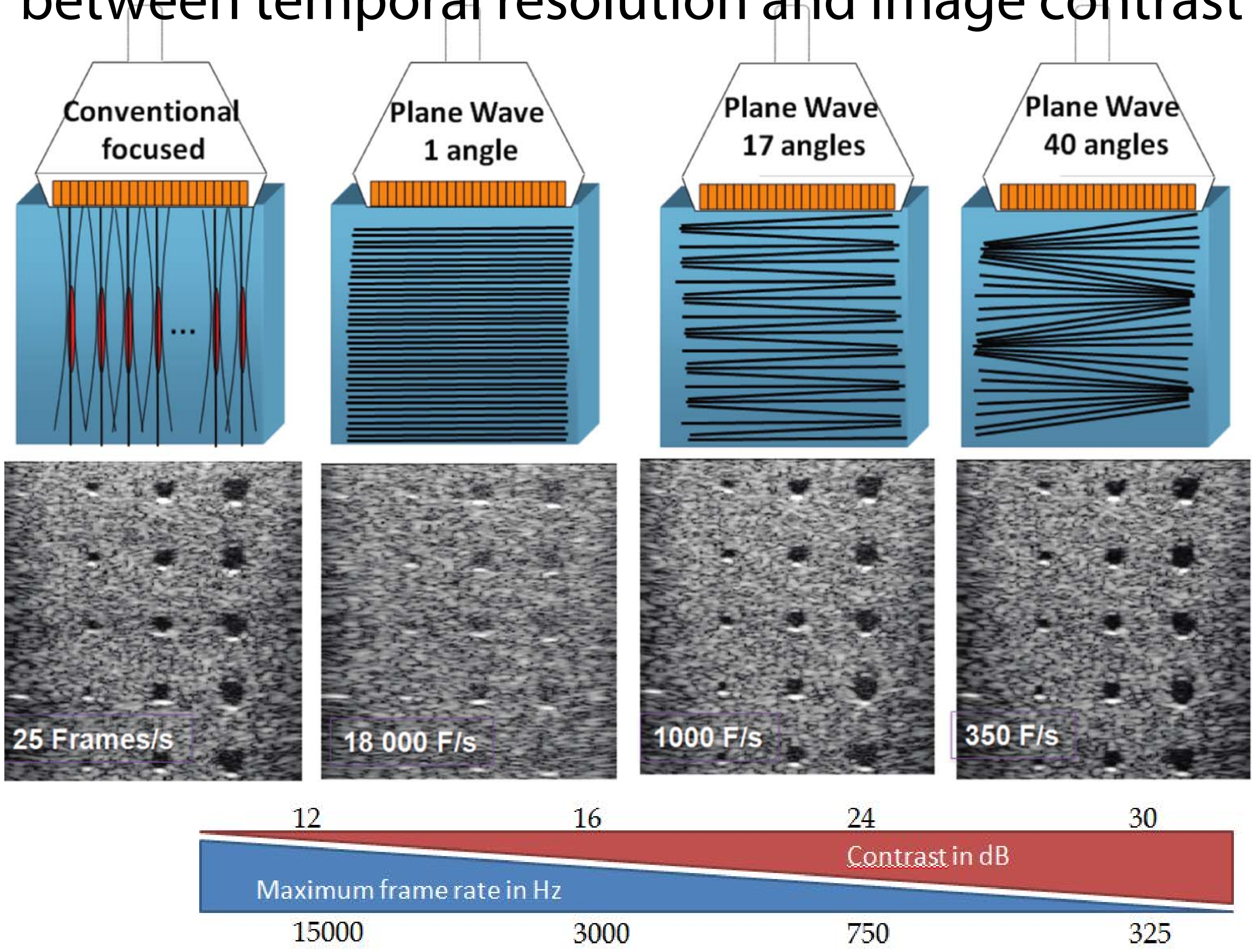
z [mm]
-15
-10
-5
0
5
10
15
x [mm]
0
-10
-20
-30
-40
-50
-60

Plane wave compounding



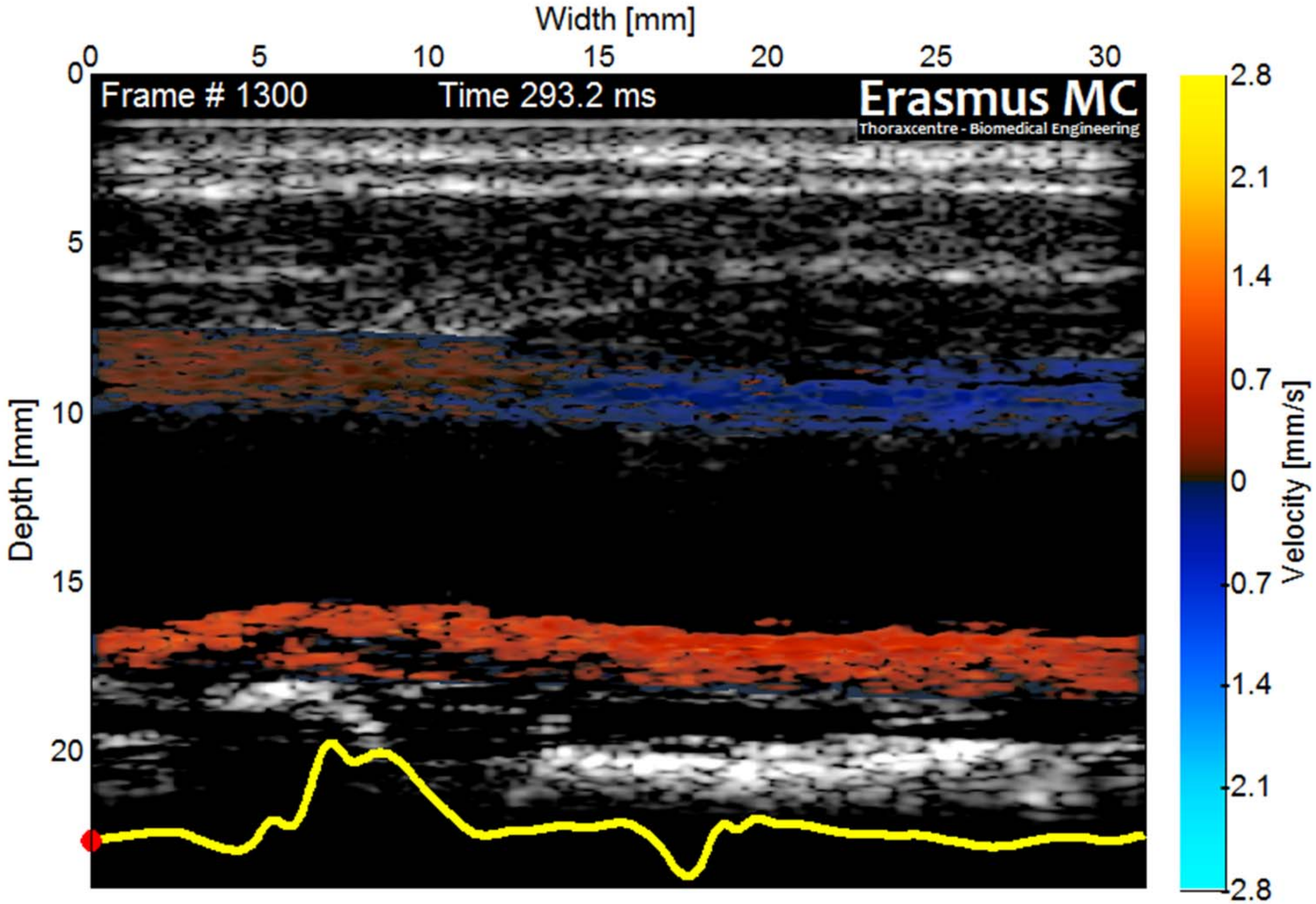
High frame rate imaging

- Trade-off between temporal resolution and image contrast

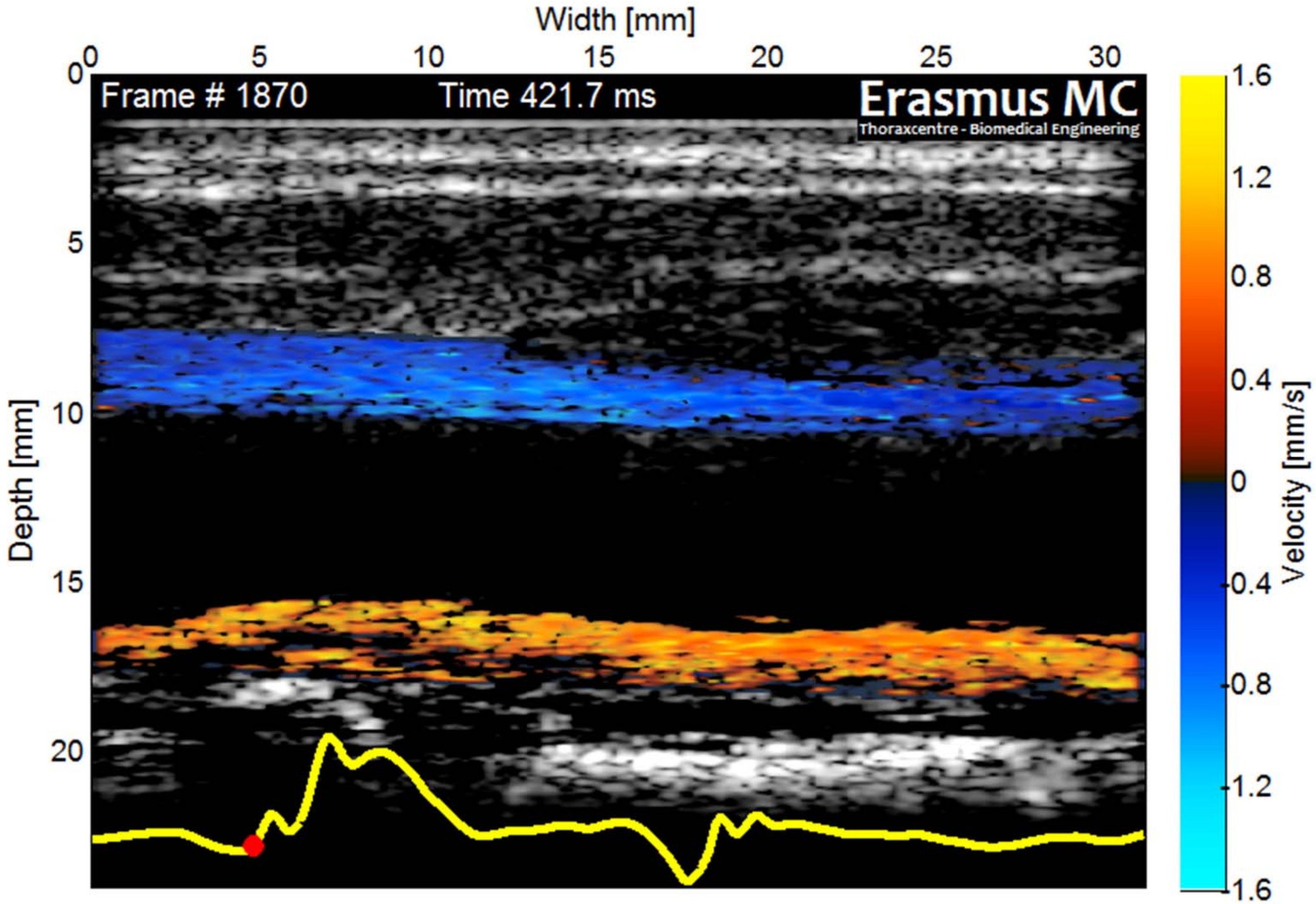


Tanter et al. IEEE UFFC 2014

High frame rate imaging – Pulse wave in carotid artery: 25 x slower



High frame rate imaging – Pulse wave in carotid artery: 1000 x slower



Synthetic aperture

- Used in RADAR and SONAR
- Single elements transmit an ultrasound pulse, one after another
- Echoes recorded by all elements

N images with low resolution/contrast

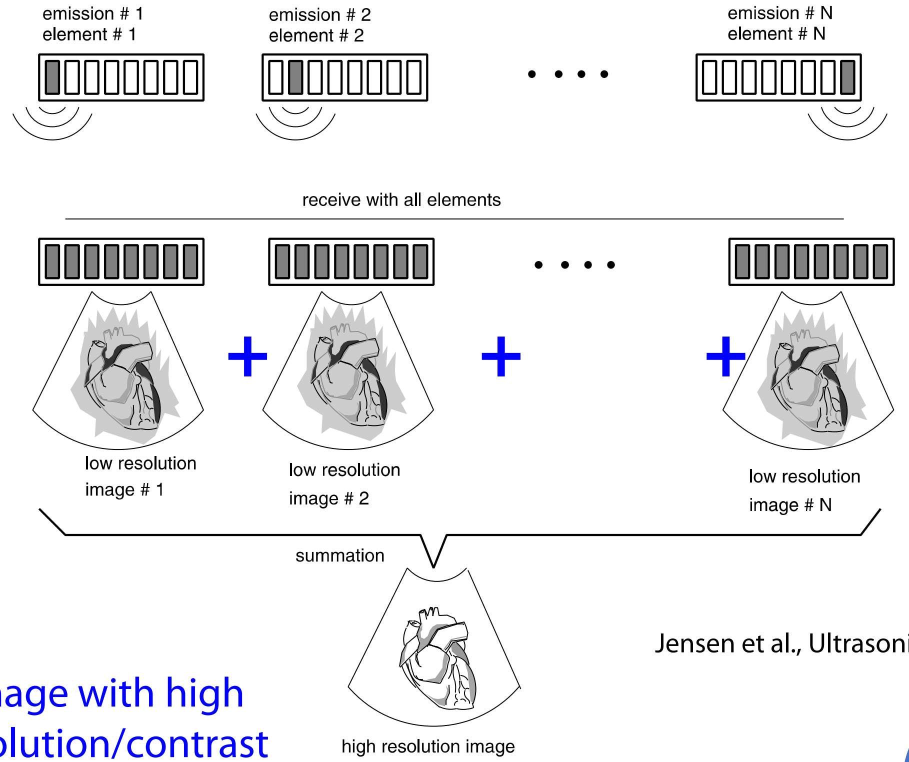


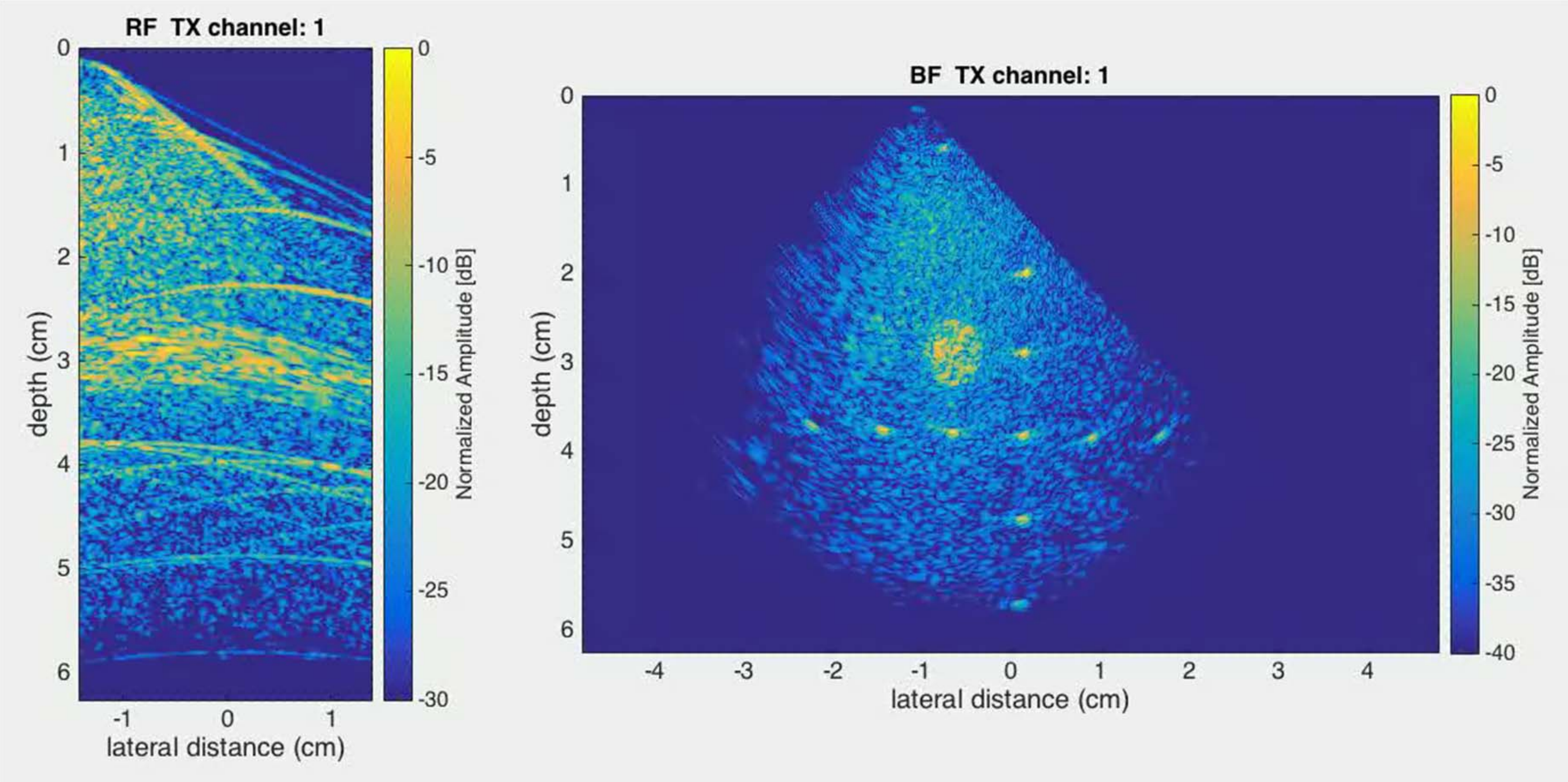
Image with high resolution/contrast

Jensen et al., Ultrasonics 2006

Synthetic aperture imaging

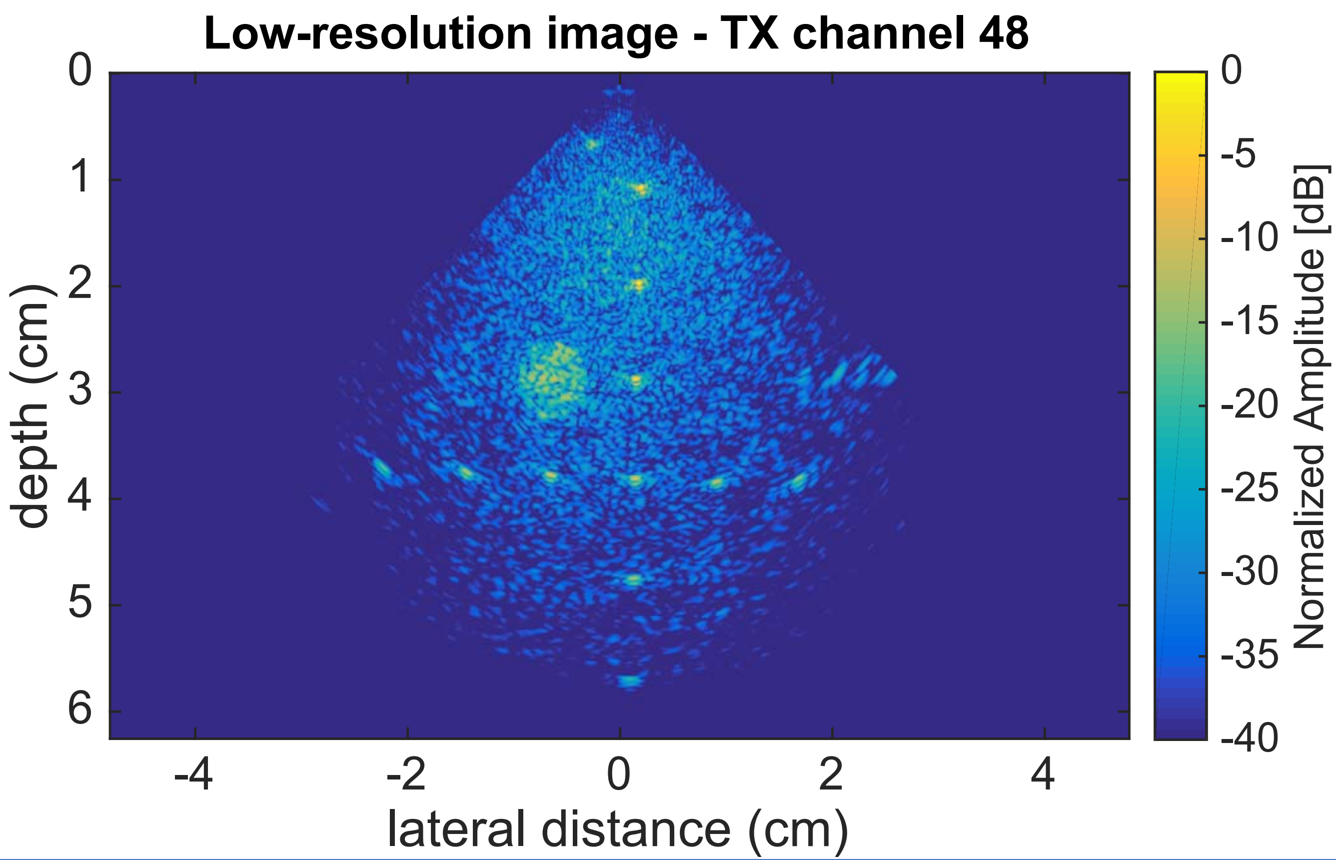
Example with a 96-element probe in a tissue phantom

Raw received signals **Low-resolution/contrast beamformed images**



Synthetic aperture imaging

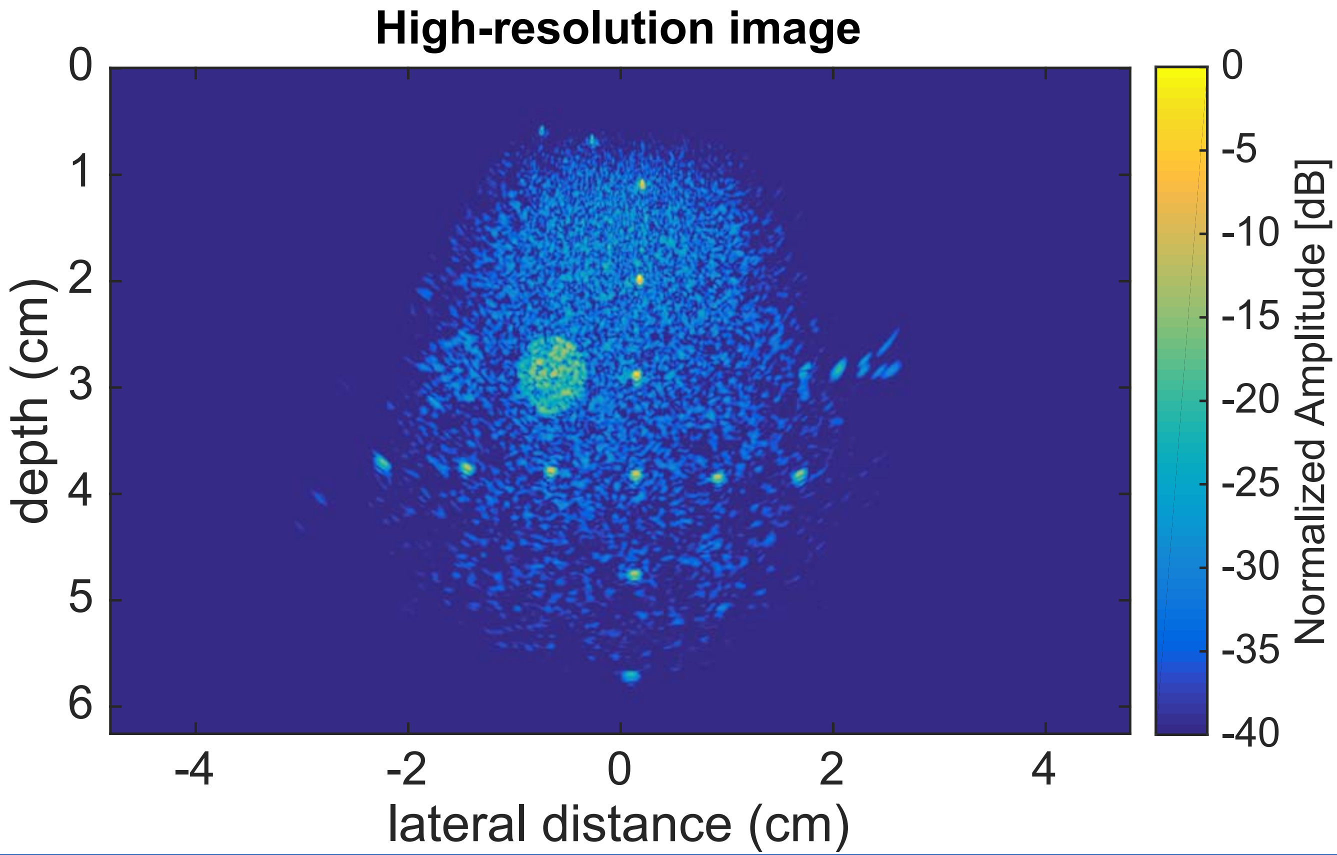
Example with a 96-element probe in a tissue phantom



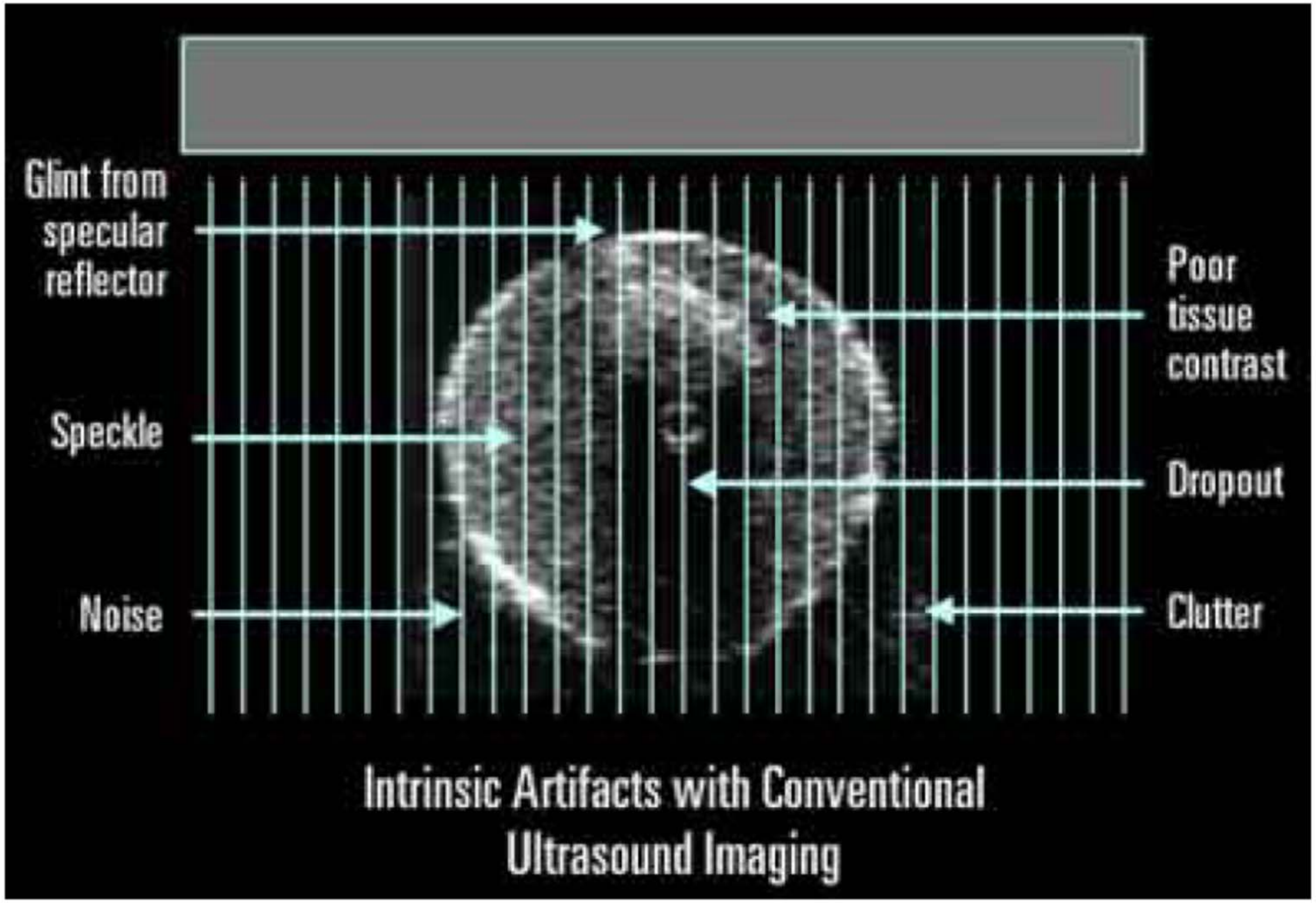
Synthetic aperture imaging

Example with a 96-element probe in a tissue phantom

- *Improved contrast and resolution*

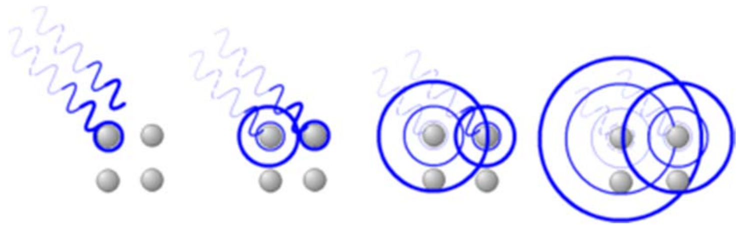


Artifacts


Glint from specular reflector
Speckle
Noise
Poor tissue contrast
Dropout
Clutter
Intrinsic Artifacts with Conventional Ultrasound Imaging

The grainy structure in ultrasound image

- Speckle
- produced by the constructive and destructive interference of echoes from scatterers



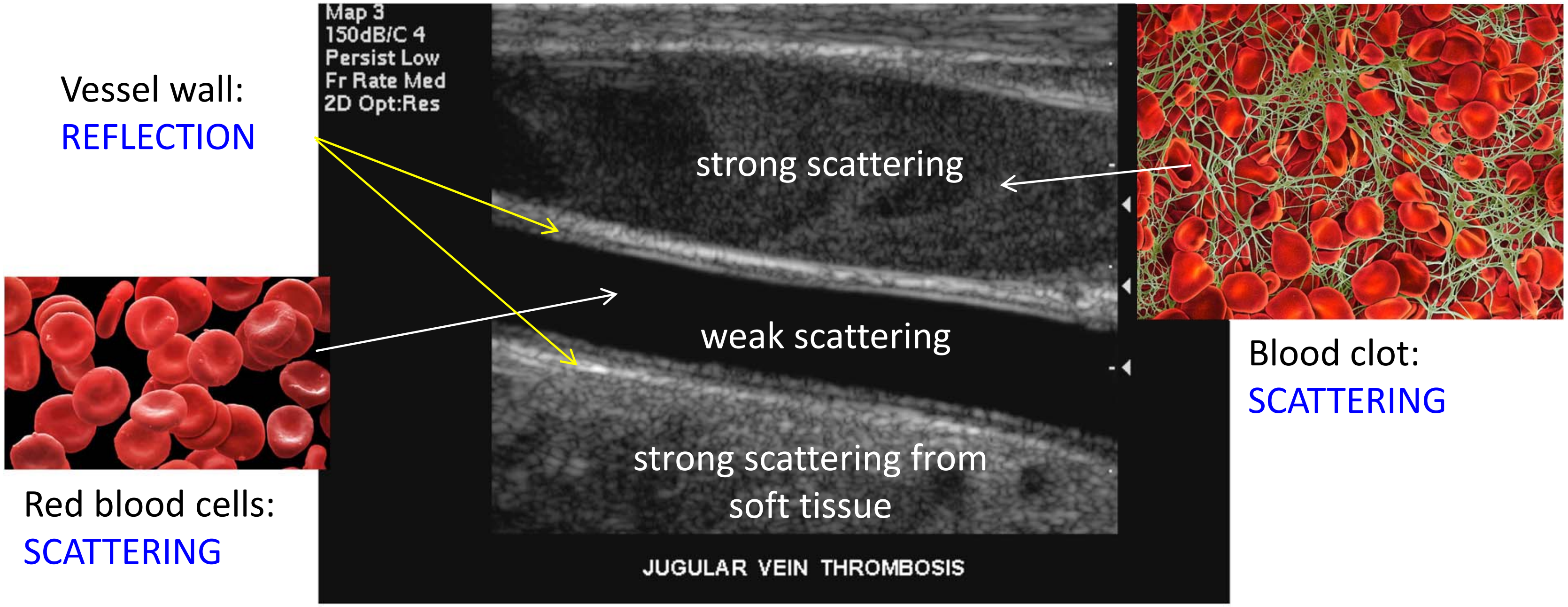
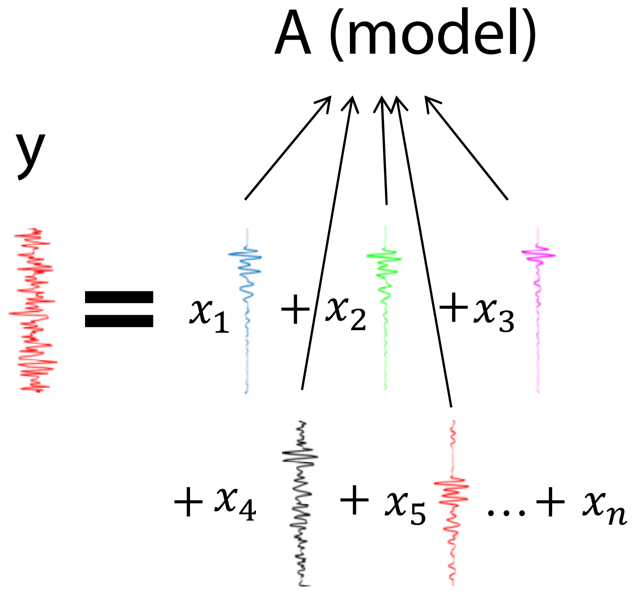


Image Reconstruction: Model Based Imaging

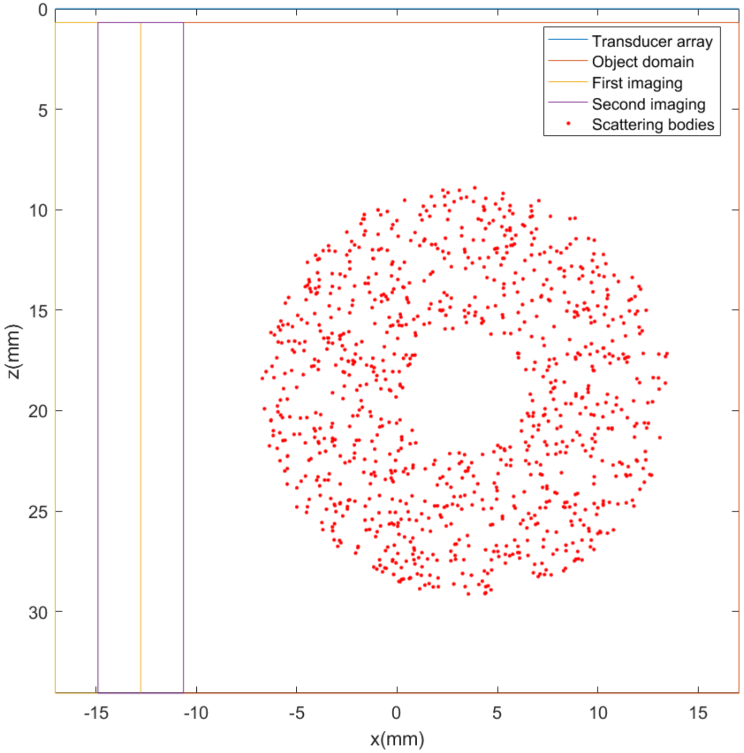
Model formulation

$$y = Ax$$

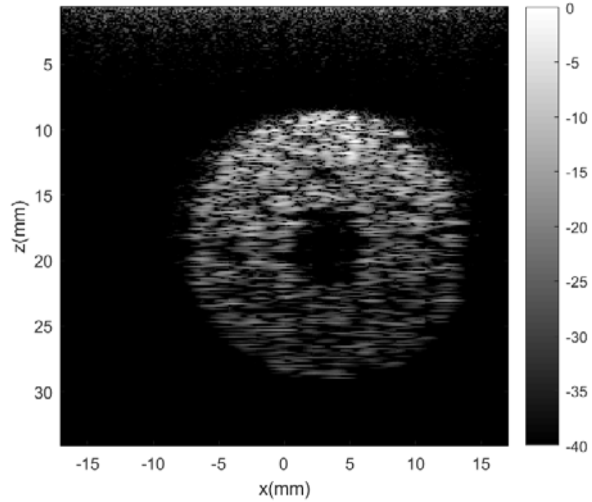


$$y = A \times [0\ 0\ 0\ 1\ 1\ 0\ 0\ 0\ 0]^T$$
$$= Ax$$

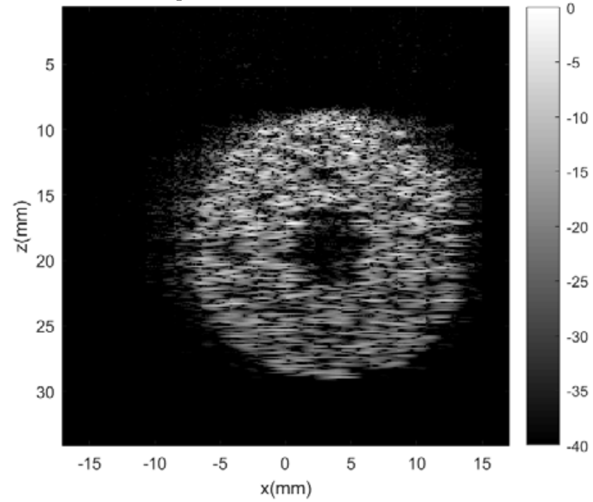
Simulation



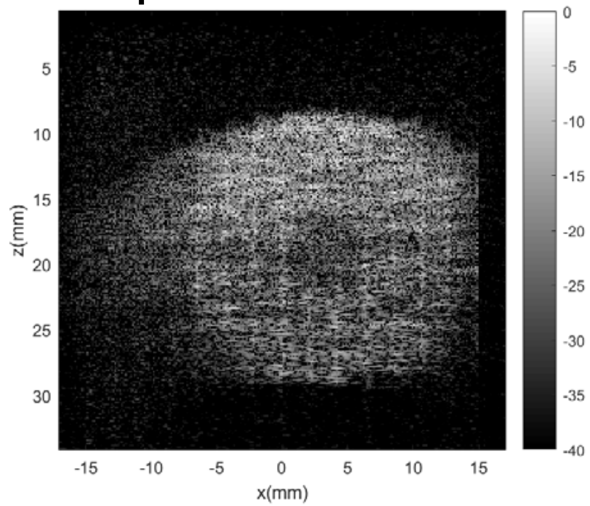
Matched Filter



Lsqr 30 iterations



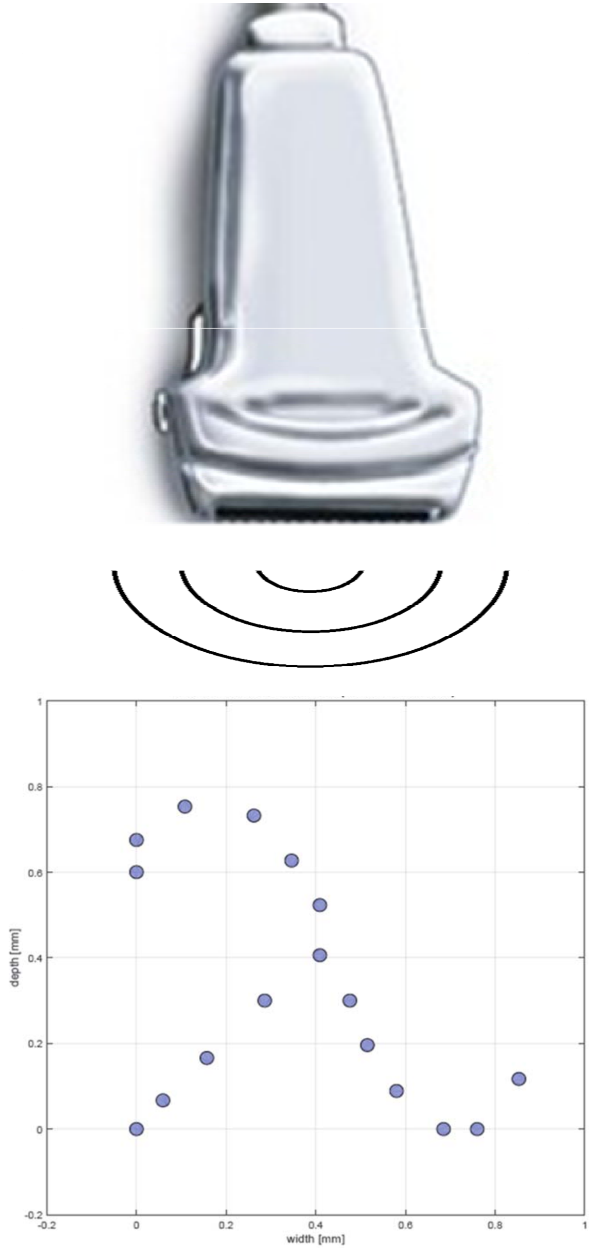
Lsqr 300 iterations



Erasmus MC

Imaging experiment

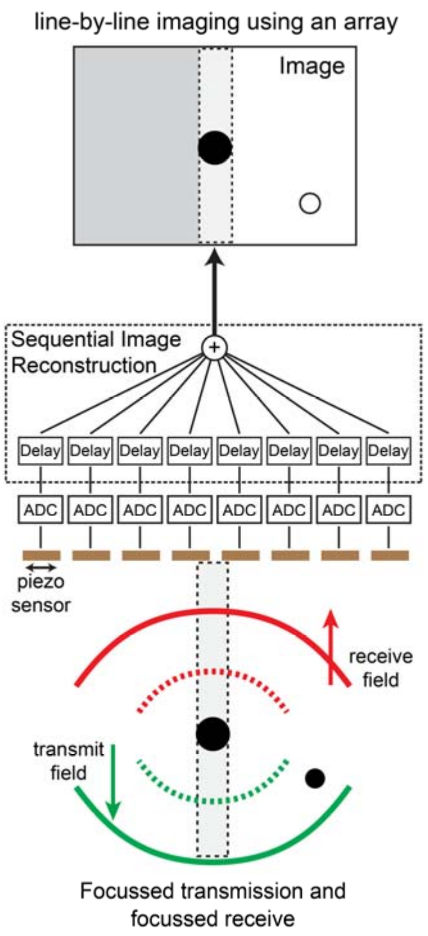
- Tikhonov Least Squares
- Tikhonov Non-negative Least squares
- Basis pursuit de-noising



Imaging experiment

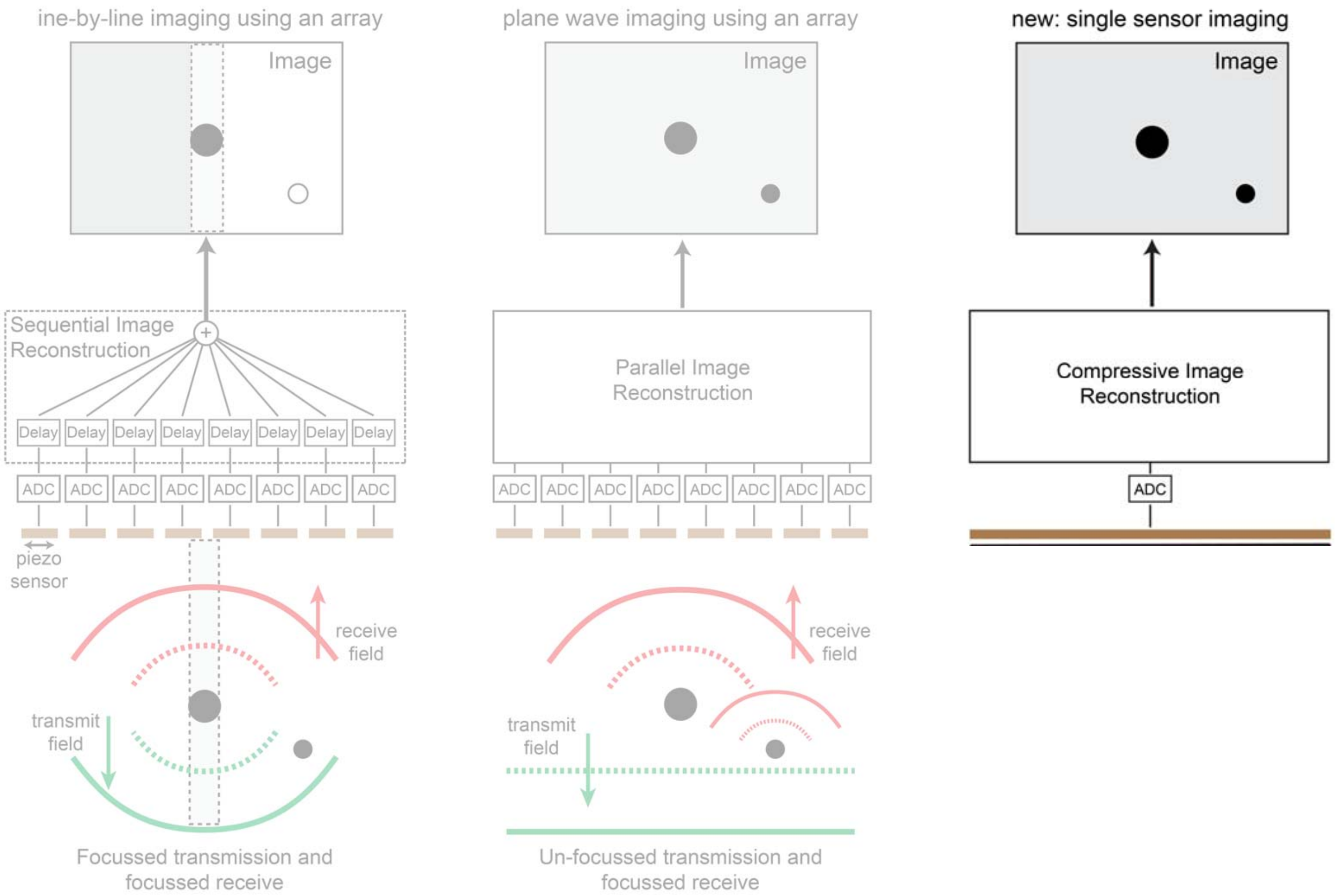
3D imaging using a single sensor

For imaging we need spatial information

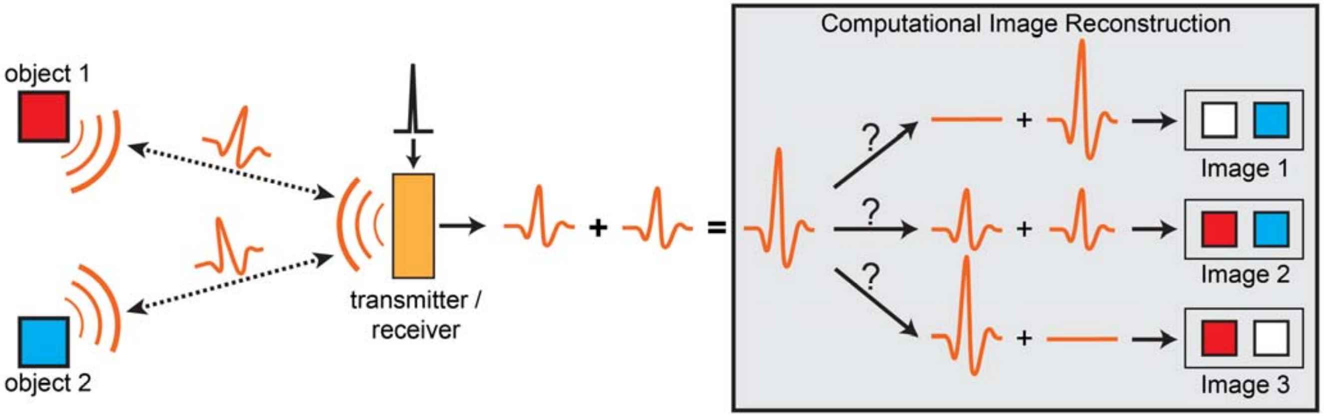


What if you only have one sensor ?

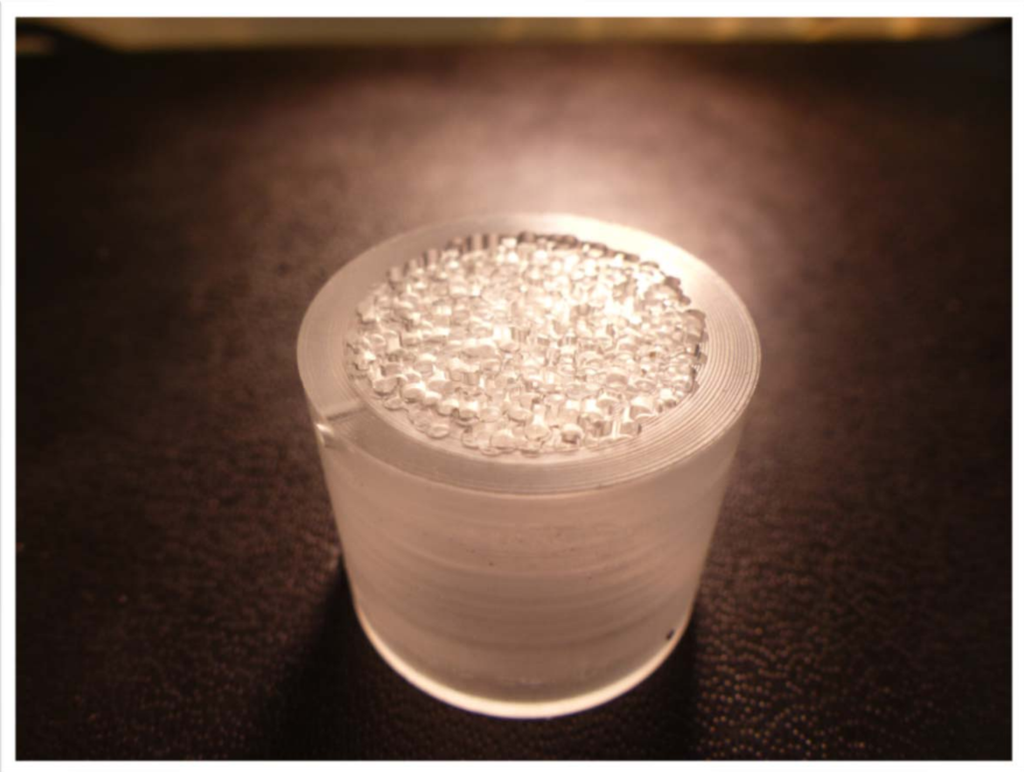
Can we encode spatial information?

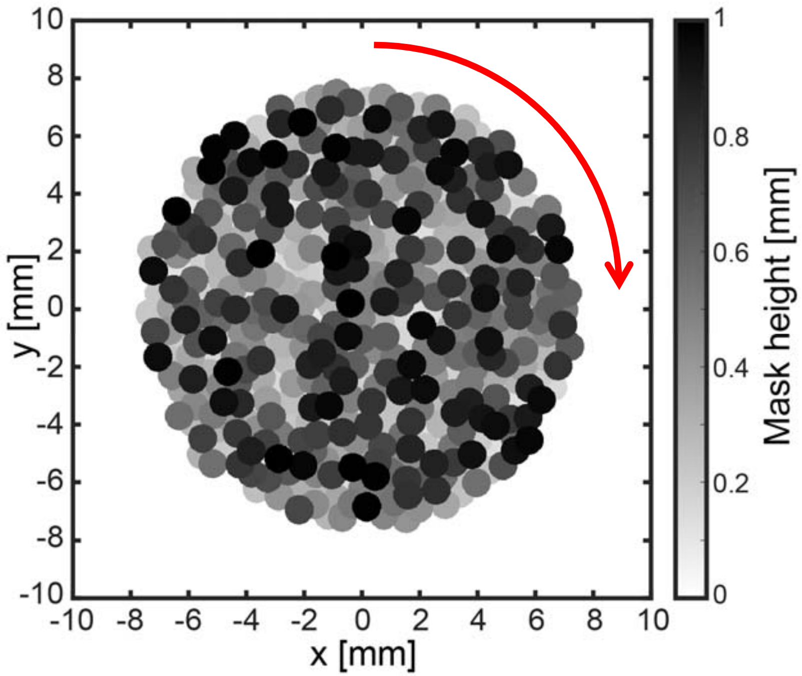


Compressive imaging: every pixel should have a unique signal

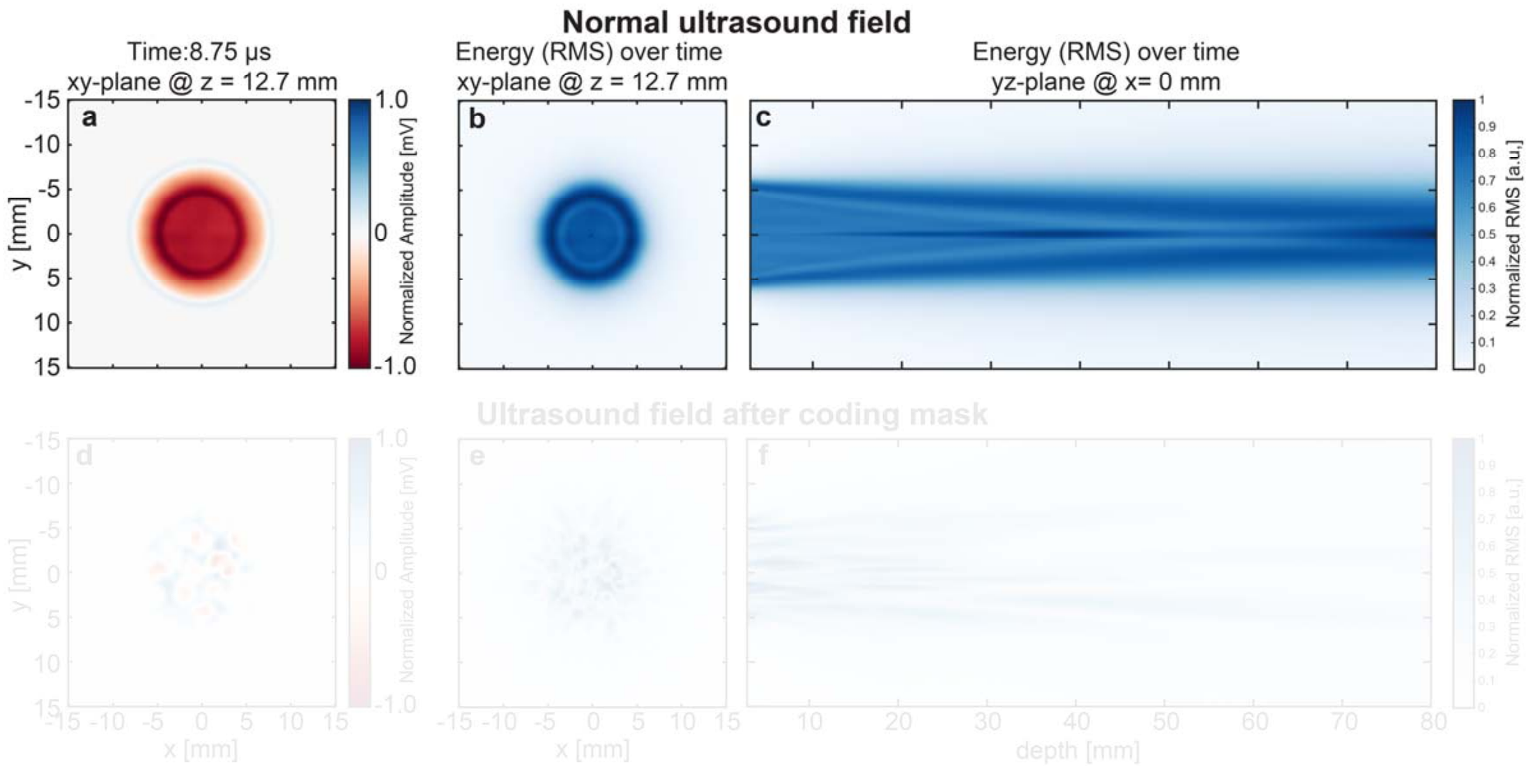


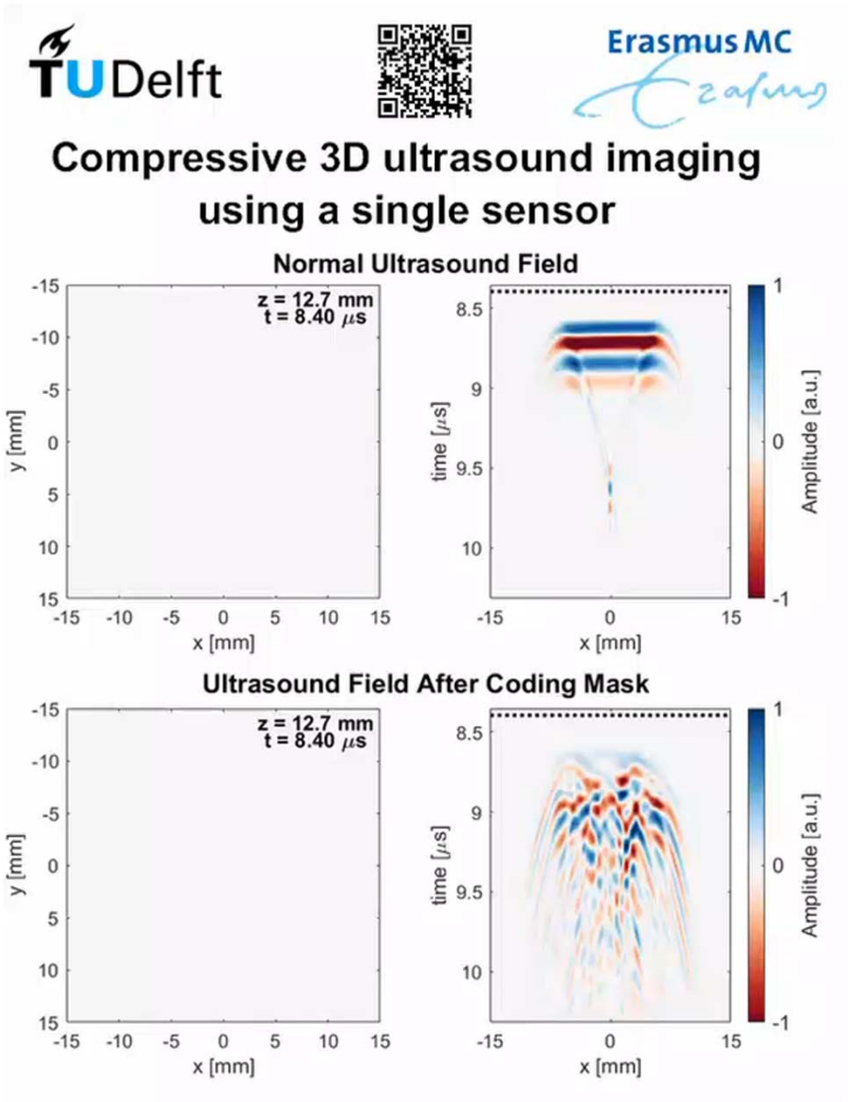
Compressive ultrasound imaging using a coded aperture mask



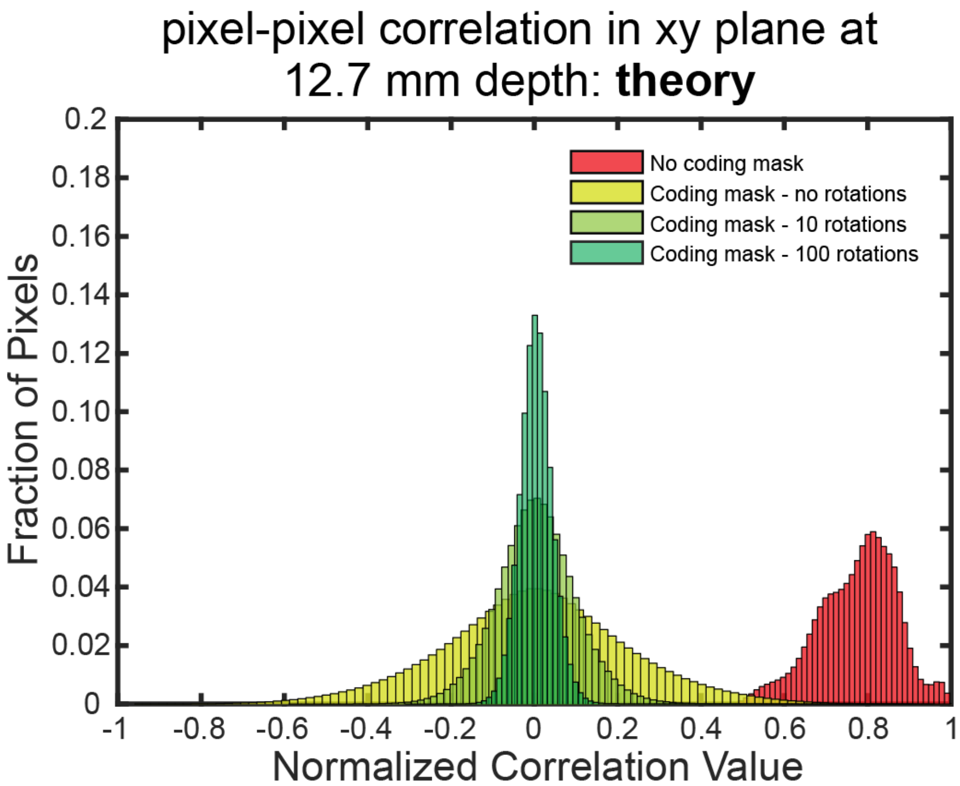


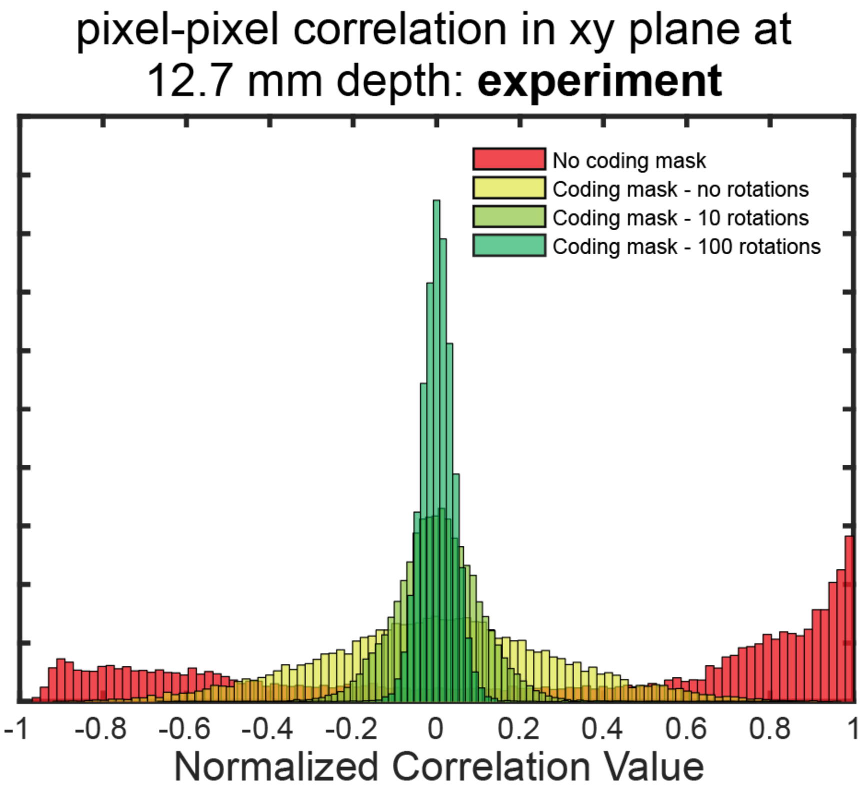
Coded aperture mask breaks the phase uniformity of the ultrasound field




TU Delft
Erasmus MC
Compressive 3D ultrasound imaging
using a single sensor
Normal Ultrasound Field
z = 12.7 mm
t = 8.40 μs
y [mm]
x [mm]
time [μs]
Amplitude [a.u.]
Ultrasound Field After Coding Mask
z = 12.7 mm
t = 8.40 μs
y [mm]
x [mm]
time [μs]
Amplitude [a.u.]

Pixels become more unique by applying a coded aperture mask!





Imaging Algorithm

Calibration (only once)

- - Map spatial impulse response with a hydrophone in xy-plane
- perpendicular to propagation axis

Build model (image dependent)

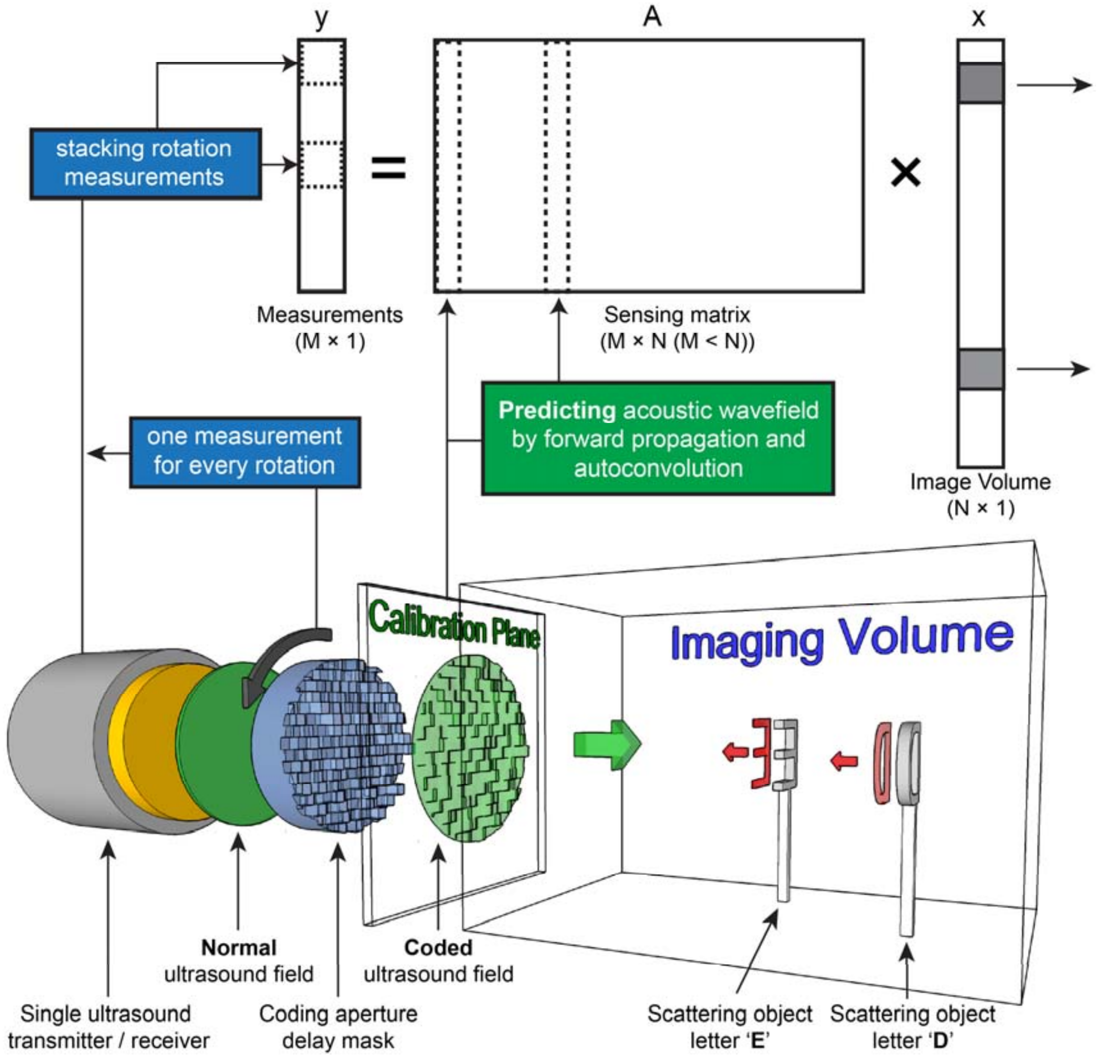
- - Use Angular Spectrum Approach to predict other z-planes
- - Per-pixel auto-convolution to account for pulse-echo
- - Store all estimated pixel signals in one big **A** (model) matrix

Get the data

- - Acquire pulse-echo measurements with different mask rotations

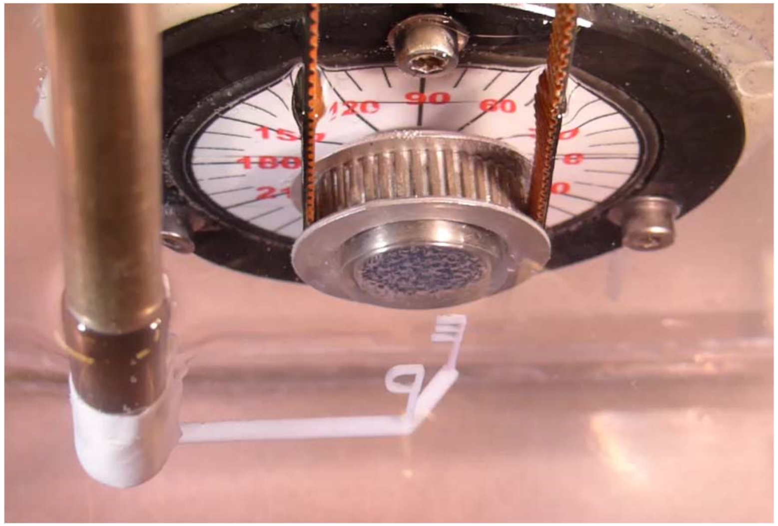
Make the image

- - Solve $\mathbf{y} = \mathbf{Ax}$ using iterative least-squares, Basis Pursuit etc.. and find image $\mathbf{x}$



y
A
x
stacking rotation measurements
=
×
Measurements
(M × 1)
Sensing matrix
(M × N (M < N))
Predicting acoustic wavefield by forward propagation and autoconvolution
one measurement for every rotation
Image Volume
(N × 1)
Calibration Plane
Imaging Volume
Normal
ultrasound field
Coded
ultrasound field
Single ultrasound
transmitter / receiver
Coding aperture
delay mask
Scattering object
letter 'E'
Scattering object
letter 'D'

The letter experiment



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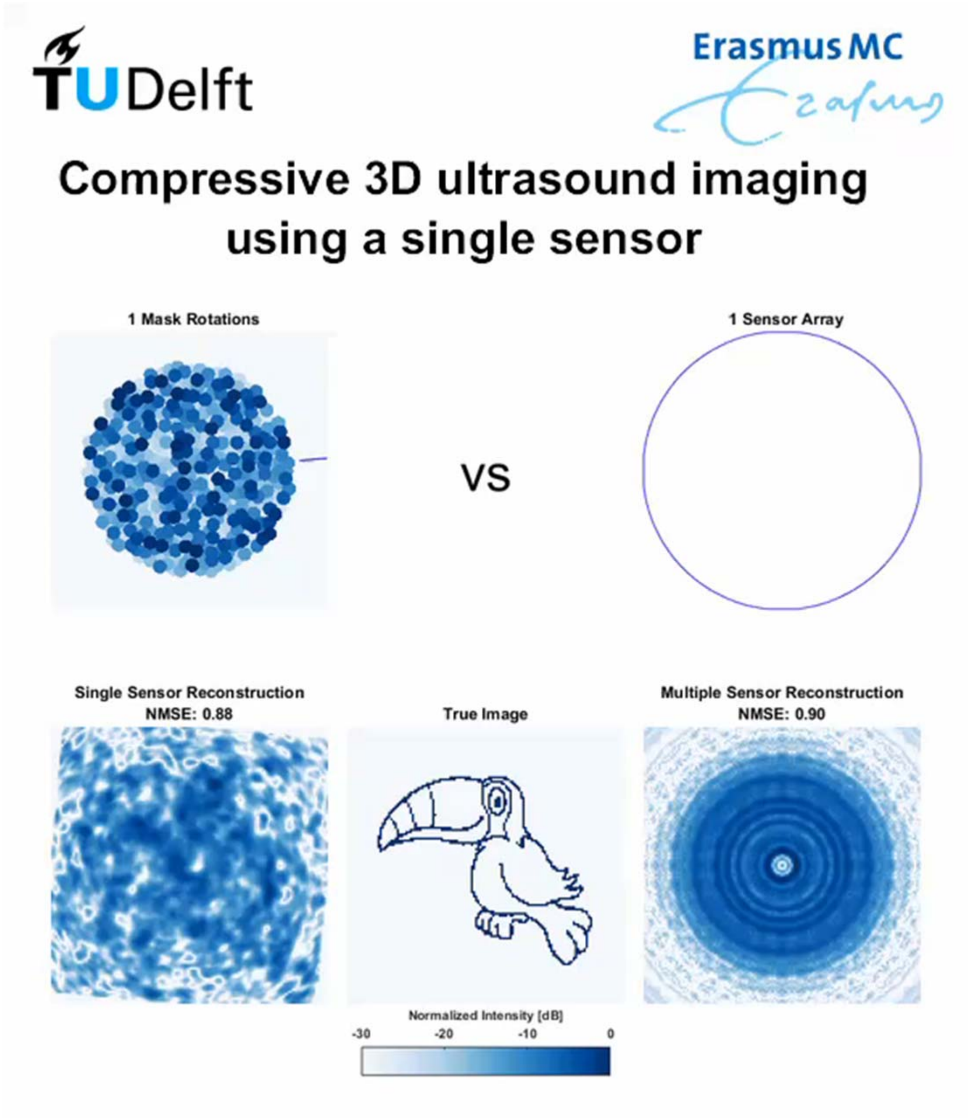
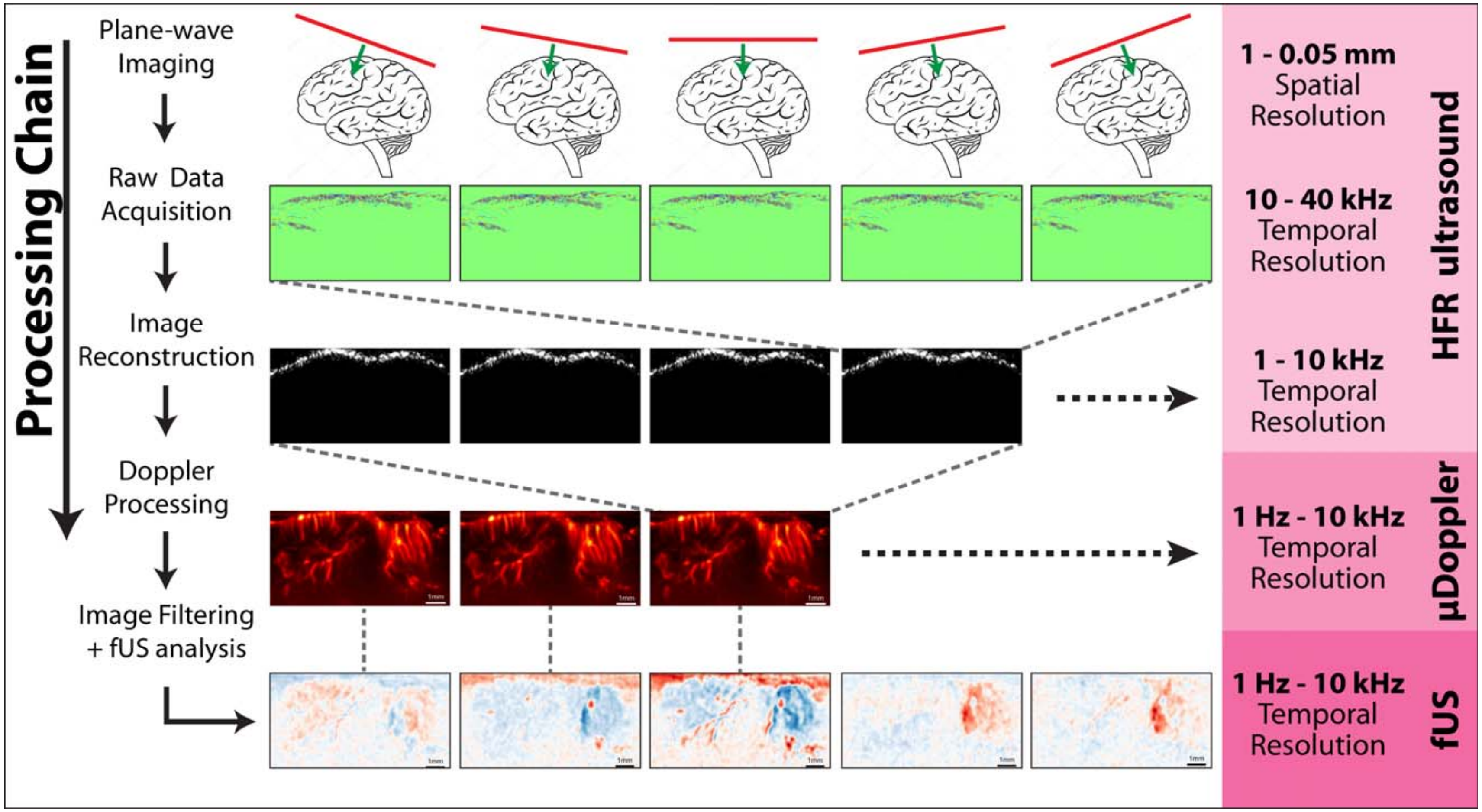

TU Delft
Erasmus MC
Compressive 3D ultrasound imaging using a single sensor
1 Mask Rotations
VS
1 Sensor Array
Single Sensor Reconstruction
NMSE: 0.88
True Image
Multiple Sensor Reconstruction
NMSE: 0.90
Normalized Intensity [dB]
-30
-20
-10
0

Functional ultrasound (fUS):
Doppler imaging of the brain

functional Ultrasound (fUS)

Erasmus MC



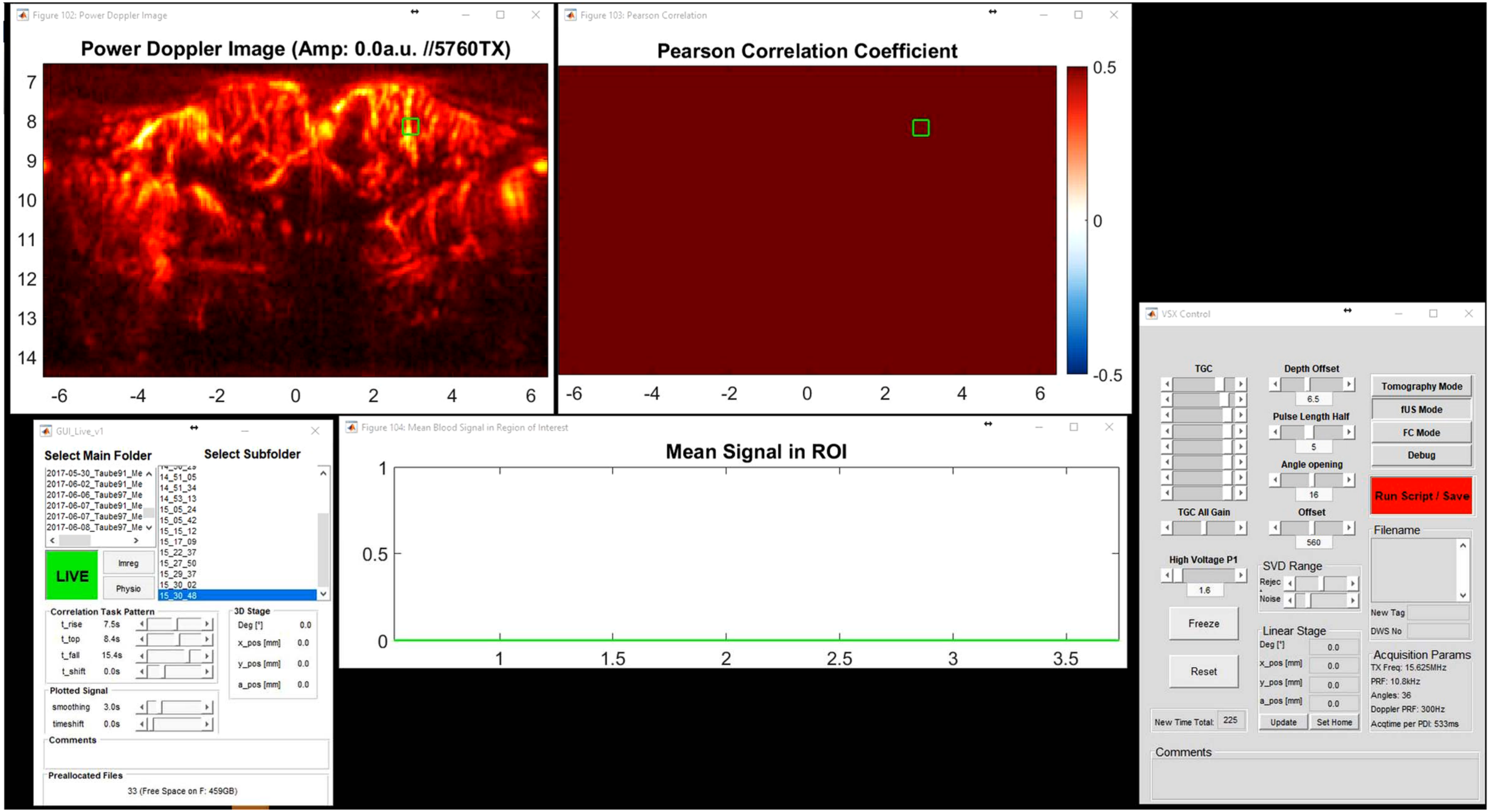
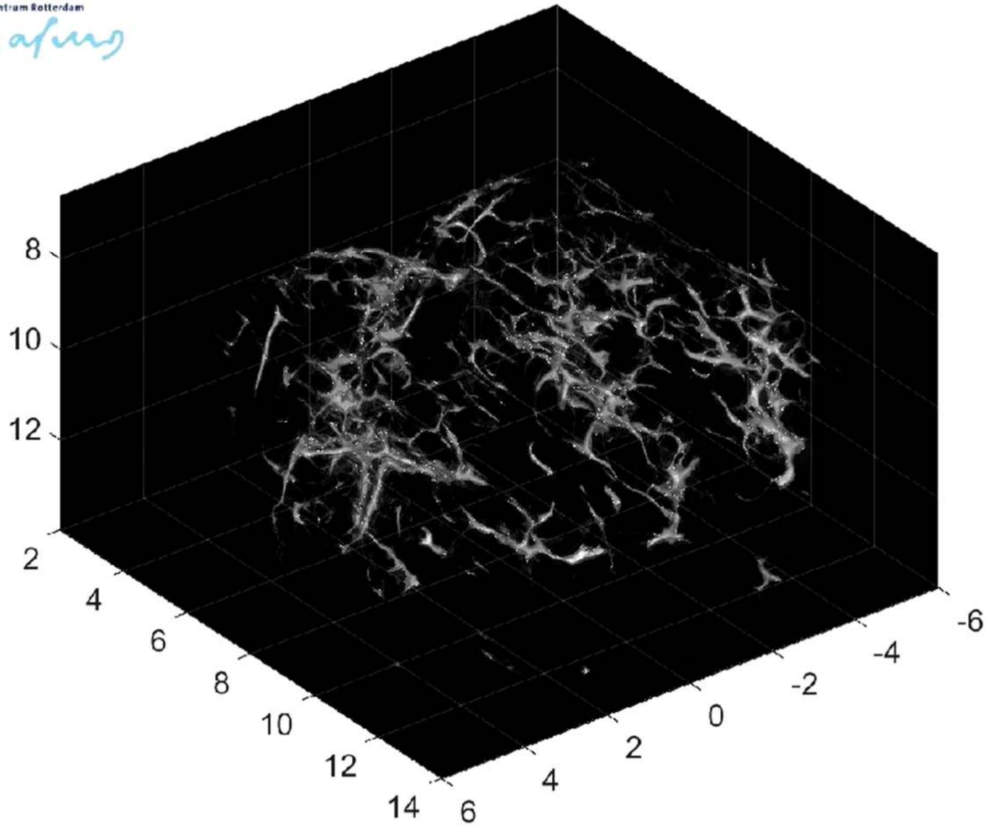
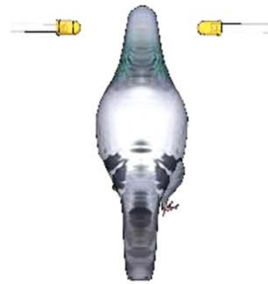


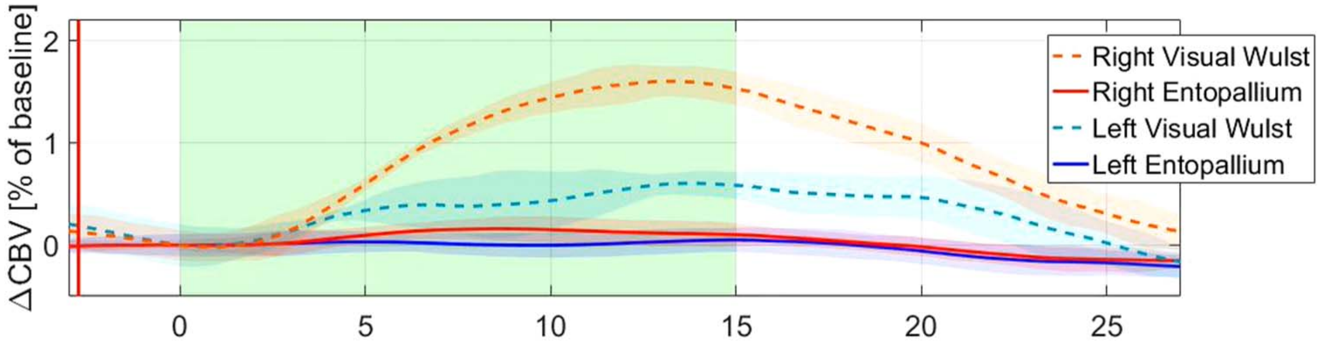
Figure 102: Power Doppler Image
Power Doppler Image (Amp: 0.0a.u. //5760TX)
Figure 103: Pearson Correlation
Pearson Correlation Coefficient
VSX Control
TGC
Depth Offset
Pulse Length Half
Angle opening
TGC All Gain
Offset
High Voltage P1
SVD Range
Freeze
Reset
Linear Stage
Tomography Mode
fUS Mode
FC Mode
Debug
Run Script / Save
Filename
New Tag
DWS No
Acquisition Params
TX Freq: 15.625MHz
PRF: 10.8kHz
Angles: 36
Doppler PRF: 300Hz
Acqtime per PDI: 533ms
New Time Total: 225
Update
Set Home
Comments
GUI_Live_v1
Select Main Folder
Select Subfolder
LIVE
Imreg
Physio
Correlation Task Pattern
3D Stage
Plotted Signal
Comments
Preallocated Files
33 (Free Space on F: 459GB)
Figure 104: Mean Blood Signal in Region of Interest
Mean Signal in ROI

Functional Ultrasound Imaging of the Pigeon Brain
LS Maret
Department of Physics



Setup





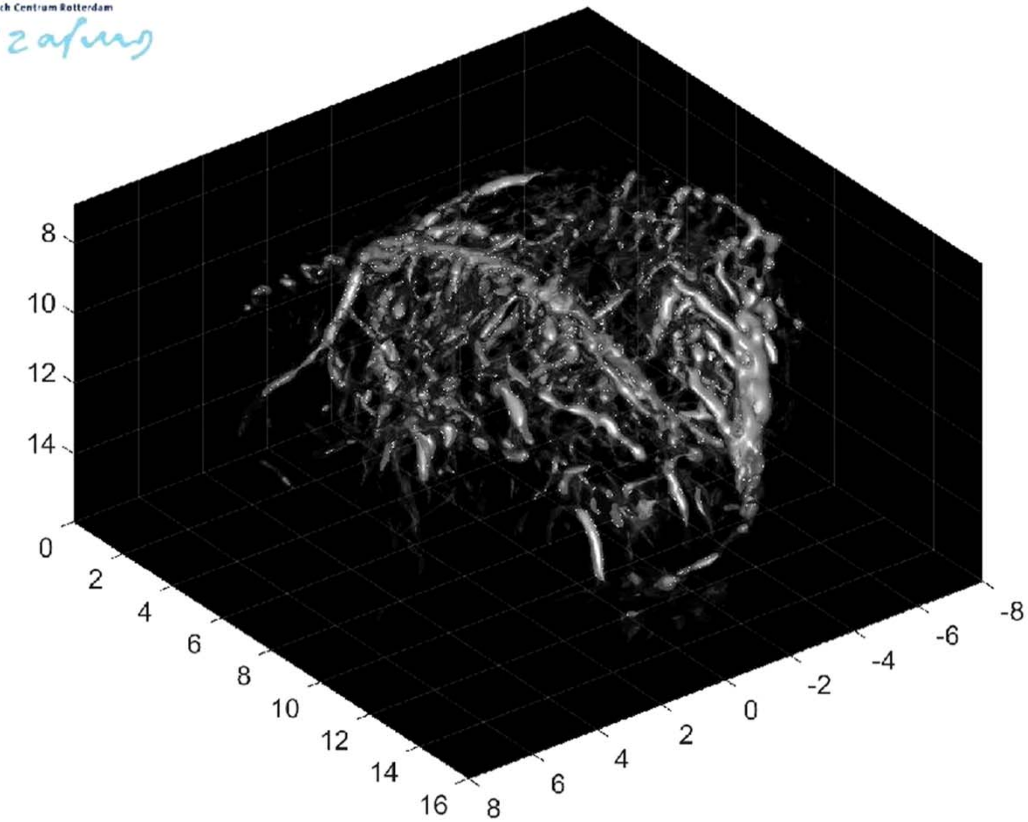
Time: -2.7s
Stimulation: off

Stimulus:	Visual (static)
Activity threshold:	> 2%
Spatial units:	mm

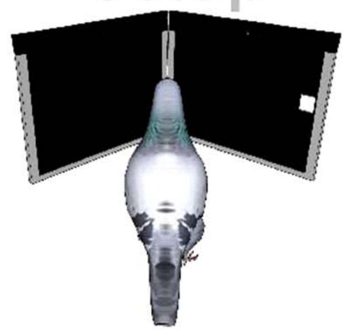
Erasmus MC

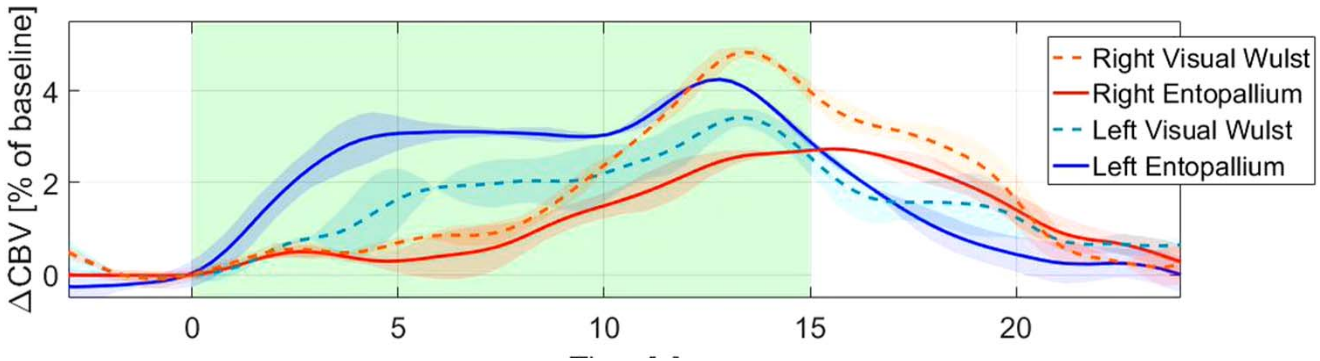
Functional Ultrasound Imaging
of the Pigeon Brain
LS Maret
Department of Physics

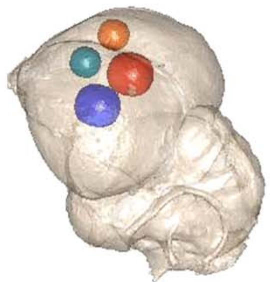
Universität Konstanz



Setup







Time: -3.1s
Stimulation: off

Stimulus:	Visual (dynamic)
Activity threshold:	> 3%
Spatial units:	mm

Advanced signal processing in fUS

Example Master student Bas Generowicz:

subspace tracking for spatiotemporal clutter filtering

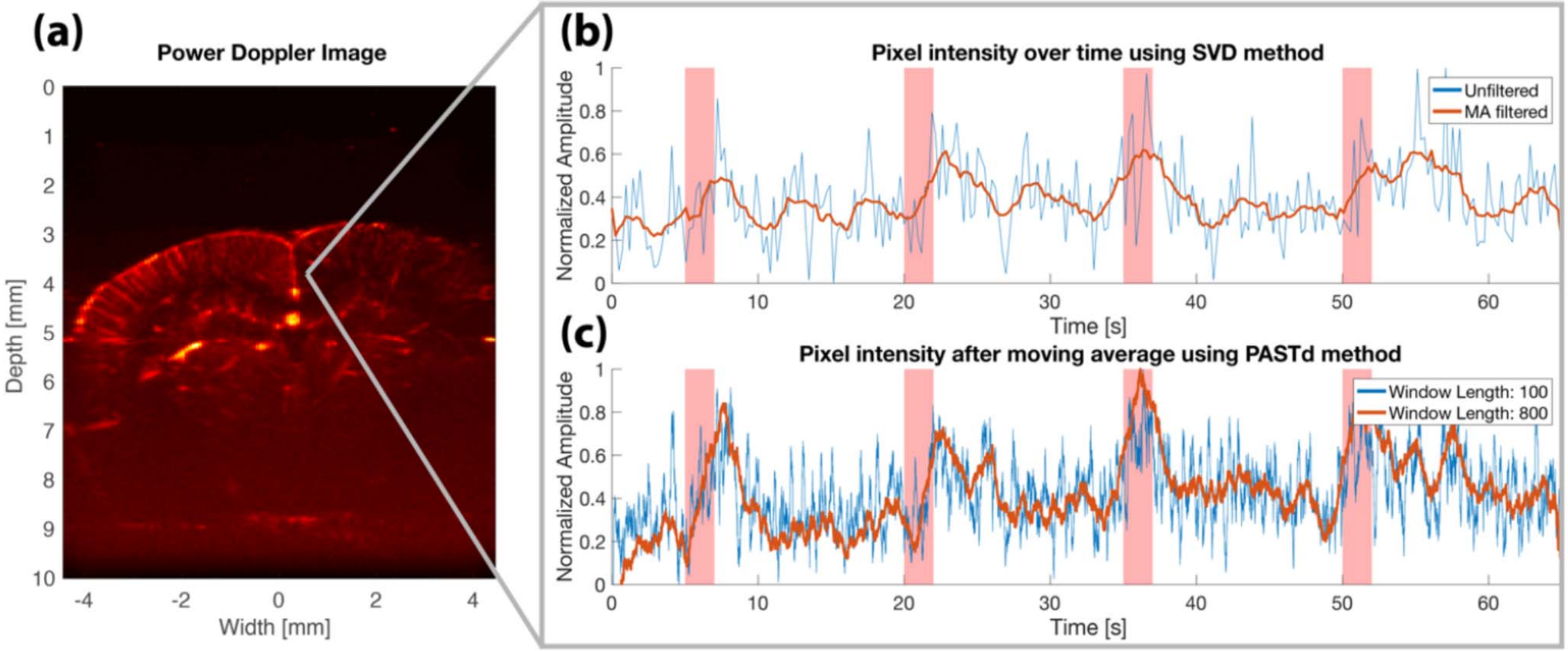


Figure 1: Efficient and flexible spatiotemporal clutter filtering of high frame rate images using subspace tracking

Acknowledgements

- **Guillaume Renaud** (General Slides)
- **Jan Somer** (Movies Phased array Scanner)
- **Klaas Bom** (Movies Linear array Scanner)
- **Pim van der Meulen** (Model Based Imaging)
- **Zheheng Liu** (Model Based Imaging)
- **Richard Rau** (Functional Ultrasound)

Many master projects available…..

- Data analytics for fUS
- Model based imaging
- Compressive Ultrasound Imaging
- Structured Ultrasound Microscopy
- Advanced Signal Processing for fUS
- ……….