WIC Midwinter Meeting 2019

SPATIAL CODING FOR HIGH RESOLUTION COMPRESSIVE ULTRASOUND IMAGING

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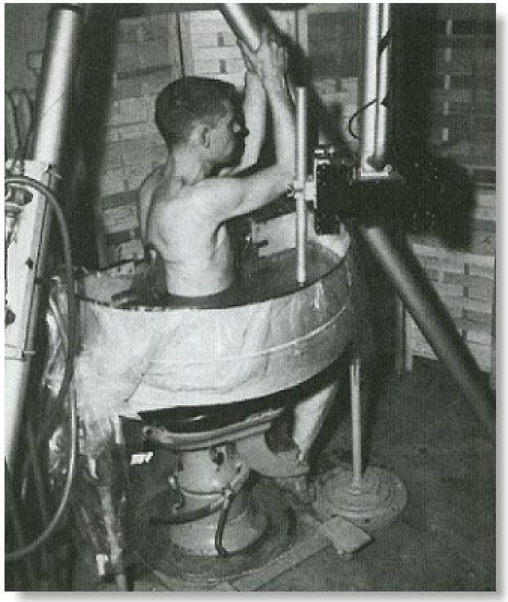
This talk:

- ❑ Ultrasound history & basic concepts
- ❑ The problem where CS may be of help
- ❑ The single sensor imager
- ❑ Aperture coding mask
- ❑ High resolution ultrasound imaging
- ❑ Some applications
- ❑ CS: hype or hope?

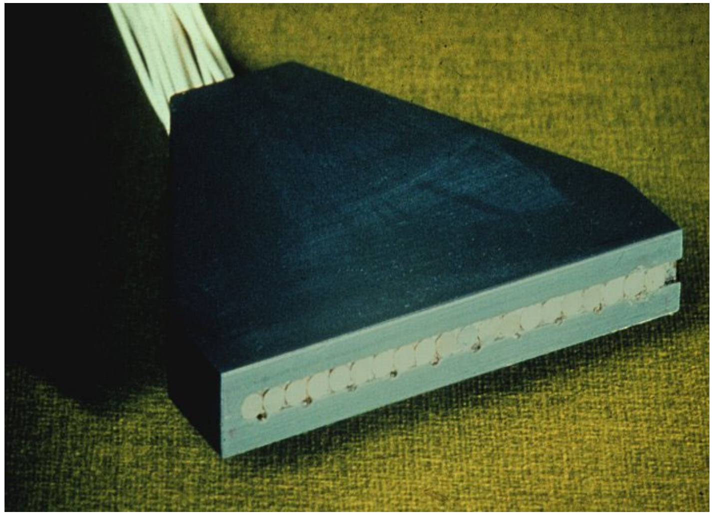
Medical ultrasound past to present



1959: Pan-scanner

Now

The revolution in 1970's: real-time imaging

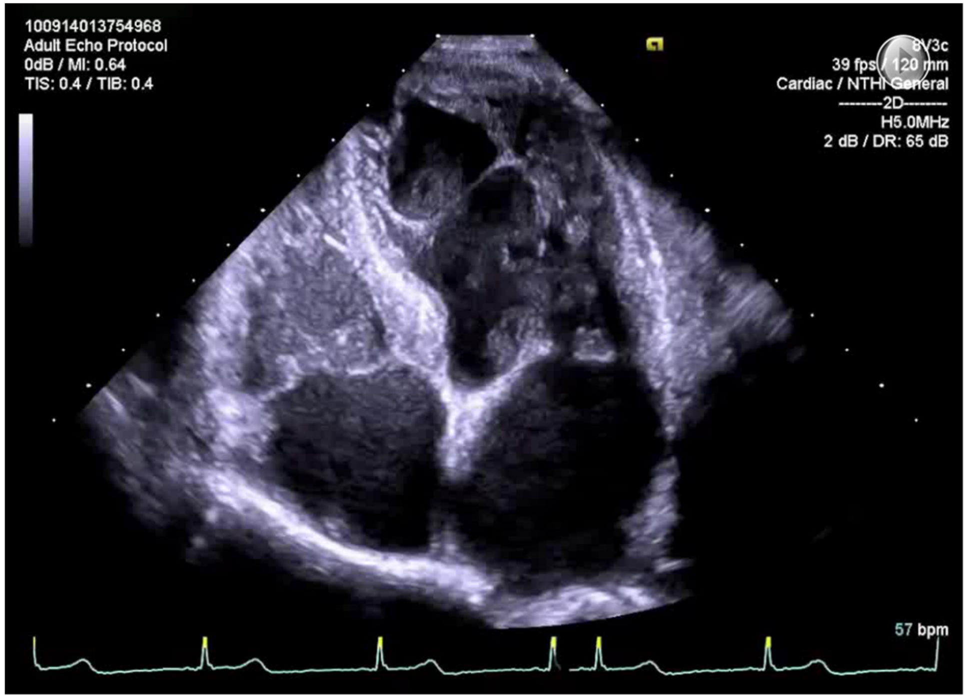


Erasmus MC Rotterdam: first linear array (1970)

First ultrasound images of the moving heart !

1980s-2010s:

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



Current state-of-the-art

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2010 -> Present

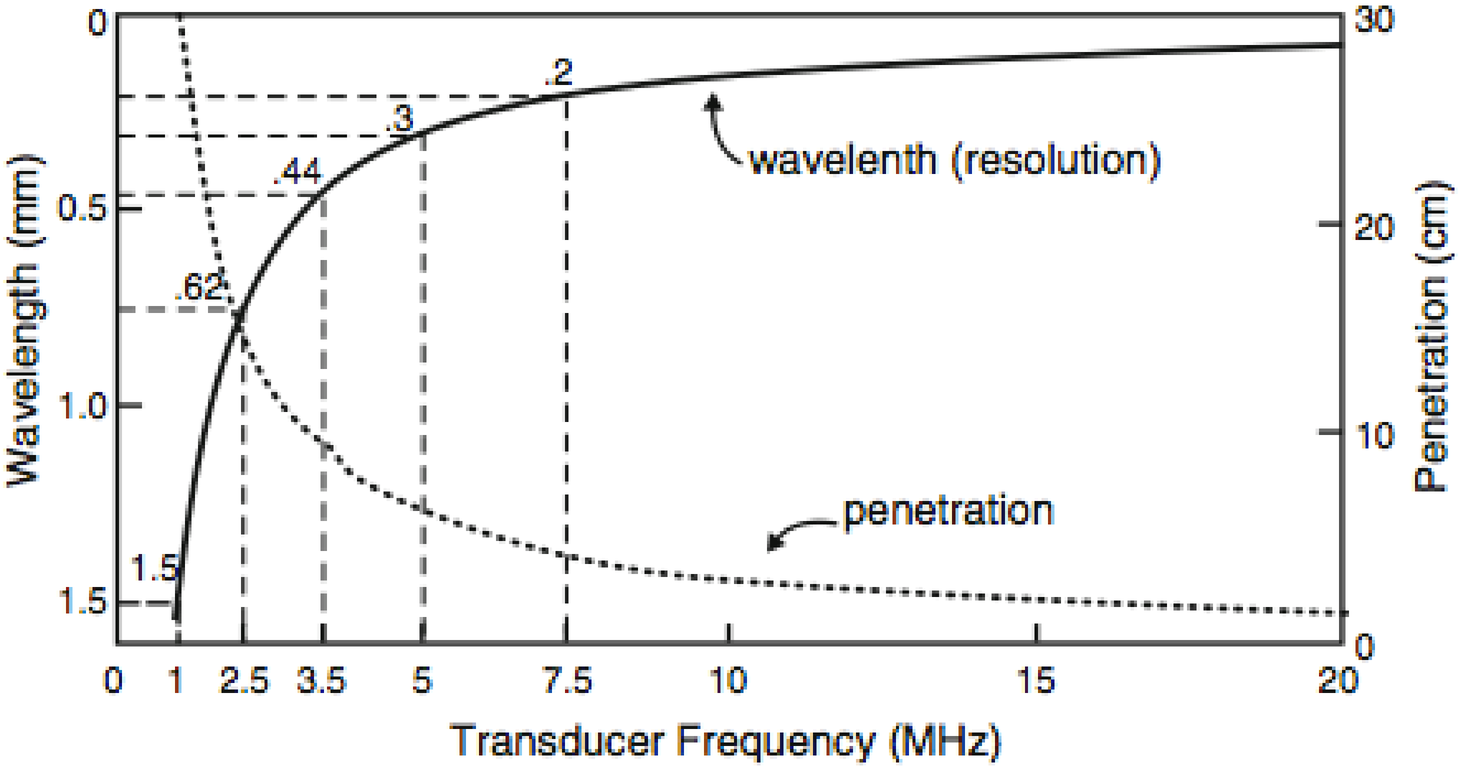
Verasonics Research System

Sound speed in tissue

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

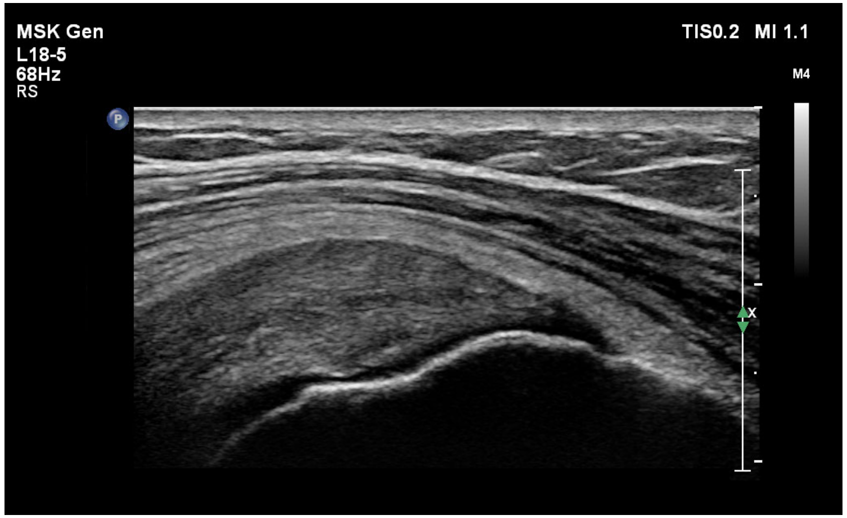
Diagnostic Ultrasound Imaging: Inside Out Thomas L. Szabo

The trade off between resolution and penetration depth

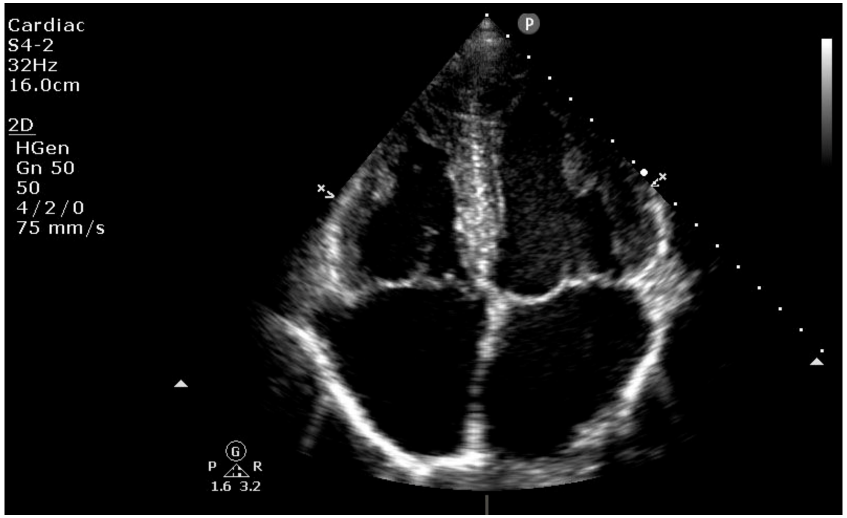


The trade off between resolution and penetration depth

Superficial muscles
Depth = 1.5 cm
Frequency = 12 MHz



Heart
Depth = 16 cm
Frequency = 3 MHz



Array of piezoelectric elements – medical probes

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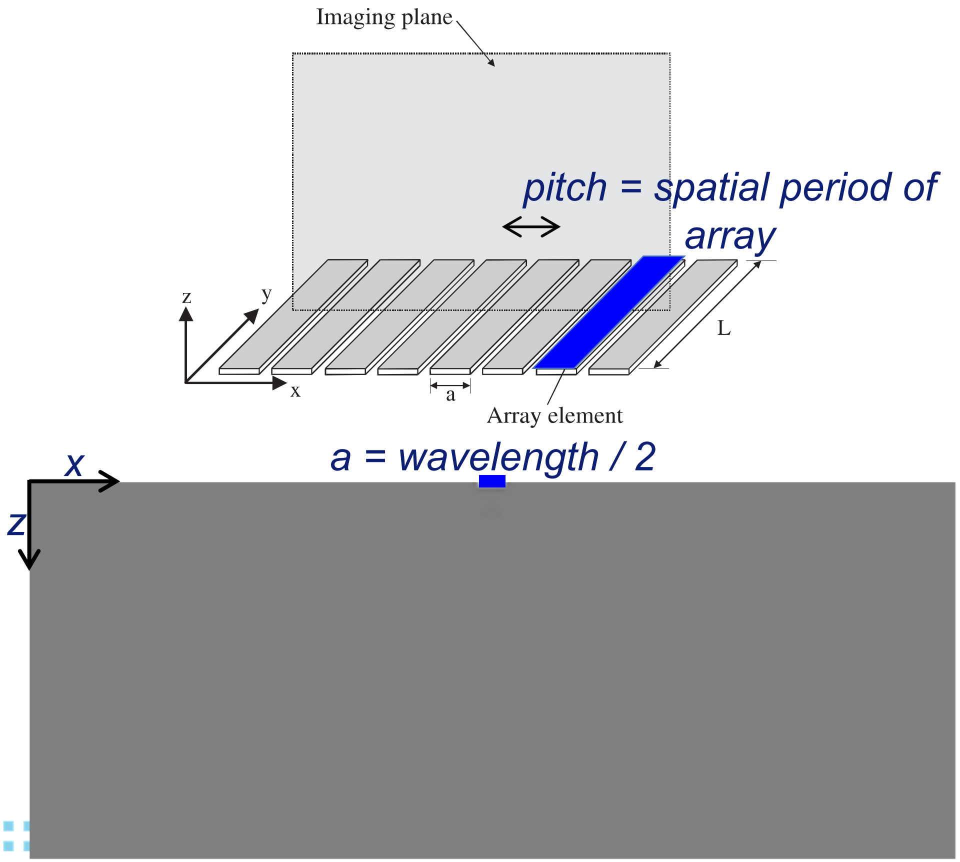
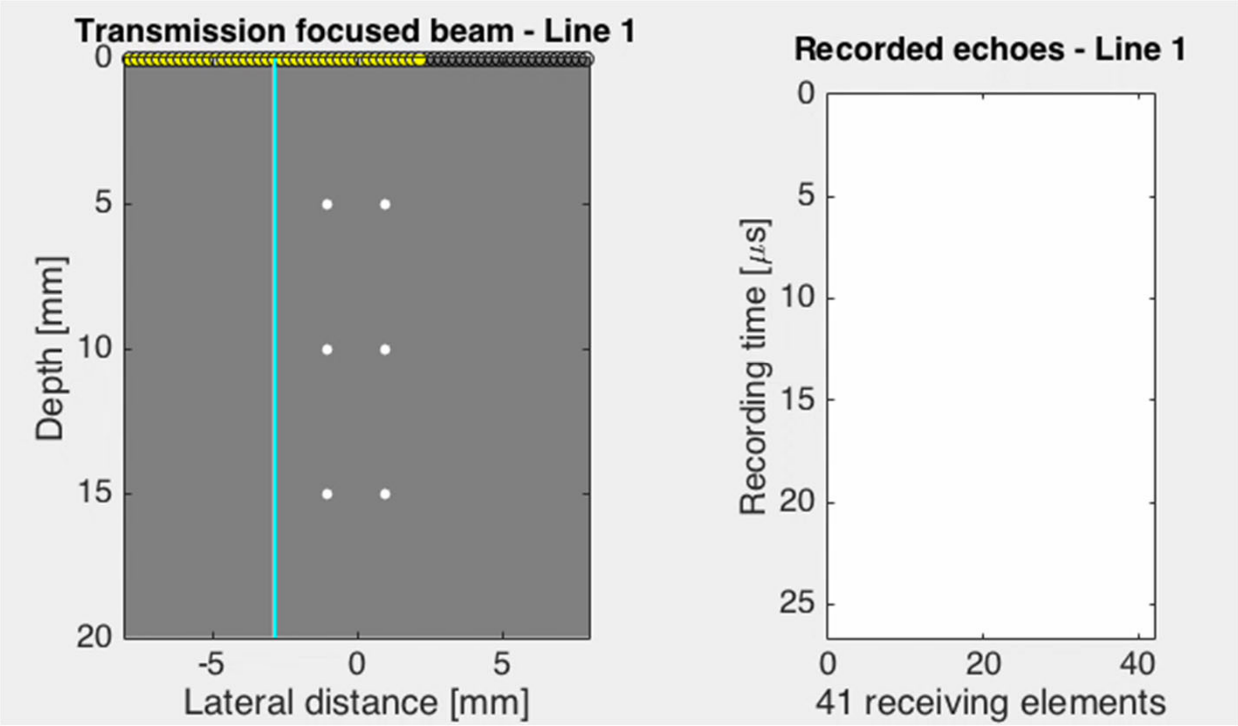
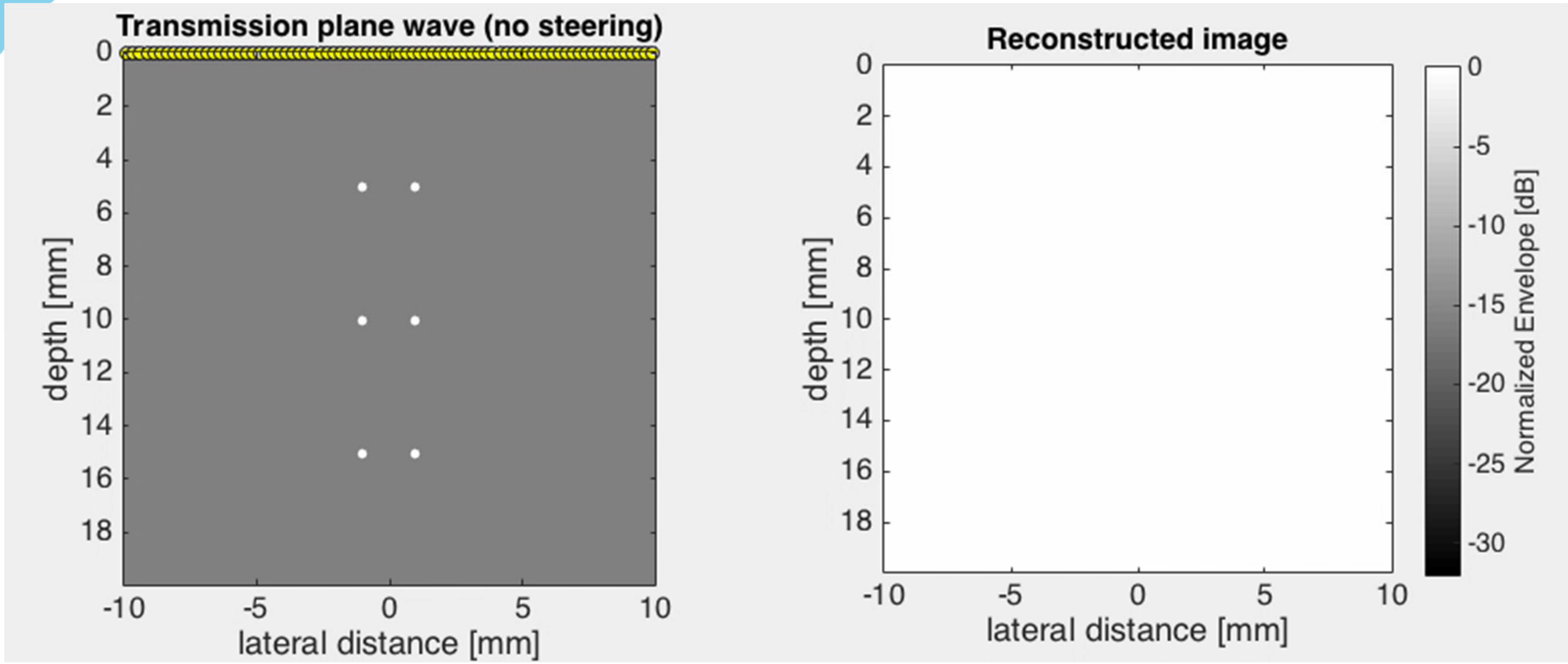
Array of small elements



Line-by-line scanning

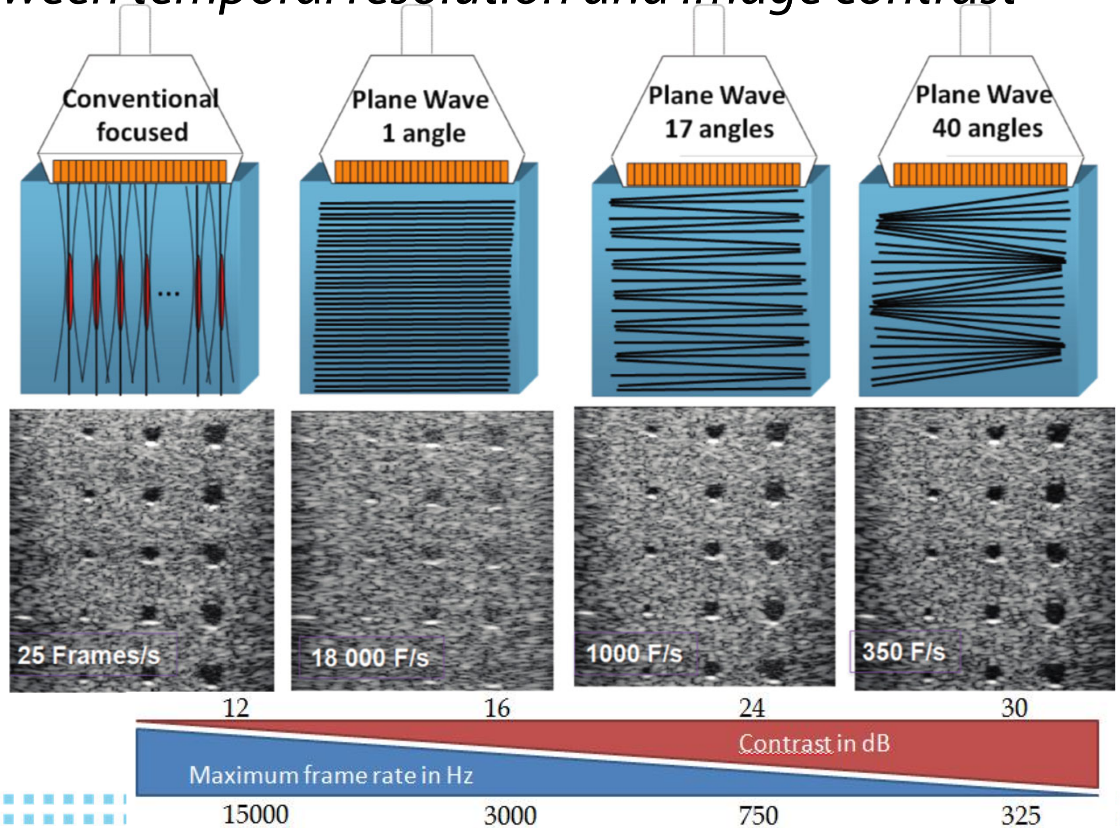


Plane-wave imaging



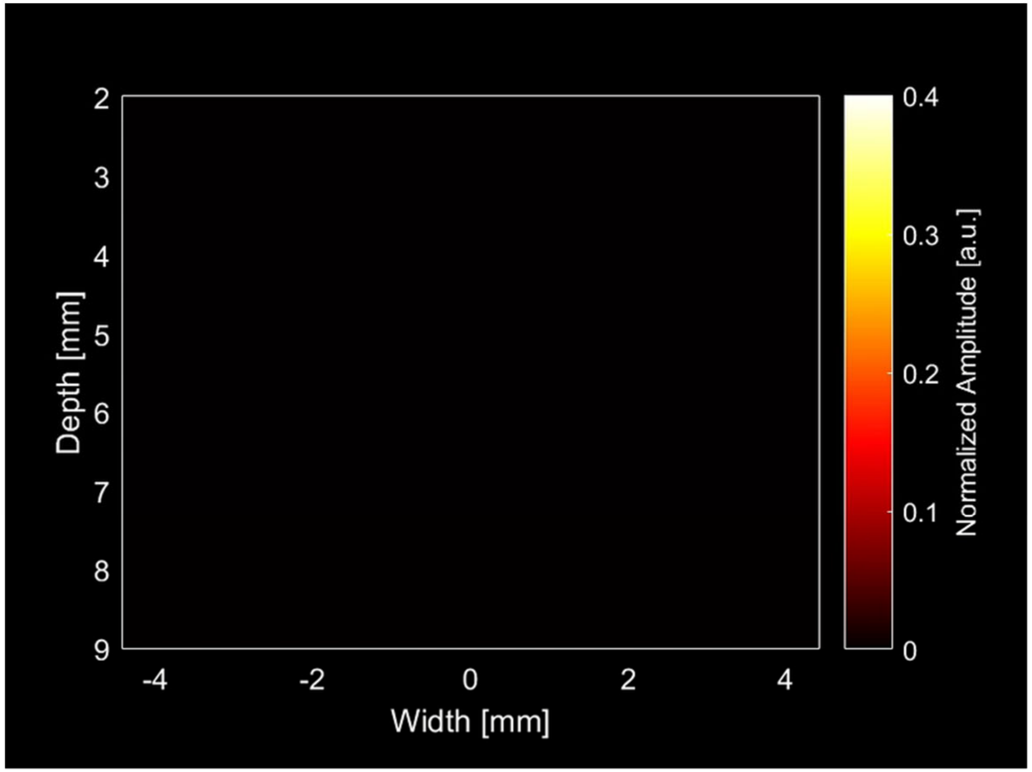
High frame rate imaging

Trade-off between temporal resolution and image contrast

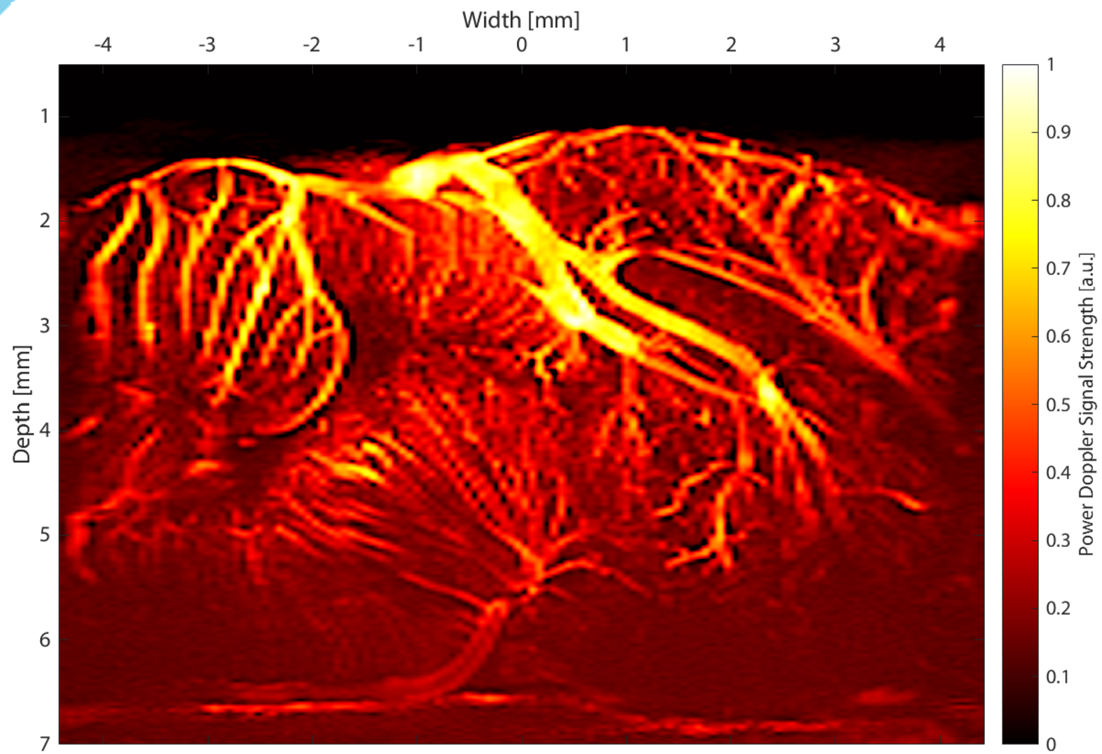


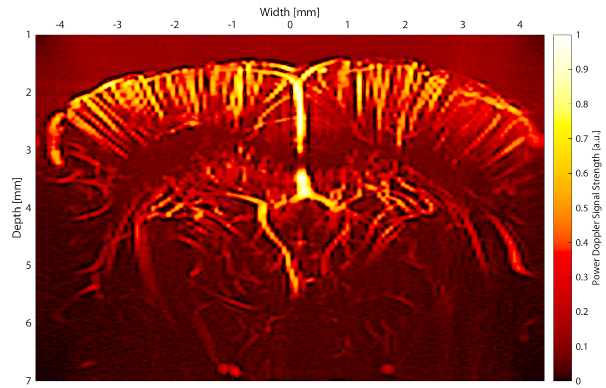
Tanter et al. IEEE UFFC 2014

Plane wave Doppler imaging reveals brain vasculature



Plane wave Doppler imaging reveals brain vasculature





CUBE Centre of Ultrasound Brain imaging @ Erasmus MC

understanding the brain with ultrasound

Imaging Science · Neuro Science · Neuro Surgery

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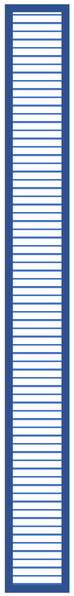
Great it works, …. so why are you a speaker on a meeting about compressive sensing ?

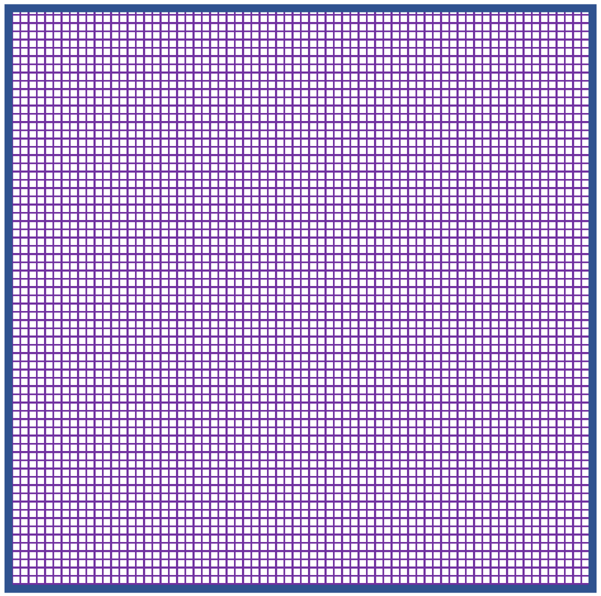
2D ultrasound is relevant in a 2D world.

Flatland: *A romance of many dimensions, Edwin Abbott 1884.*

The sensor problem for medical ultrasound



VS

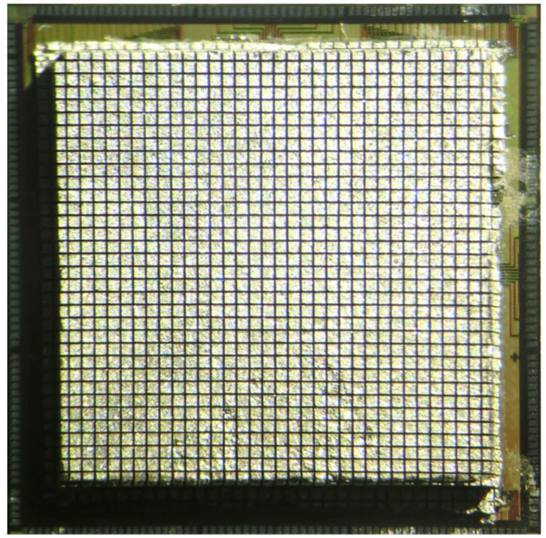


2D

128 sensors

3D

16384 sensors !!

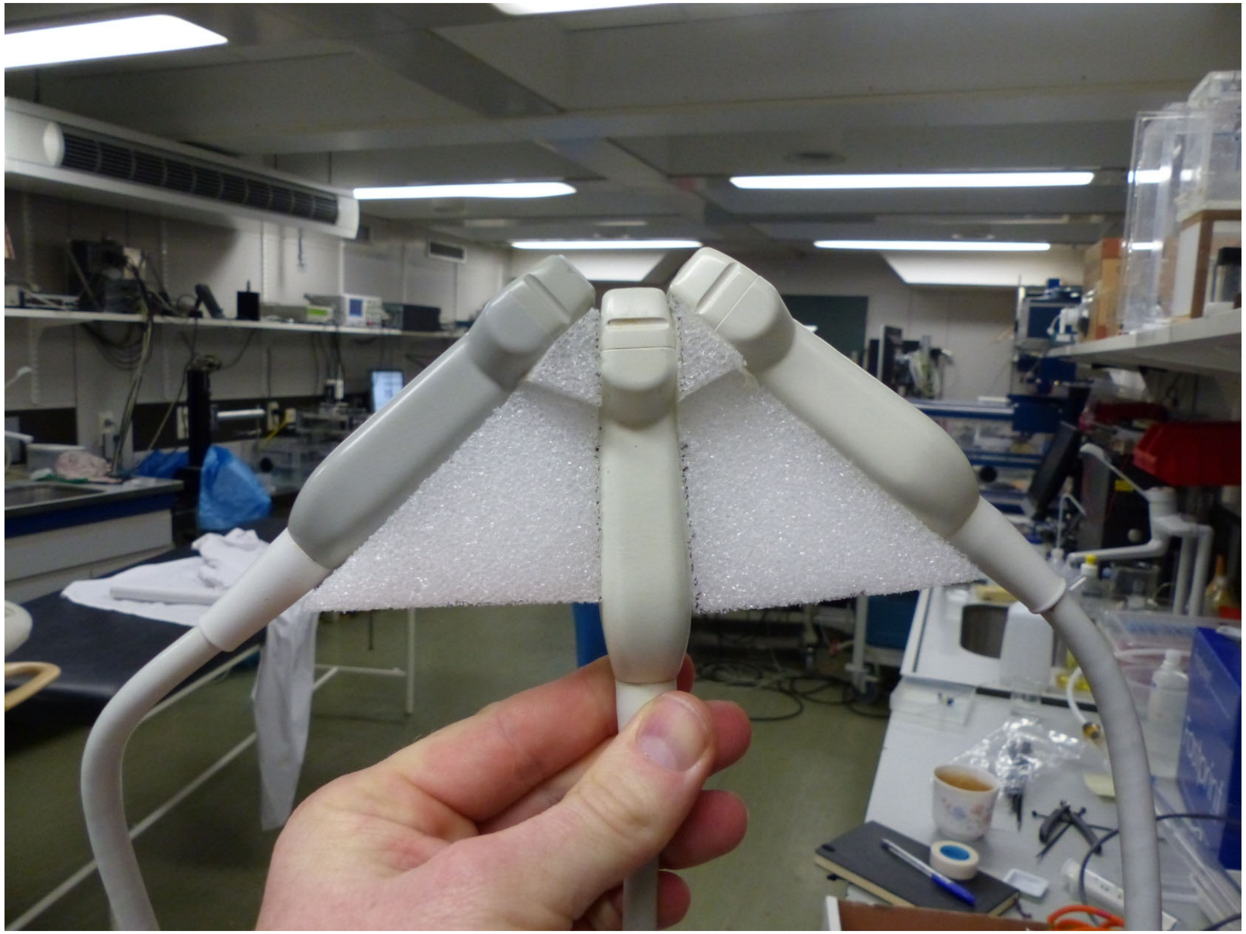


Matrix sensor array (32x32)
with integrated electronics

Nìco de Jong, Martin Verweij and Michel Pertijs

TUDelft

sMC



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Possible solution may come from the discovery of **compressive sensing!**

The camera that made compressive sensing famous

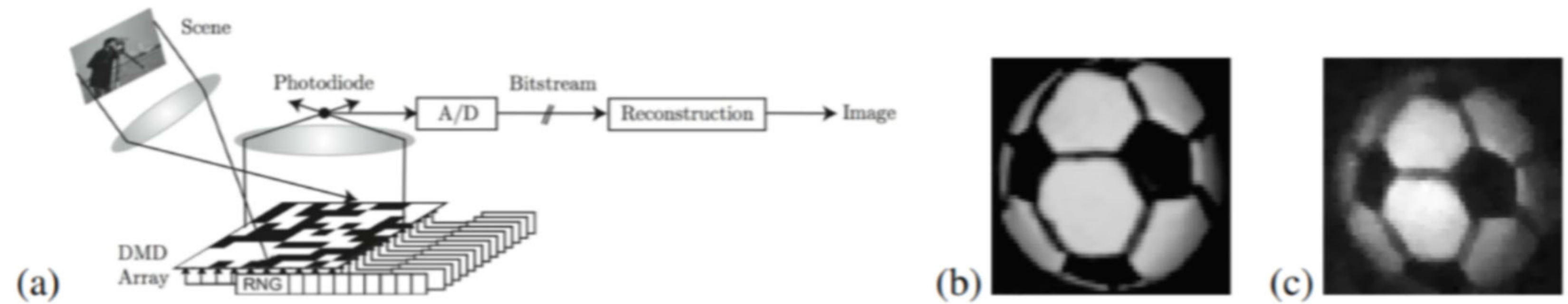
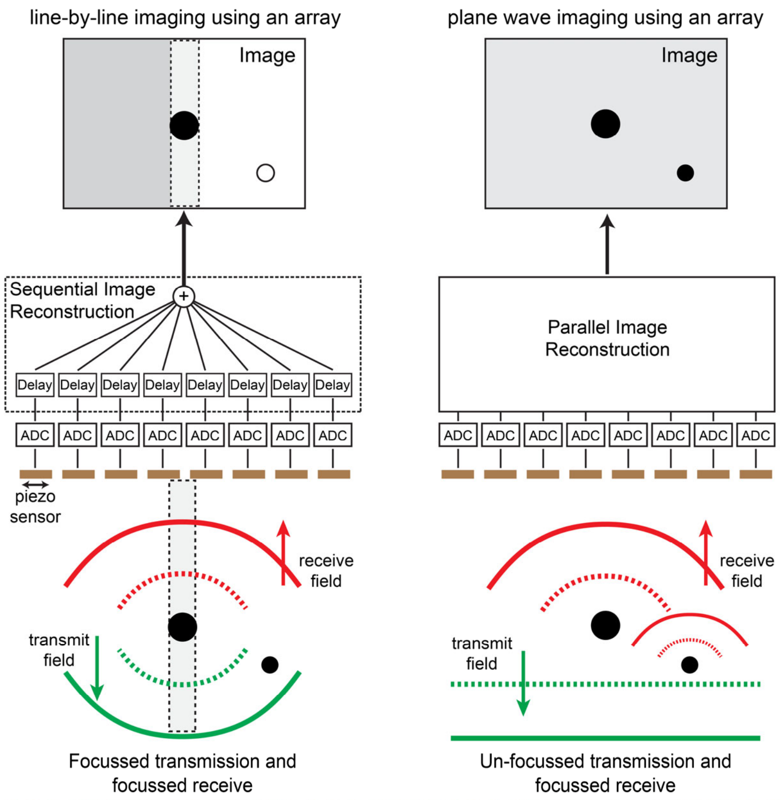


Figure 3: *(a) Single-pixel, compressive sensing camera. (b) Conventional digital camera image of a soccer ball. (c)* 64×64 *black-and-white image* $\widehat{\mathbf{x}}$ *of the same ball (*$N = 4096$ *pixels) recovered from* $M = 1600$ *random measurements taken by the camera in (a). The images in (b) and (c) are not meant to be aligned.*

Duarte, Marco F., et al. "Single-pixel imaging via compressive sampling." IEEE signal processing magazine 25.2 (2008): 83-91.

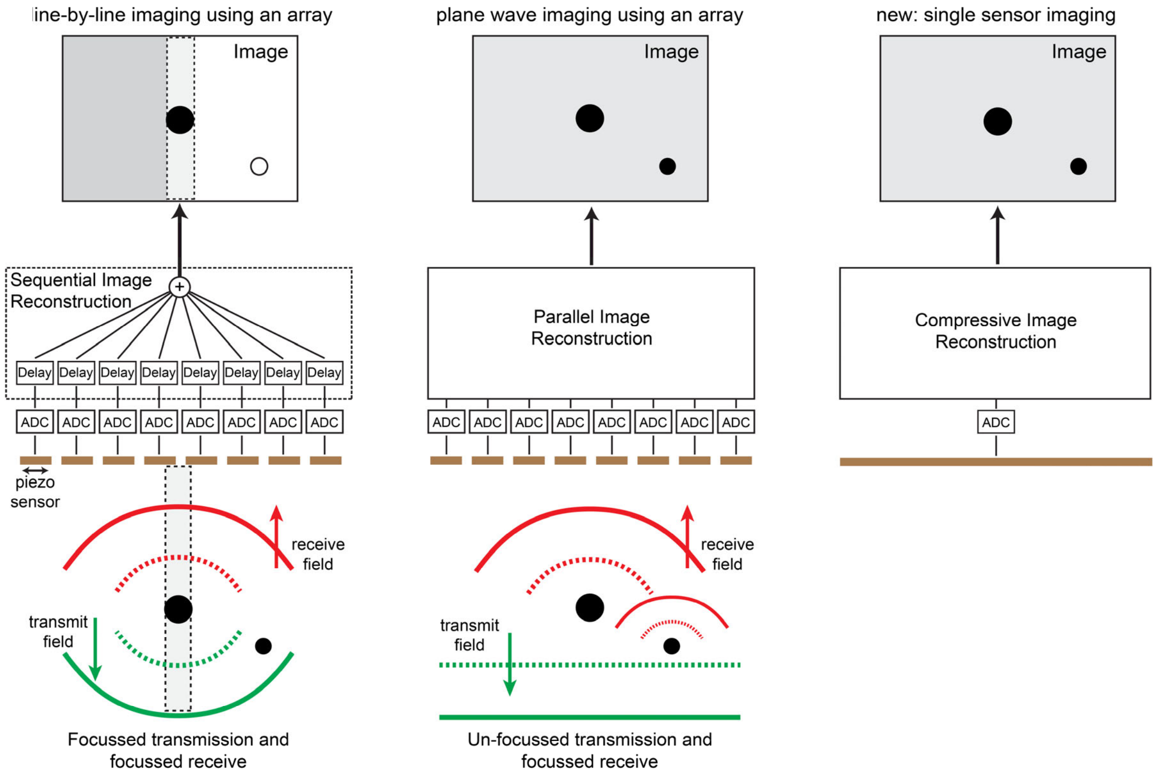
How does this idea translate to medical ultrasound?

For imaging we need spatial information



What if you have only one sensor?

Can we encode spatial information ?



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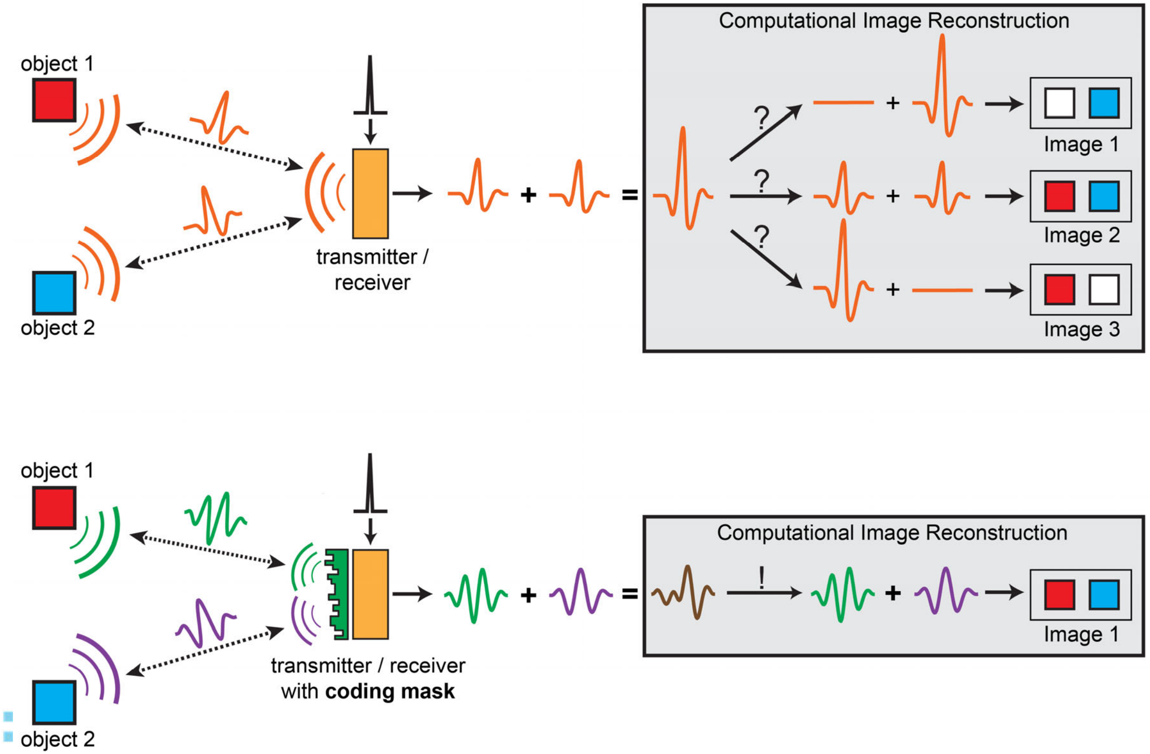
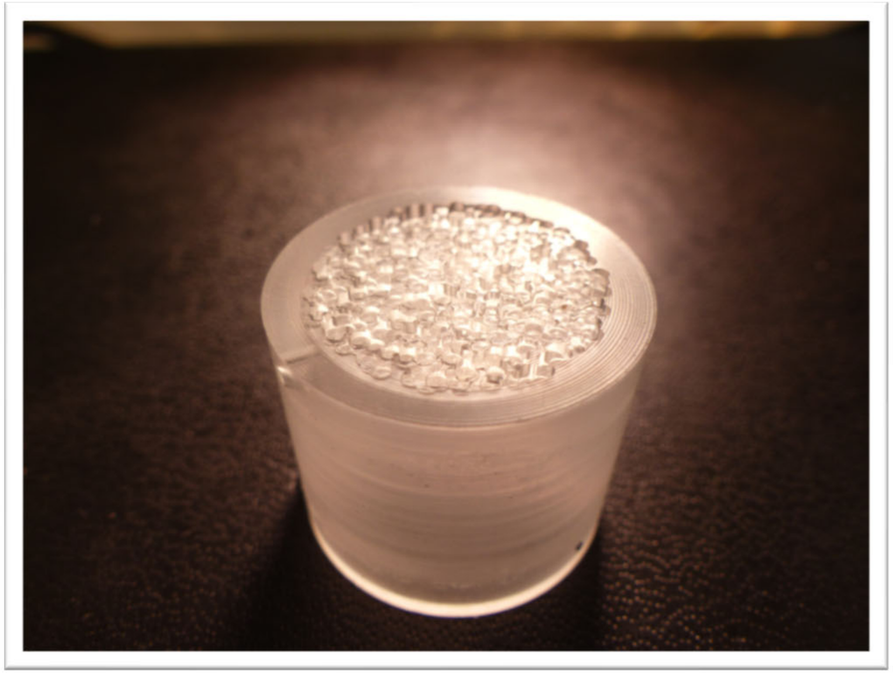
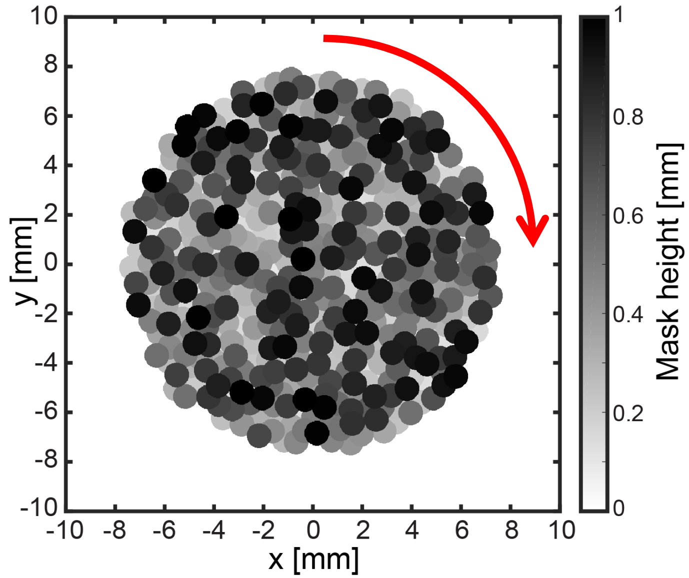
Compressive imaging: every pixel should have a unique signal

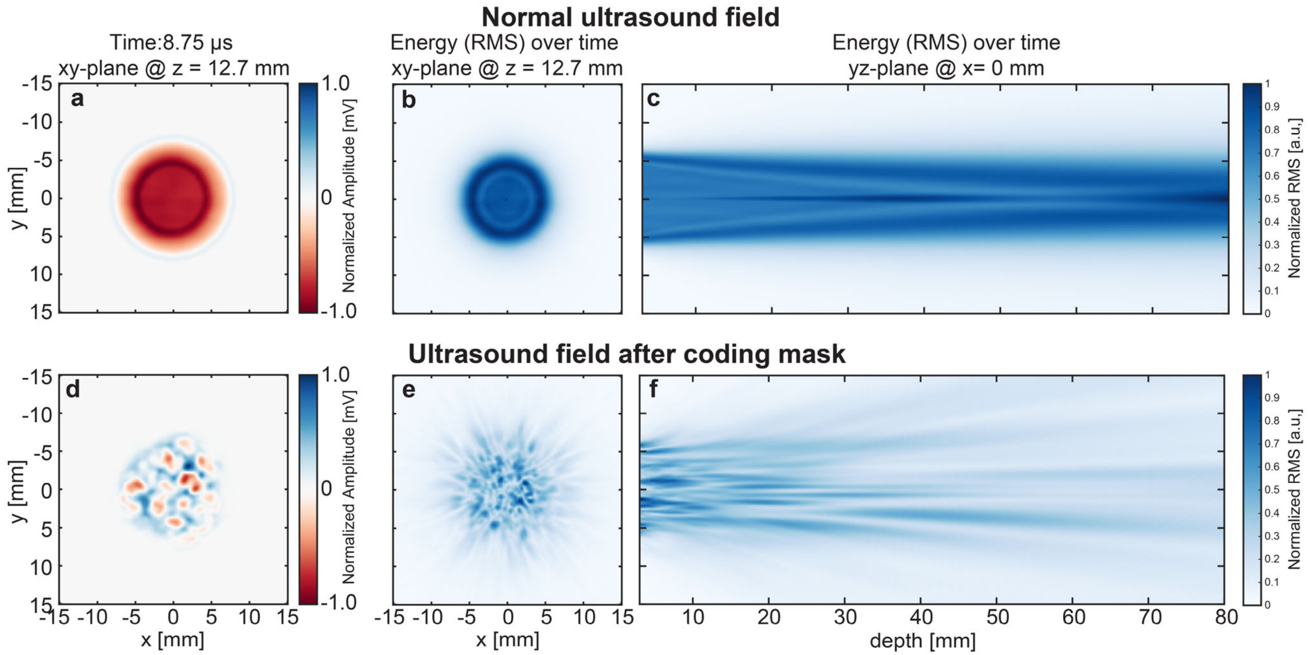


Compressive ultrasound imaging using a coded aperture mask





Coded aperture mask breaks the phase uniformity of the ultrasound field



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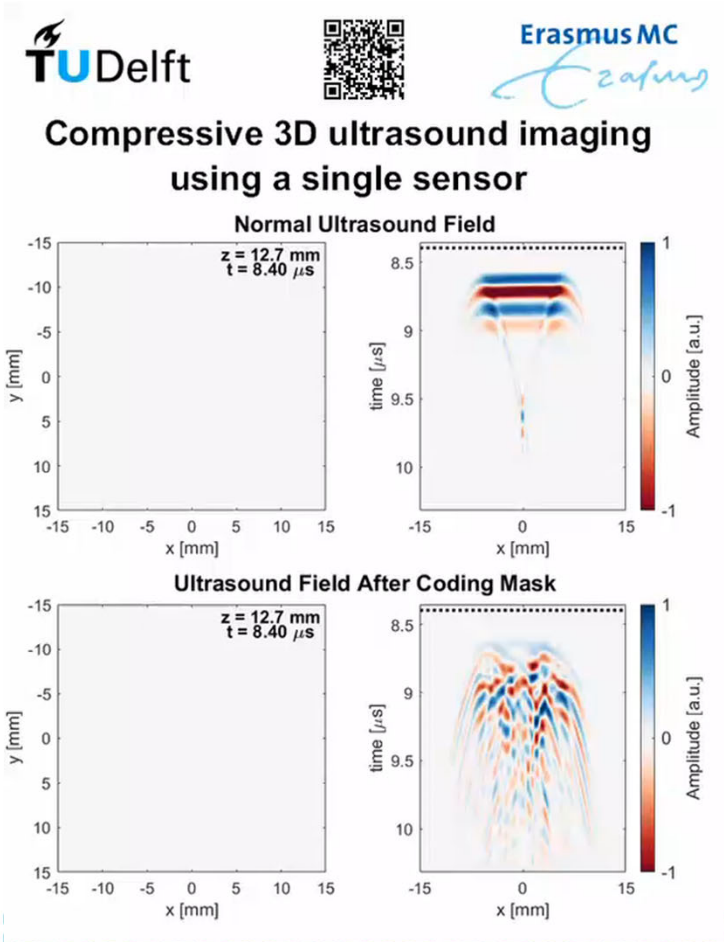
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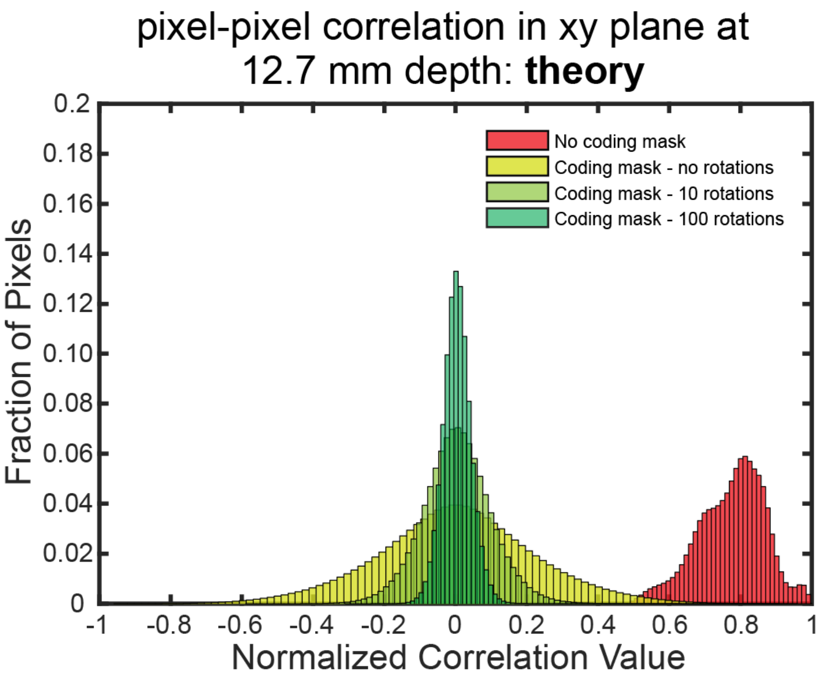
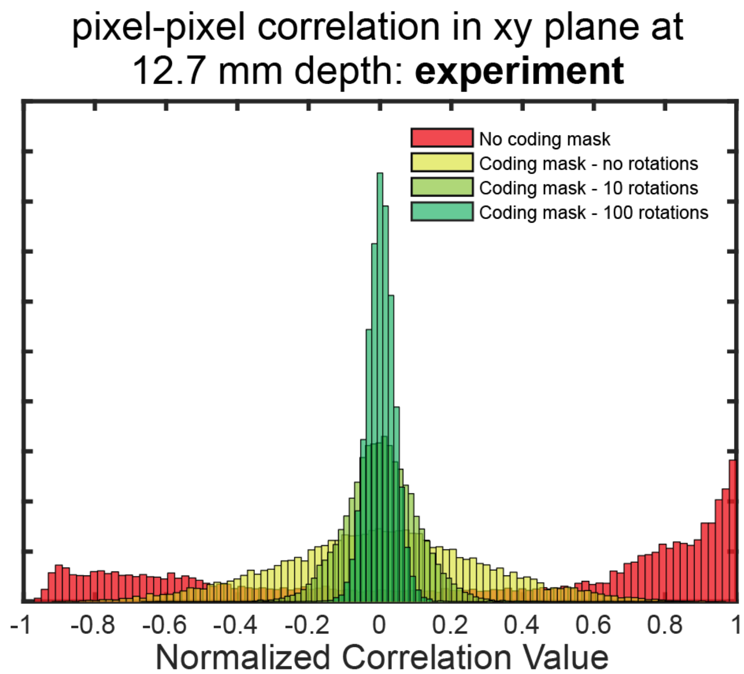
Compressive 3D ultrasound imaging using a single sensor
Normal Ultrasound Field
z = 12.7 mm
t = 8.40 μs
y [mm]
x [mm]
time [μs]
Amplitude [a.u.]
Ultrasound Field After Coding Mask
z = 12.7 mm
t = 8.40 μs
y [mm]
x [mm]
time [μs]
Amplitude [a.u.]

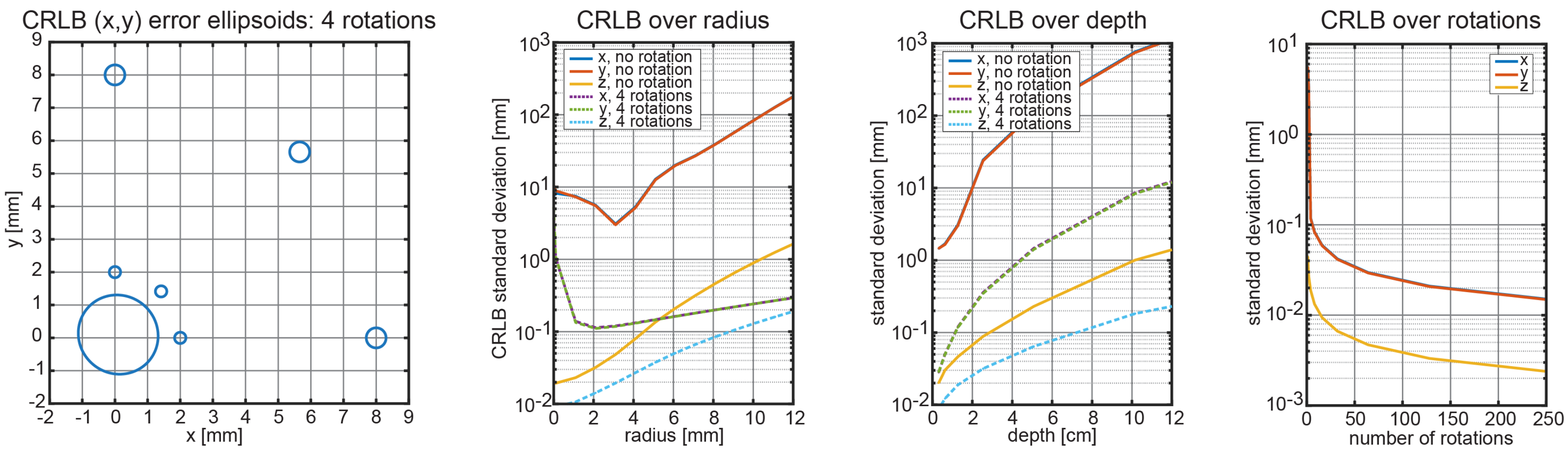
Pixels become more unique by applying a coded aperture mask!



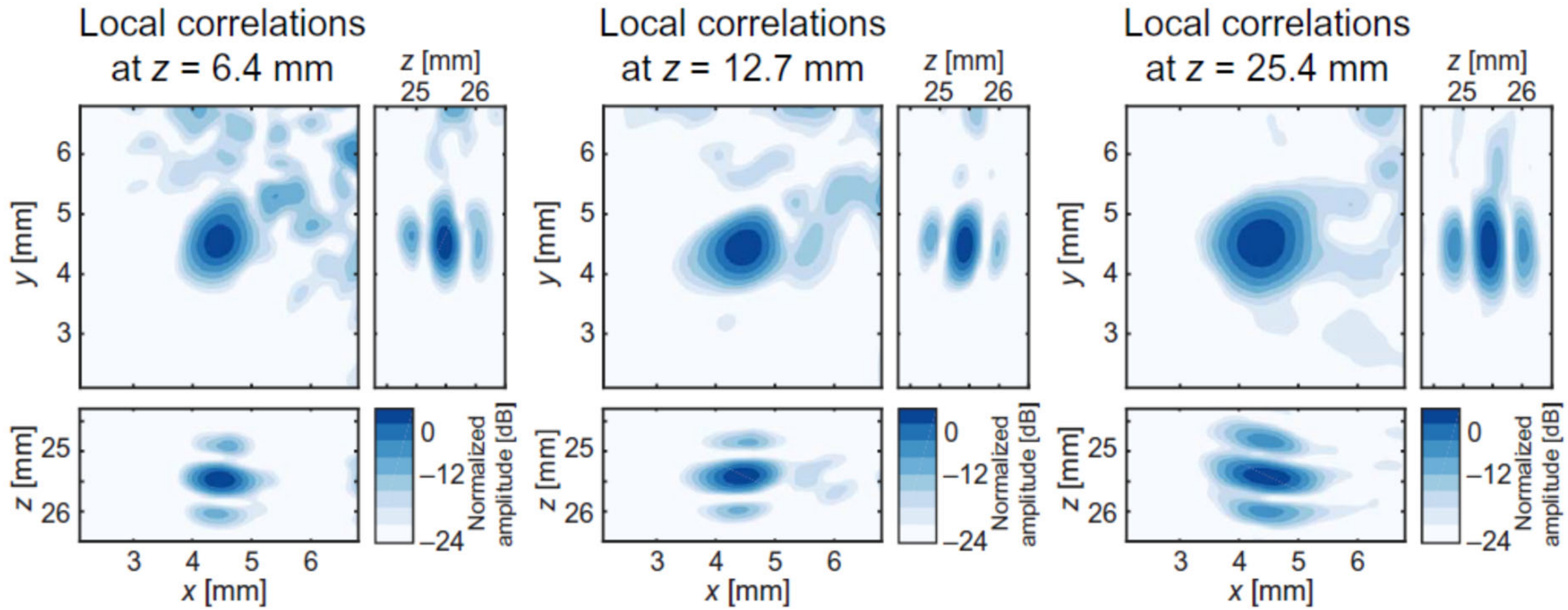


ISMC

Cramer-Rao Lower Bound reveals imaging performance



Psf by matched filter



Imaging Algorithm

Calibration (only once)

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

Build model (image dependent)

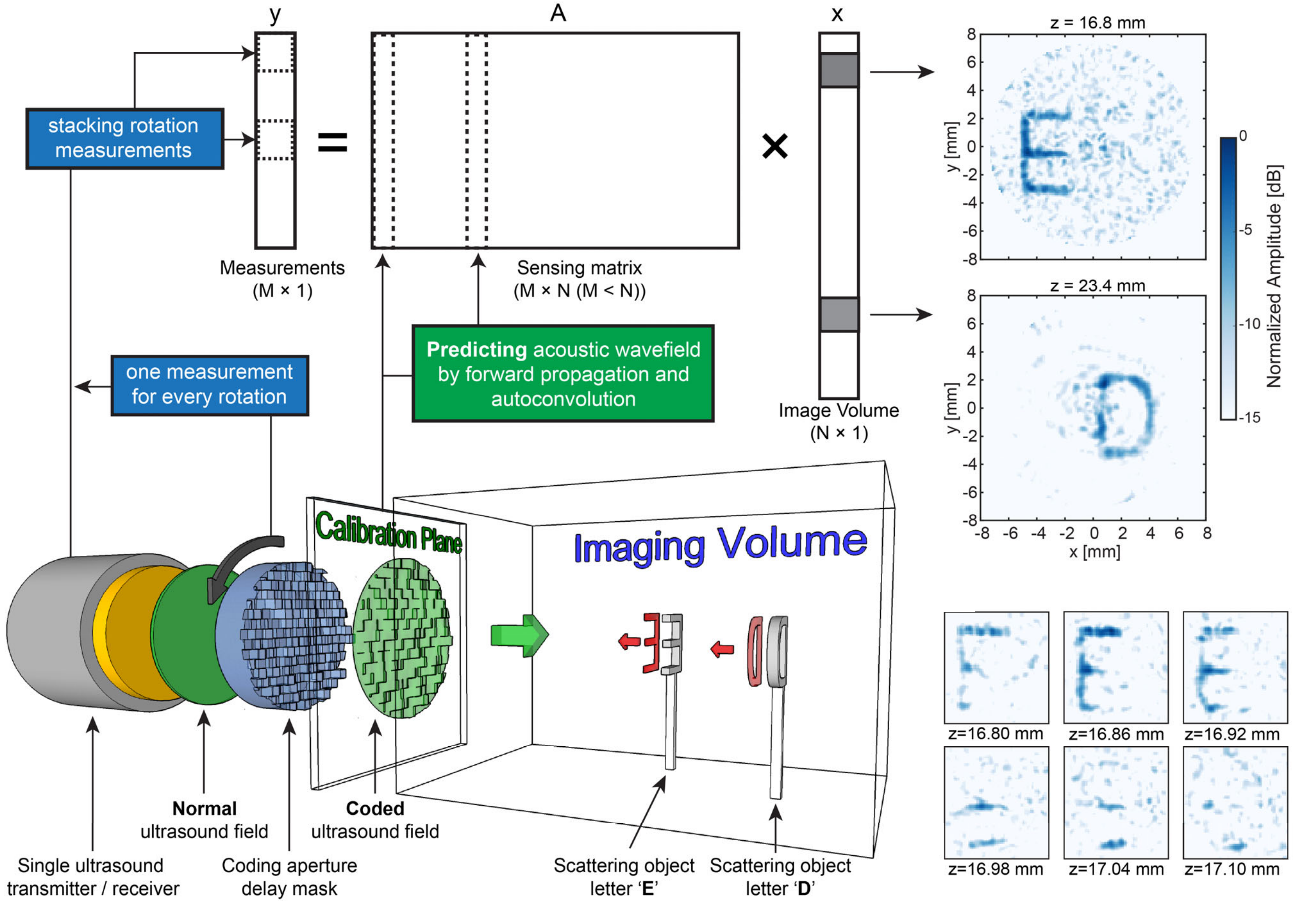
- Use Angular Spectrum Approach to predict other z-planes
- Per-pixel auto-convolution to account for pulse-echo
- Store all estimated pixel signals in one big **A** (model) matrix

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))
Image Volume
(N × 1)
one measurement for every rotation
Predicting acoustic wavefield by forward propagation and autoconvolution
Calibration Plane
Imaging Volume
Single ultrasound transmitter / receiver
Normal ultrasound field
Coding aperture delay mask
Coded ultrasound field
Scattering object letter 'E'
Scattering object letter 'D'
z = 16.8 mm
z = 23.4 mm
y [mm]
x [mm]
Normalized Amplitude [dB]
z=16.80 mm
z=16.86 mm
z=16.92 mm
z=16.98 mm
z=17.04 mm
z=17.10 mm

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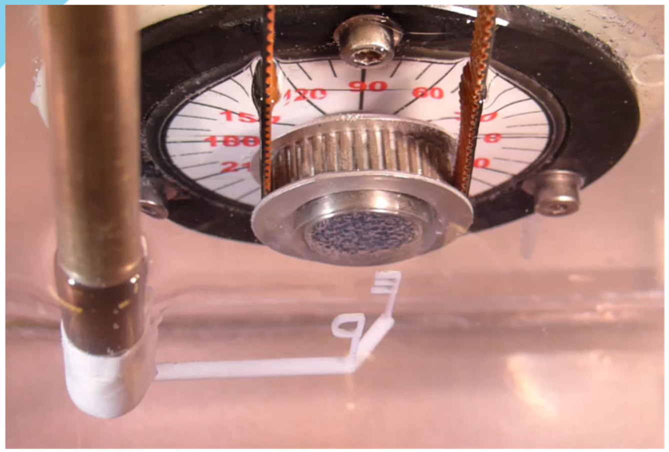
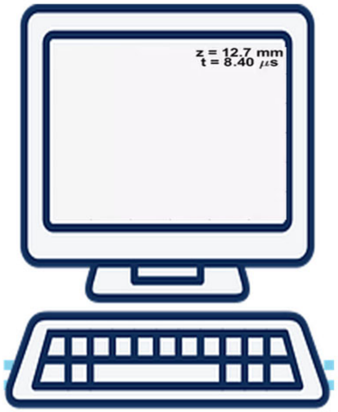
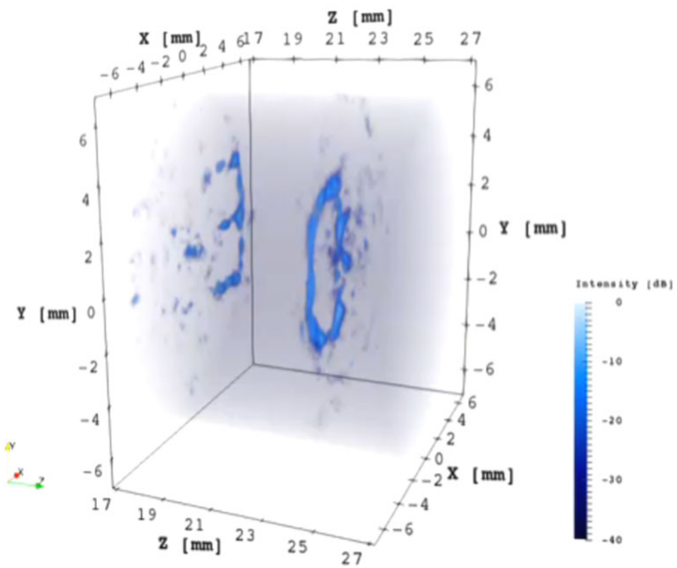
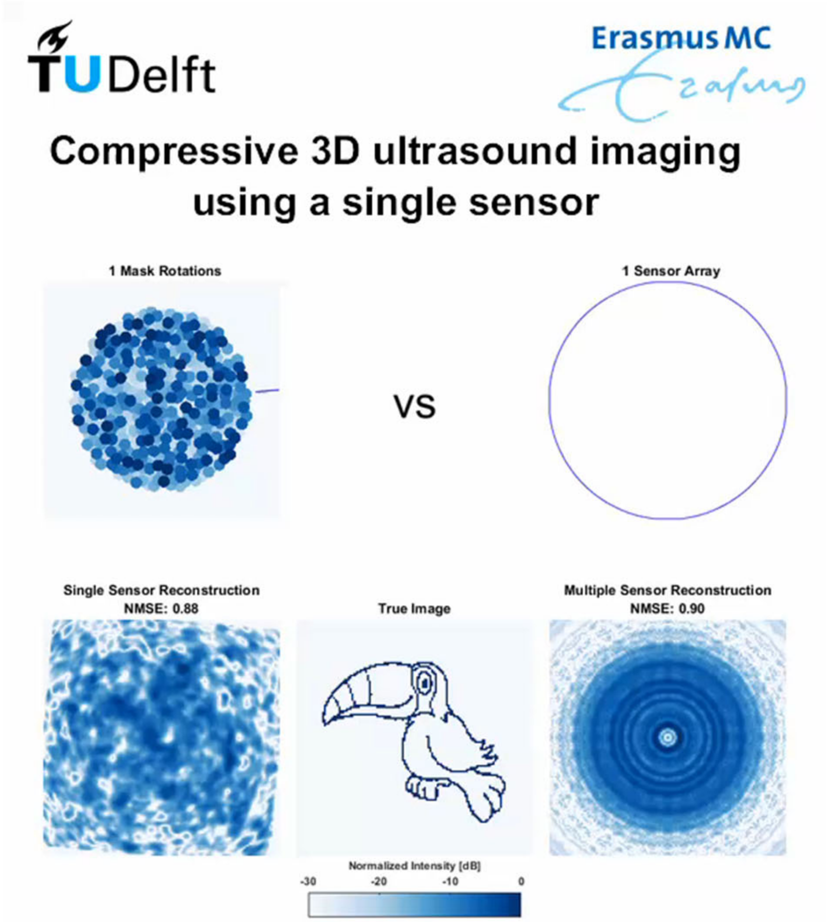
The letter experiment





Acoustical Compressive Imaging

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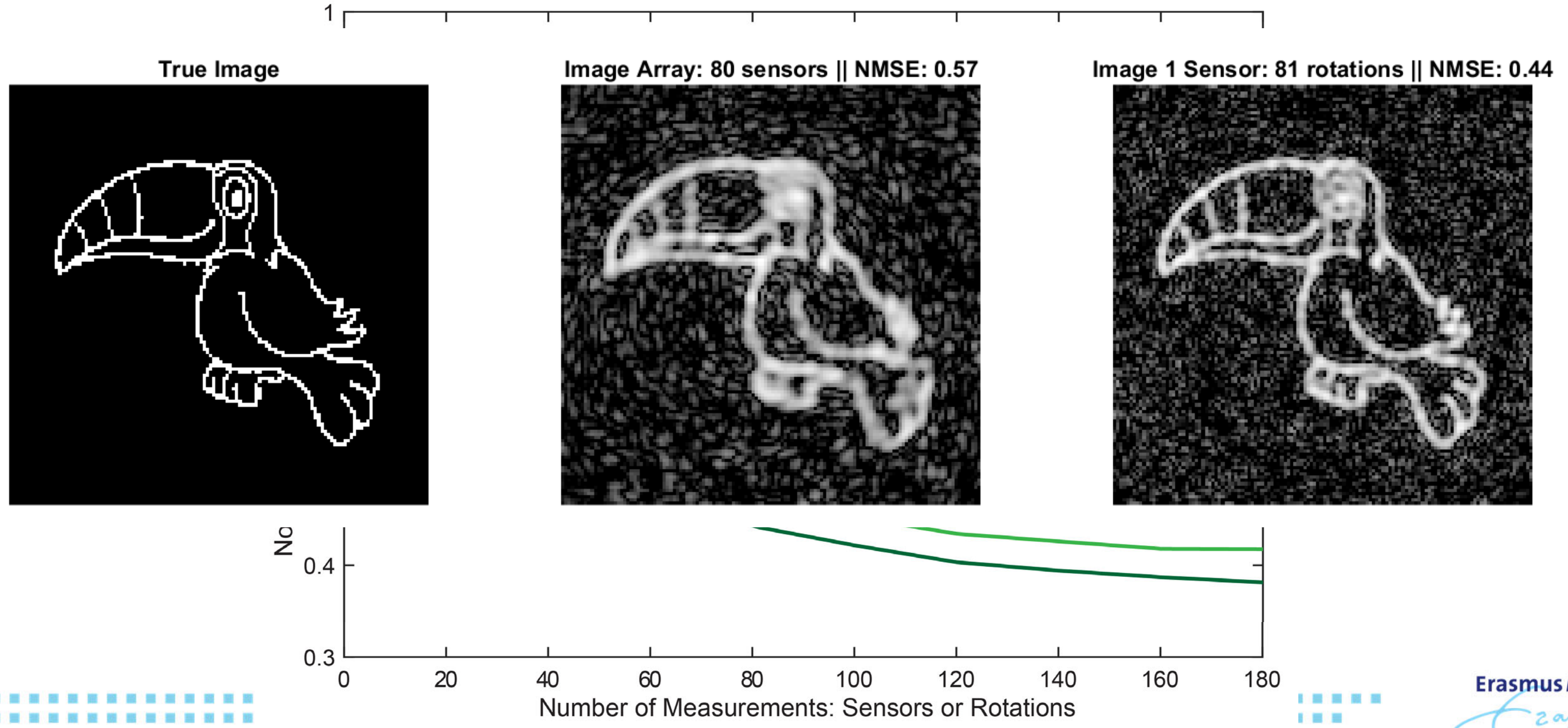
Compressive 3D ultrasound imaging
using a single sensor
1 Mask Rotations
VS
1 Sensor Array
Single Sensor Reconstruction
NMSE: 0.88
True Image
Multiple Sensor Reconstruction
NMSE: 0.90
Normalized Intensity [dB]
-30
-20
-10
0

Multi-sensor array versus single sensor and mask rotations

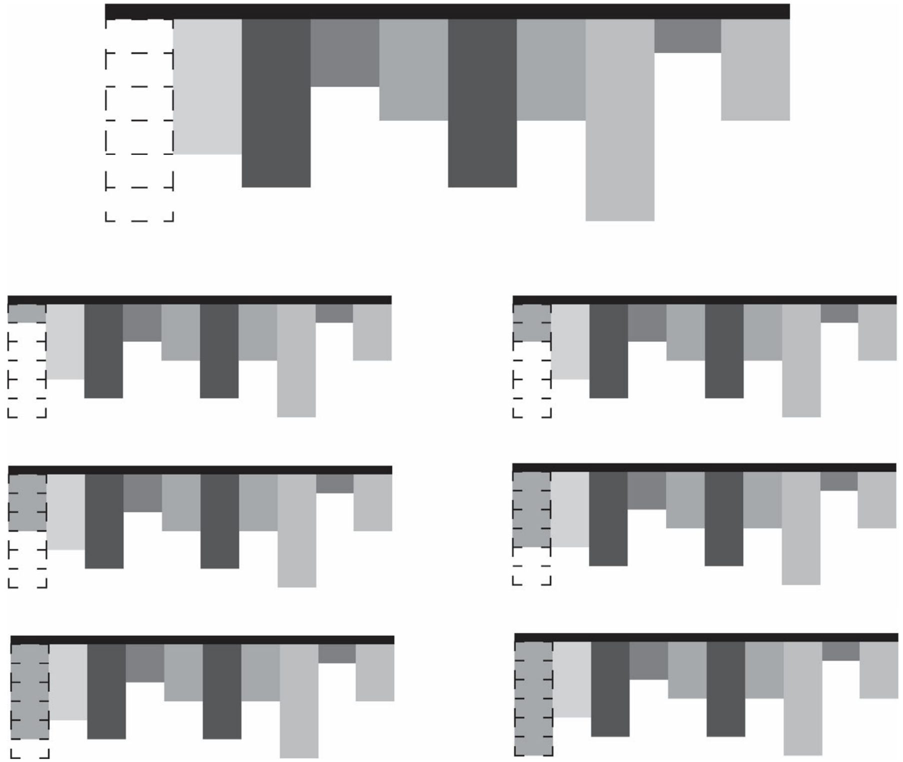


Coding mask optimization

Main idea: allow several mask thickness levels in each 'channel'

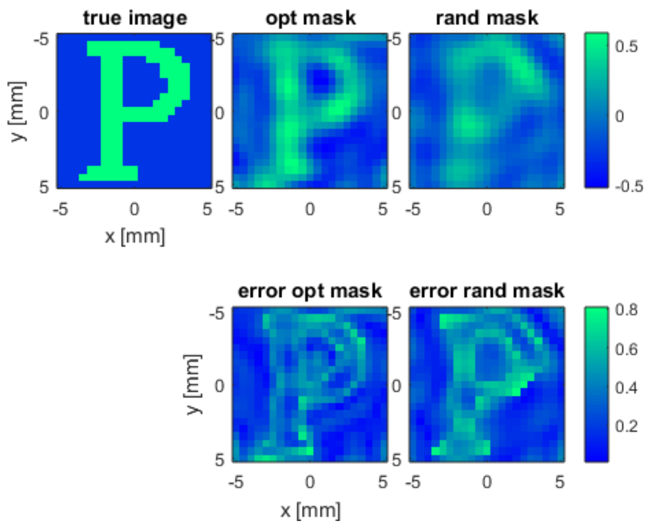
Optimization problem:

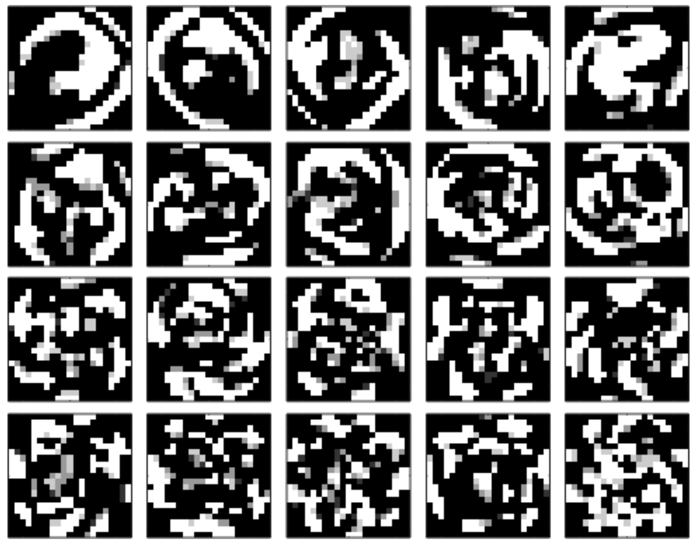
Select one thickness level for each mask 'channel', such that $\mathrm{MSE}_{\hat{\mathbf{x}}} = \mathrm{Tr}(\mathbf{A}^T\mathbf{A})^{-1}$ *is minimized.*



Simulation results

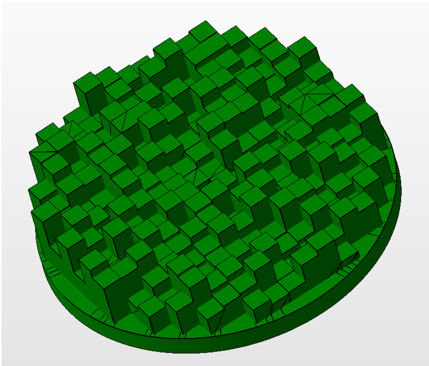
Case 2: 20 different masks

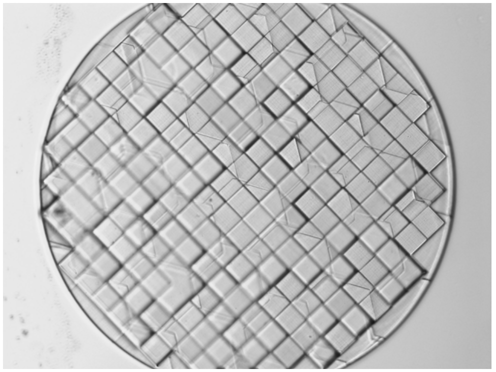




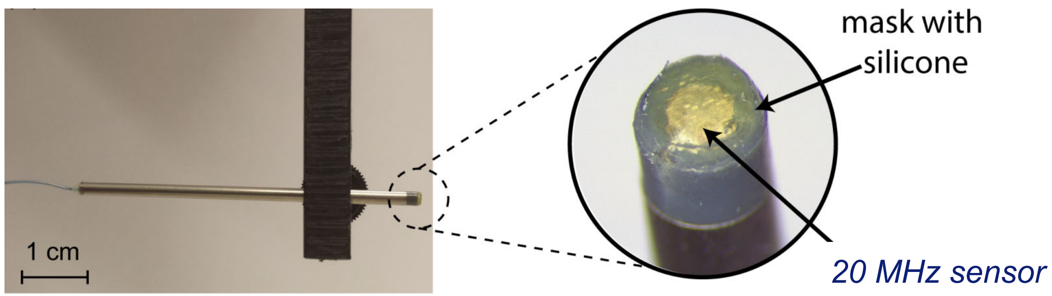
It seems like we can *encode* or *emphasise* spatial information using an aperture coding mask.

The coded aperture mask for intravascular imaging



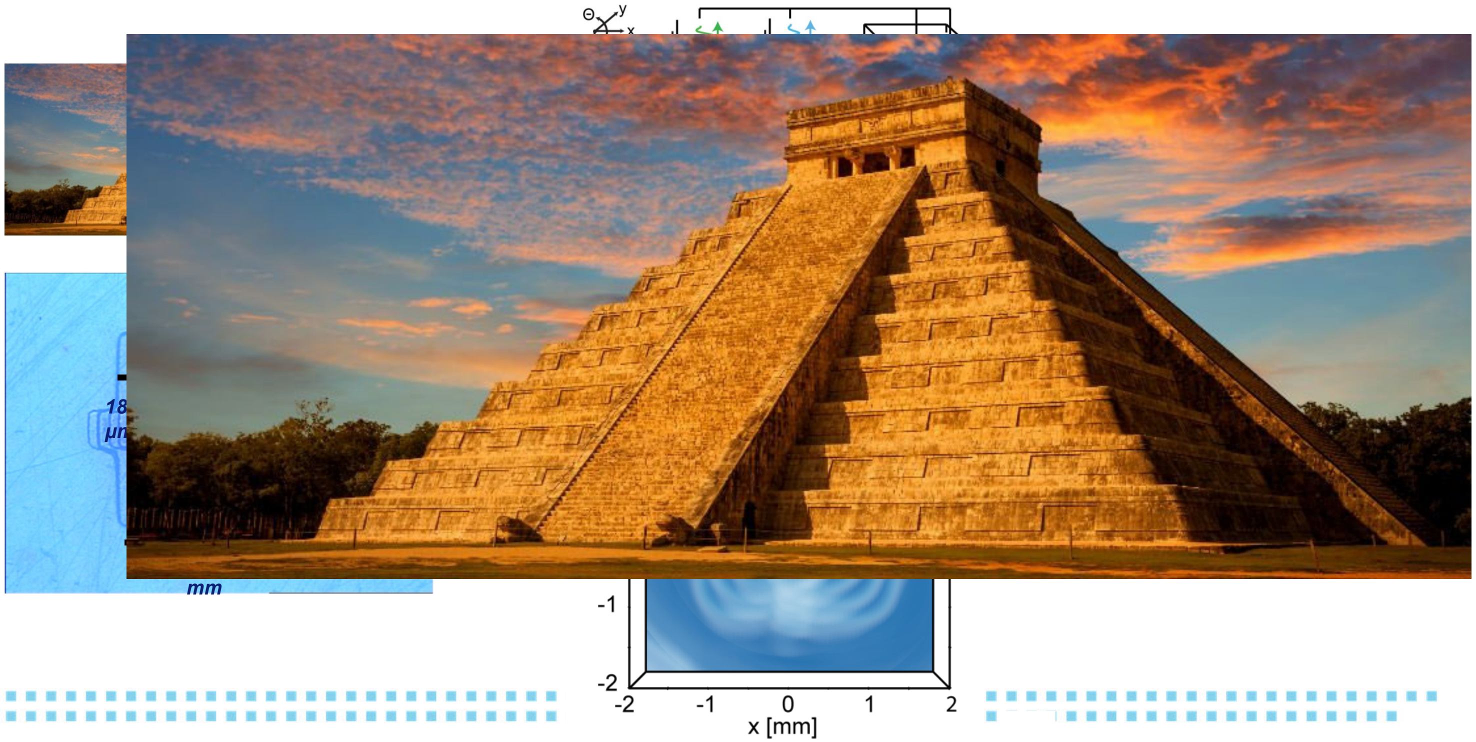


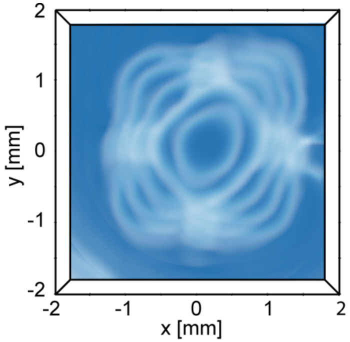
Diameter: 1.5 mm
Thickness: 0.04-0.32 mm



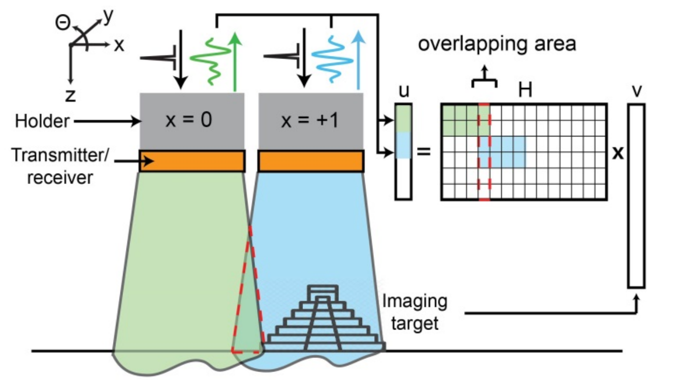
First test against normal ultrasound microscopy: El Castillo

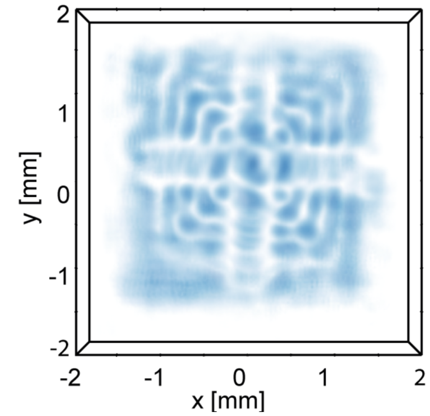
Scanning Acoustic Microscopy



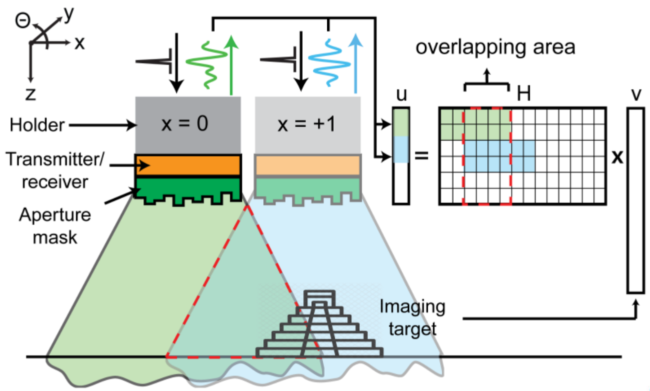


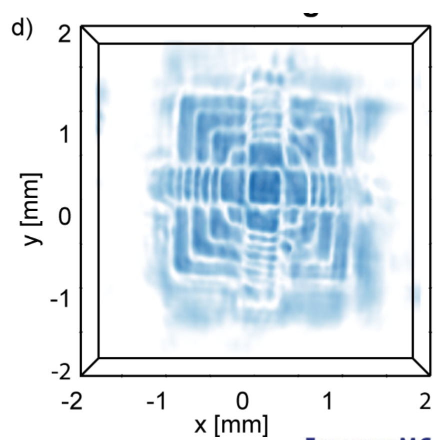
Reconstructed Ultrasound Microscopy





Structured Ultrasound Microscopy





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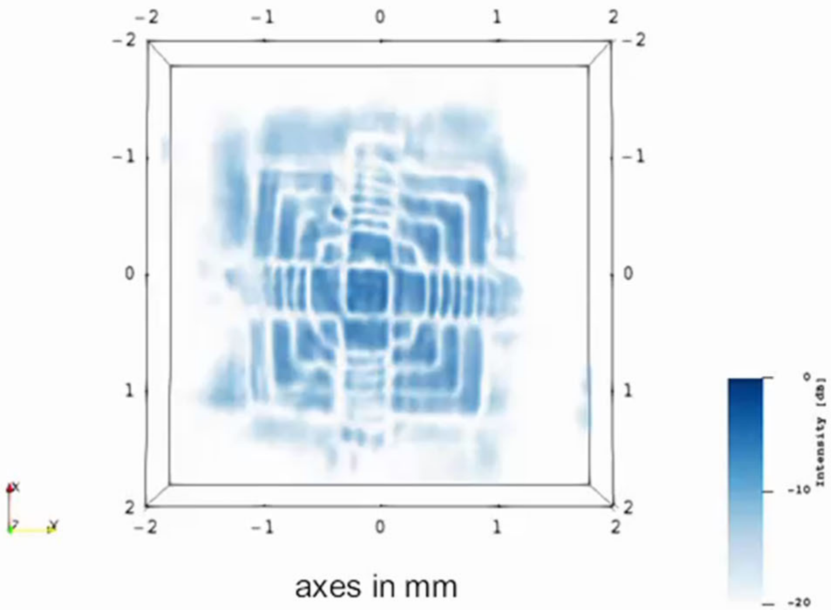
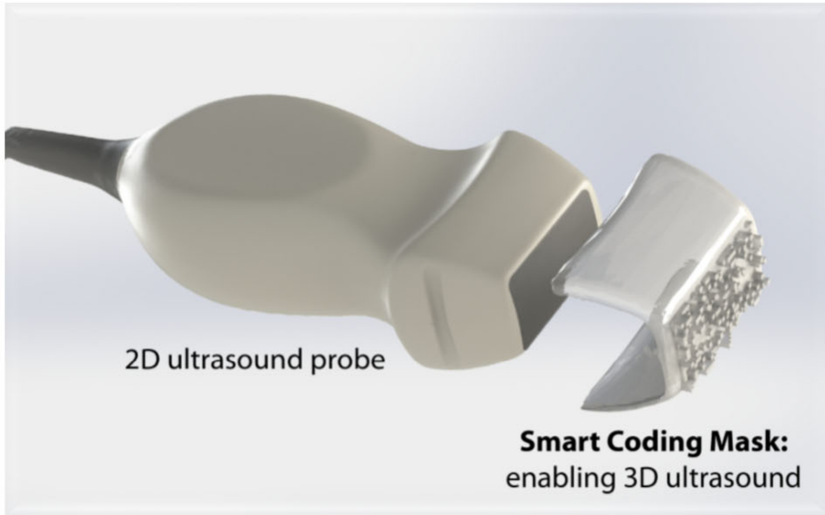
Structured Ultrasound Microscopy

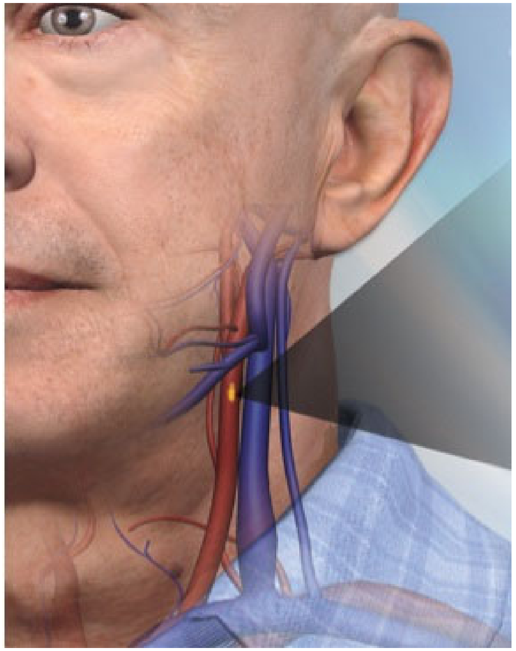


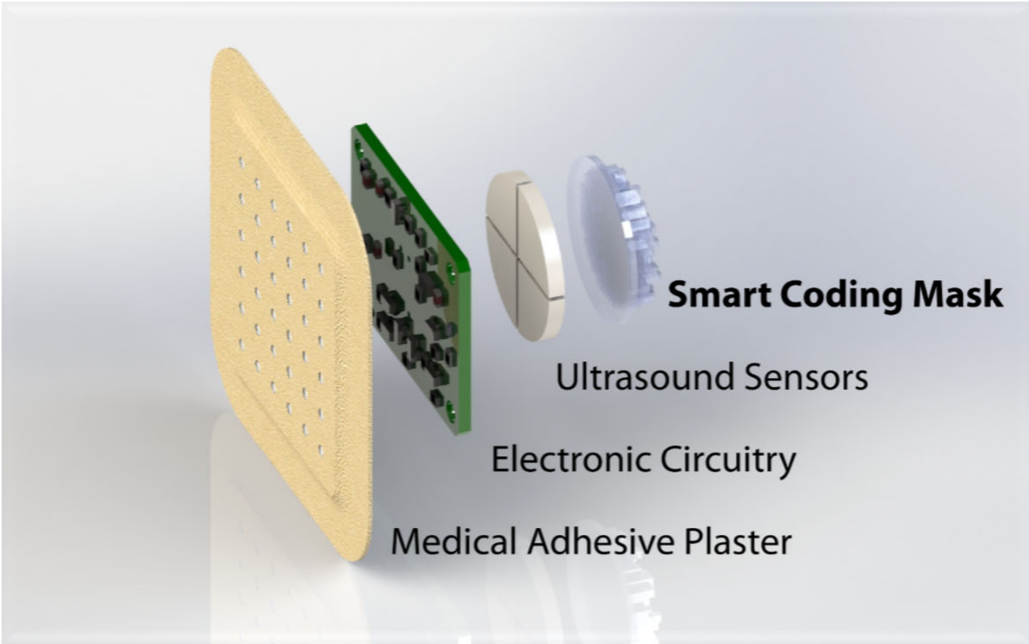
Application ideas ?

Cheap 3D ultrasound for developing countries

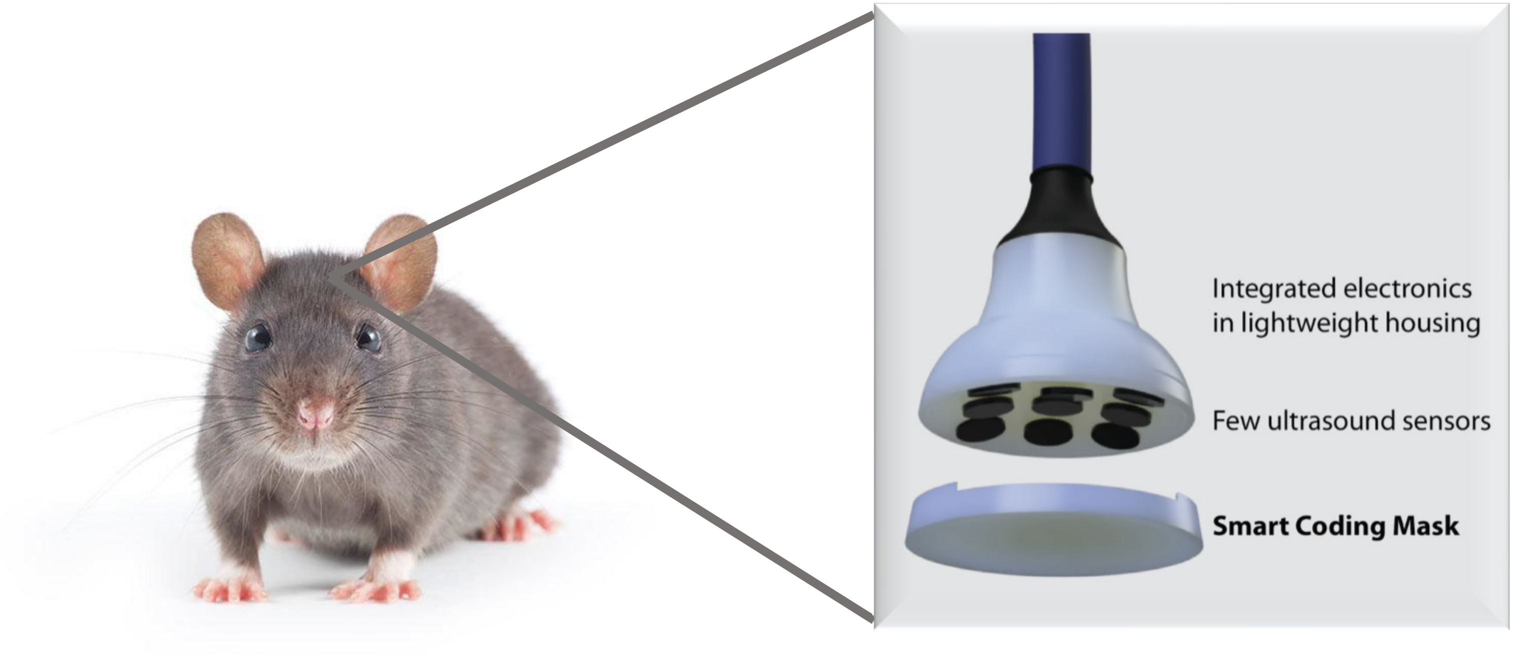


Continuous monitoring





Brain imaging for the neurosciences



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Compressive Sensing: Hype or Hope ?

Some reflections from the lab:

1. Applying local delays in the ultrasound field to uniquely address every pixel seems to work. <u>Ultimately, it will be these kinds of physical parameters that will dictate whether and to what extent true compressive imaging is possible.</u>
2. The physics of our ultrasound (bandwidth, reflection mode, etc…..) makes the measurements compressed in some sort.
3. Reconstruction (finding x) using our fat matrices is possible because the dependence between columns is typically very local in space.
4. Finding bases where the ultrasound image is sparse is very difficult.
5. Many papers on CS + ultrasound but no great examples like in MRI or CT.
6. Maybe we should not focus on finding the true x (*what is exact recovery in biomedical imaging ?*).

Hype or Hope ?

Ultrasound + Compressive sensing: **Hype of today**

3D Ultrasound + Compressive sensing: **Hope of tomorrow**

Spatial Coding for High Resolution Compressive Ultrasound Imaging

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