



KIT 3D Ultrasound Computer Tomography – a data & computing intensive approach at multimodal ultrasound imaging

M. Zapf, T. Hopp, H. Gemmeke, N. V. Ruiter, et al.

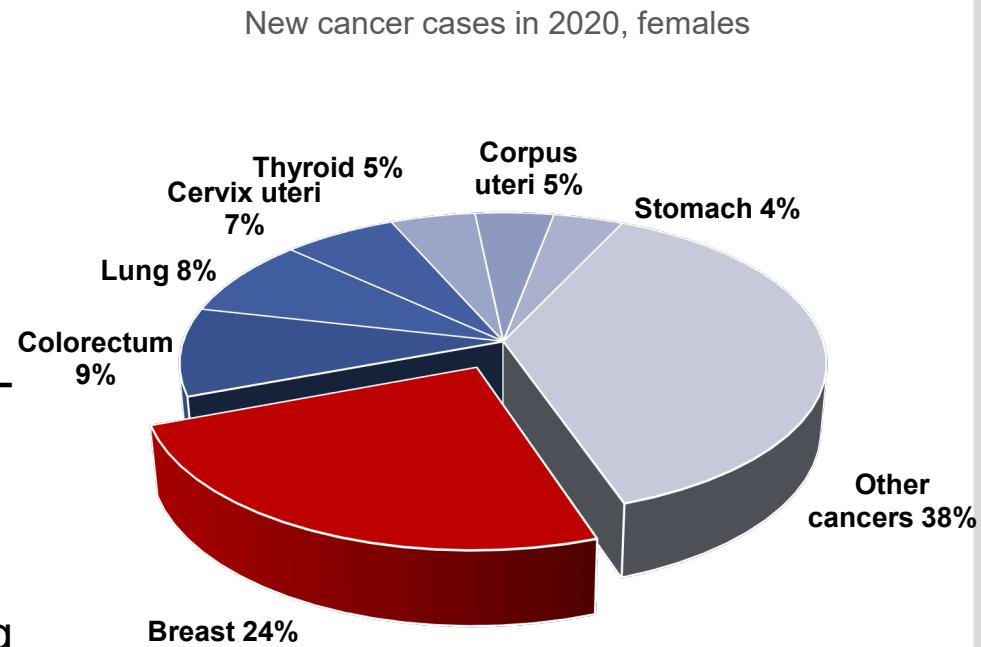
INSTITUTE FOR DATA PROCESSING AND ELECTRONICS



Background: Medical situation

Motivation: Breast cancer

- Most common cancer of women in western world (every 10th woman)
- Deadly, despite not being a non-vital organ
- Challenge & solution: Early diagnosis
- Current diagnosis and screening methods have disadvantages



Source: International Agency for research on cancer, <https://gco.iarc.fr>
 Data source: WHO cancer statistics 2020, GLOBOCAN 2020

Background: Medical situation

Screening



X-Ray Mammography

Symptomatic patients



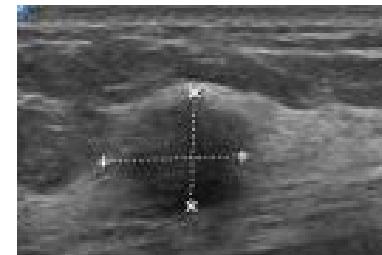
Ultrasound (US) Sonography



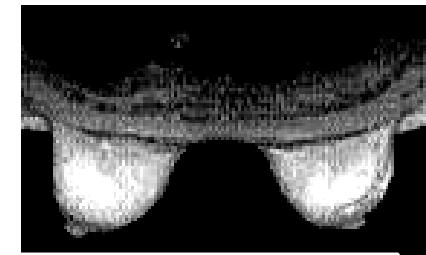
Magnetic Resonance Imaging (MRI)



X-ray mammography image



Sonography B-Scan image



MRI image (transversal cut)

- Current diagnosis and screening methods have disadvantages
 - Uncomfortable, ionizing (harming), 2D, non-reproducible, expensive, specificity problems (“false positives”), requires contrast agents...

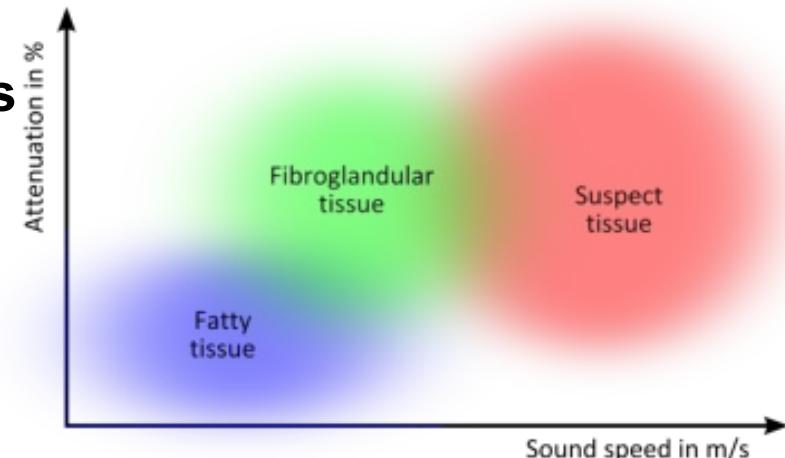
Vision

Basic idea: why not combining the best of these methods?

- As sensitive as XR mammography
- 3D like MRT
- Non-ionizing like ultrasound sonography

Diagnostic value: Specificity

- Ultrasound can contain **three modalities** concurrently:
 - **Reflection / morphology** information
High quality “B-scans” from sonography
 - **Speed of sound and attenuation**
Quantitative information



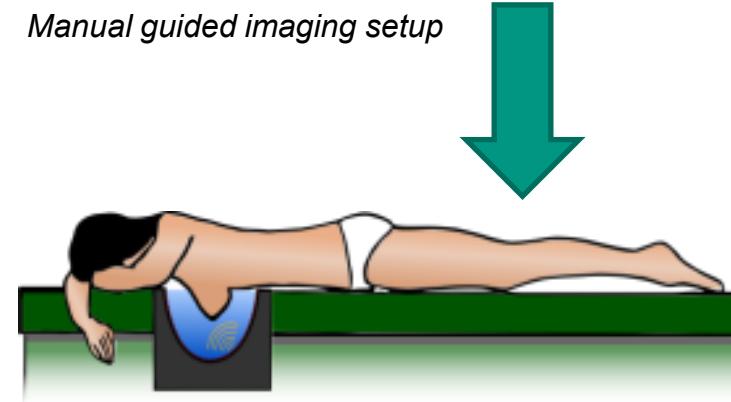
Simplified from Greenleaf et al., 1981

Vision (2)

- Technical properties
 - Fixed and reproducible measurements
 - Surround object with (unfocused) ultrasound transducers
 - Milimeter to sub-mm resolution
 - Water as imaging medium
 - MHz ultrasound
 - Multimodal
 - Measure reflection and transmission signals
- Object surrounding aperture
 - Many ultrasound transducers surround the object hemisphere



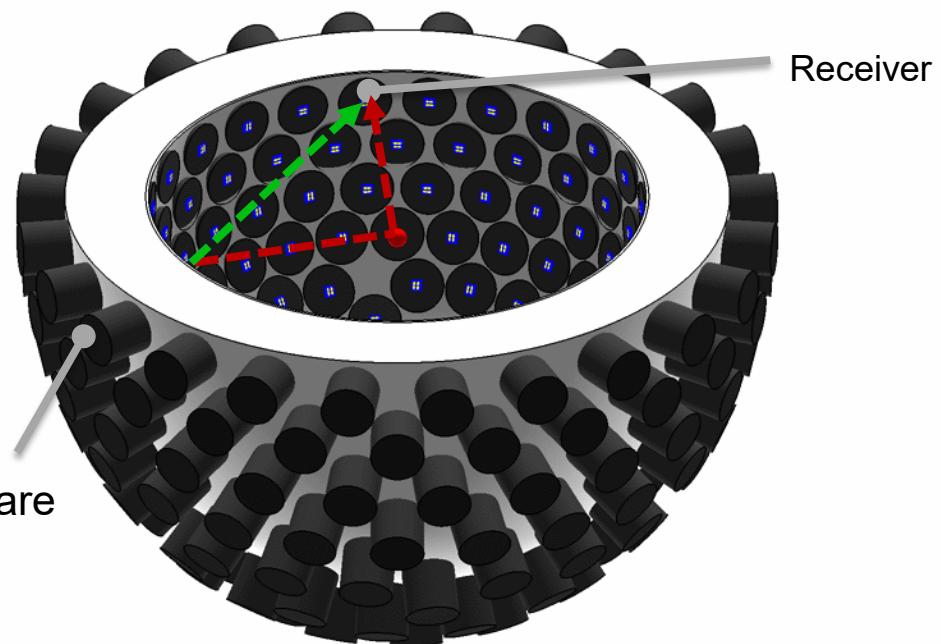
Manual guided imaging setup



Breast imaging in fixed setup

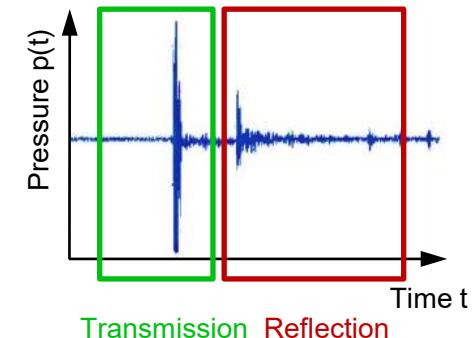
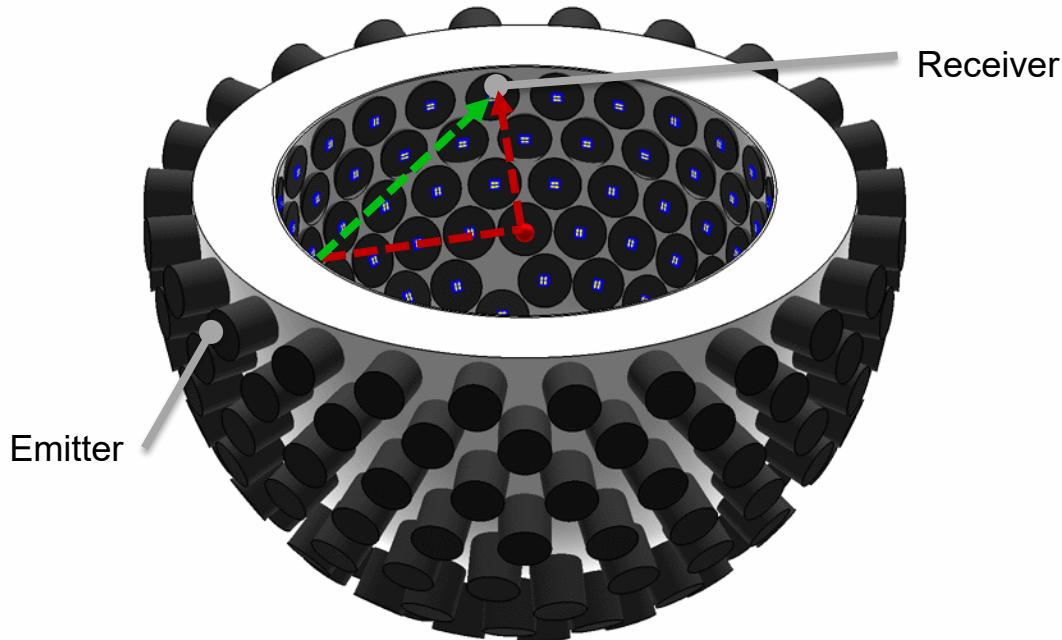
Vision (3)

- Operation principle
 - 3D phased array imaging like sonography takes too long
 - ⇒ shifting to software
 - ⇒ Synthetic aperture focussing technique (SAFT)
- One transducer emits only, many transducer receive
 - Many DAQ channels (RX), a singular excitation channel (TX)
 - Iterative, sequential excitation
 - Focussing and imaging in software on raw data
 - Not a real time system



3D USCT: measurement principle and signals

- Separation of **measurement phase + imaging phase**

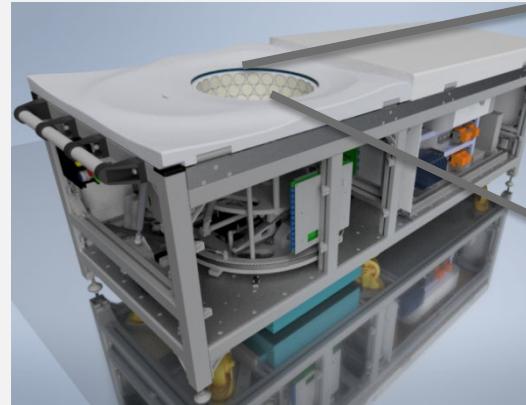


Pressure over time ultrasound signal, so called AScan

Multimodal imaging:

- Sound speed
- Attenuation
- Reflection

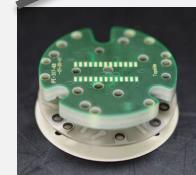
Realization: KIT 3D USCT III



KIT 3D USCT III patient bed



Measurementcontainer



Transducer Array System

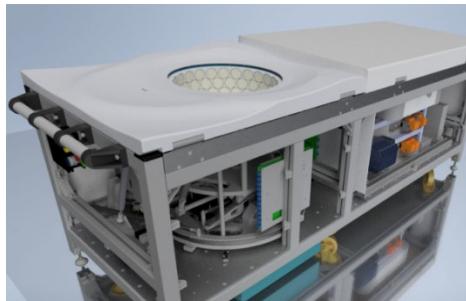


Detail view of DAQ system

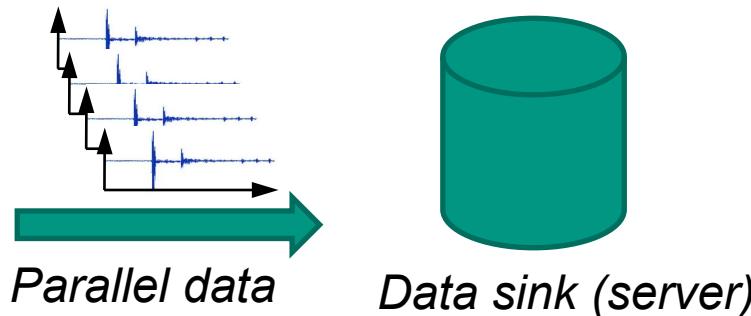
- 3D hemisphere
- Diameter: 35 cm
- 2304 US transducers (TX + RX), pseudo-random
- 2.6 MHz center freq (3.4 MHz bandwidth @ -10dB)

- 384 channels 20MHz sample rate
- 96 GB memory buffer

3D USCT III: Measurement time and data



3D USCT III system



- Measurement process
 - 2304 emitters are excited individually and iteratively
 - Measurement window: 400µs
 - => 1 to 10 minutes (parameter dependend)
- DAQ
 - 384 channels, 6x time muxing (2304 channels)
 - 10 MHz sample rate, 400µs window, 16 bit datatype
 - => 80GByte

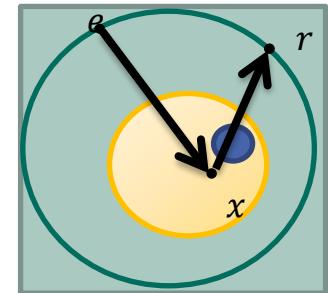
=> Clinical applicable with ~ 10 min

Image reconstruction: reflectivity

- „Weakly scattering assumption“: first reflection only
- Ellipsoid backprojection: Synthetic Aperture Focusing Technique (3D SAFT)**

$$I(x) = \sum_{e,r} A_{e,r}(t) \quad \text{with } t = \frac{|e - x| + |x - r|}{c}$$

- Extensions:
 - Sound speed correction $c_{\text{water}} \rightarrow c_{\text{path}(e,x,r)}$ [1]
 - Attenuation correction [2] $A_{e,r}(t) \rightarrow a_{\text{path}(e,x,r)} \cdot A_{e,r}(t)$
- „Ridiculous easy paralizable“: over data, over image
 -But on modern systems bandwidth limited
- Typical use case:
 - Data: 10^6 Ascans, length 4096 samples (10MHz), datatype double (8Byte)
 - Image: ROI $20 \times 20 \times 20 \text{ cm}^3$, 0.2mm resolution => 1024^3 voxel ,
 => data read bandwidth: $(4096 \times 2304 \times 128 \times 18 \times 2 \times 8) / 1024^3 = 324 \text{ GByte}$
 => Image write bandwidth: $((2304 \times 128 \times 18 \times 2 \times 8) \times 1024^3) / 1024^5 = 81 \text{ PetaByte}$
 => Reconstruction time (8x RTX 2080 TI GPUs): ~30 min.



I: image
x: voxel position
A: amplitude scan
e: emitter position
r: receiver position
c: sound speed
t: time of flight

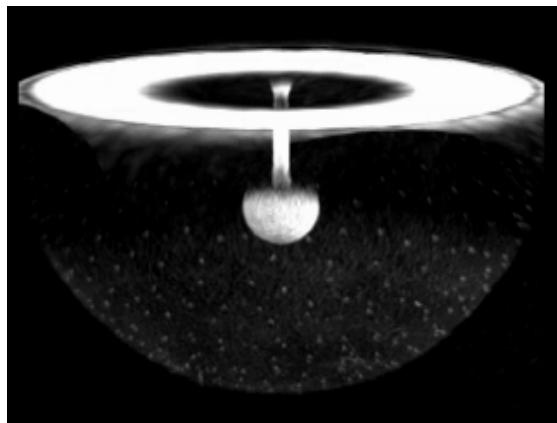
=> Clinical applicable with ~ 30min

[1] E. Kretzschmar, N. V. Ruiter, "GPU based 3D SAFT reconstruction including phase aberration," Proc. SPIE 9040, Medical Imaging 2014: Ultrasonic Imaging and Tomography, 90400W (2014)

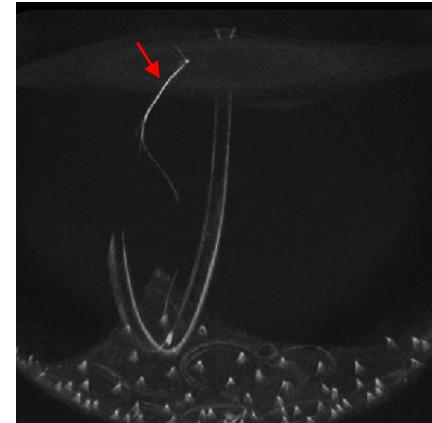
[2] E. Kretzschmar, T. Hopp, N. V. Ruiter, "GPU-based 3D SAFT reconstruction including attenuation correction," Proc. SPIE 9419, Medical Imaging 2015: Ultrasonic Imaging and Tomography, 94190E (2015)

Results: 3D Reflectivity imaging (1)

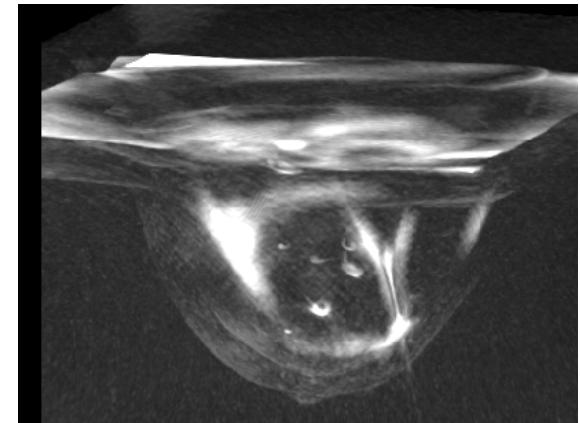
- Phantom images
 - Maximum intensity projection from 3D volume



Steel sphere



0.2 mm soldering tin wire

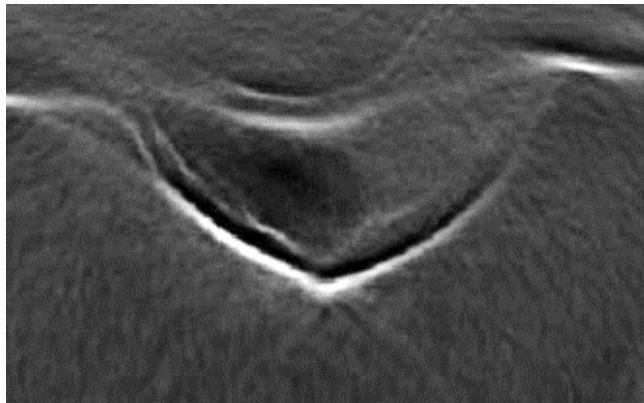


CIRS triple modality phantom

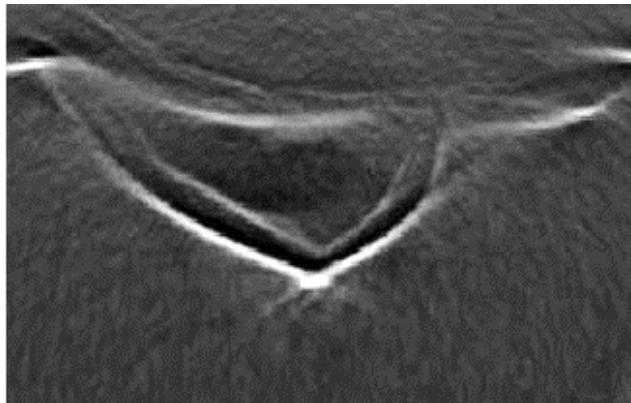
Results: 3D Reflectivity imaging (2)

- Healthy volunteer reflectivity images
 - 2D slices out of 3D volume

Transversal plane



Sagittal plane



Coronal plane

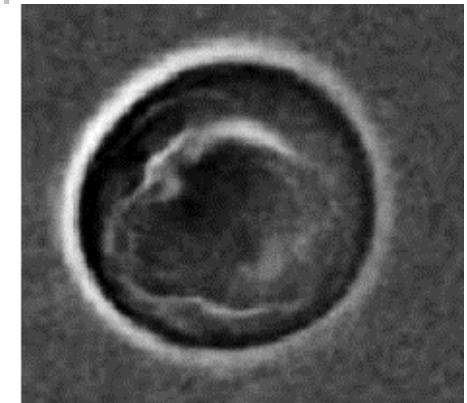


Image reconstruction: transmission

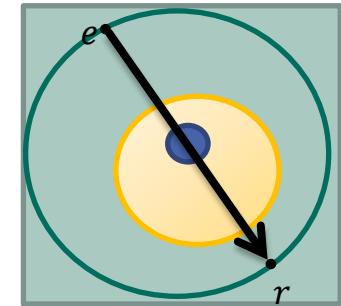
- Ray based back-projection for quantitative soundspeed or attenuation images
 - Not trivial paralizable
- Bent ray reconstruction
 - Fast marching method to update M [1]
- Algebraic Reconstruction Technique (ART)

$$t = M^{-1} / c$$

Matrix Size: 128^3 voxels $\times 10^7$ measurements $\times 8$ Byte $\Rightarrow 153$ PetaByte (dense)

- Total variation minimization (TVAL3)
- Reconstruction time: ~15 min.

=> Clinical applicable with ~ 15min



M :	system matrix
e :	emitter position
r :	receiver position
c :	sound speed
t :	time of flight

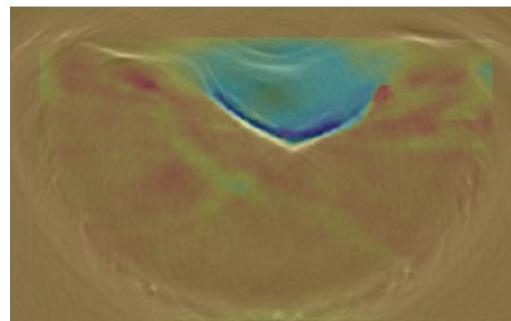
[1] R. Dapp: Abbildungsmethoden für die Brust mit einem 3D-Ultraschall-Computertomographen, Dissertation, KIT, 2013

Results: transmission image

- Healthy volunteer
- Image fusion with transmission images

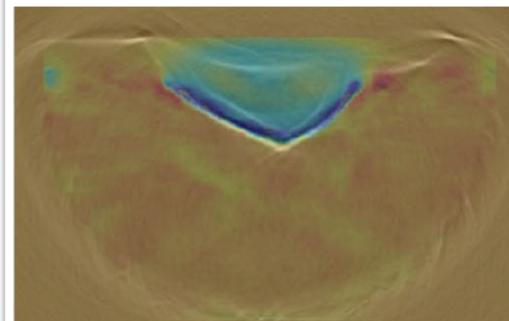
Reflectivity +
Sound speed

Transversal plane

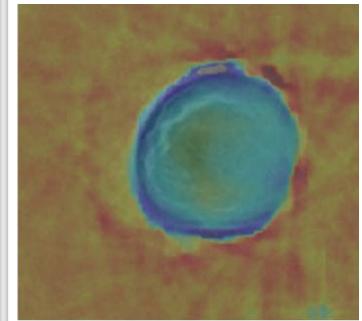


Reflectivity +
attenuation

Sagittal plane

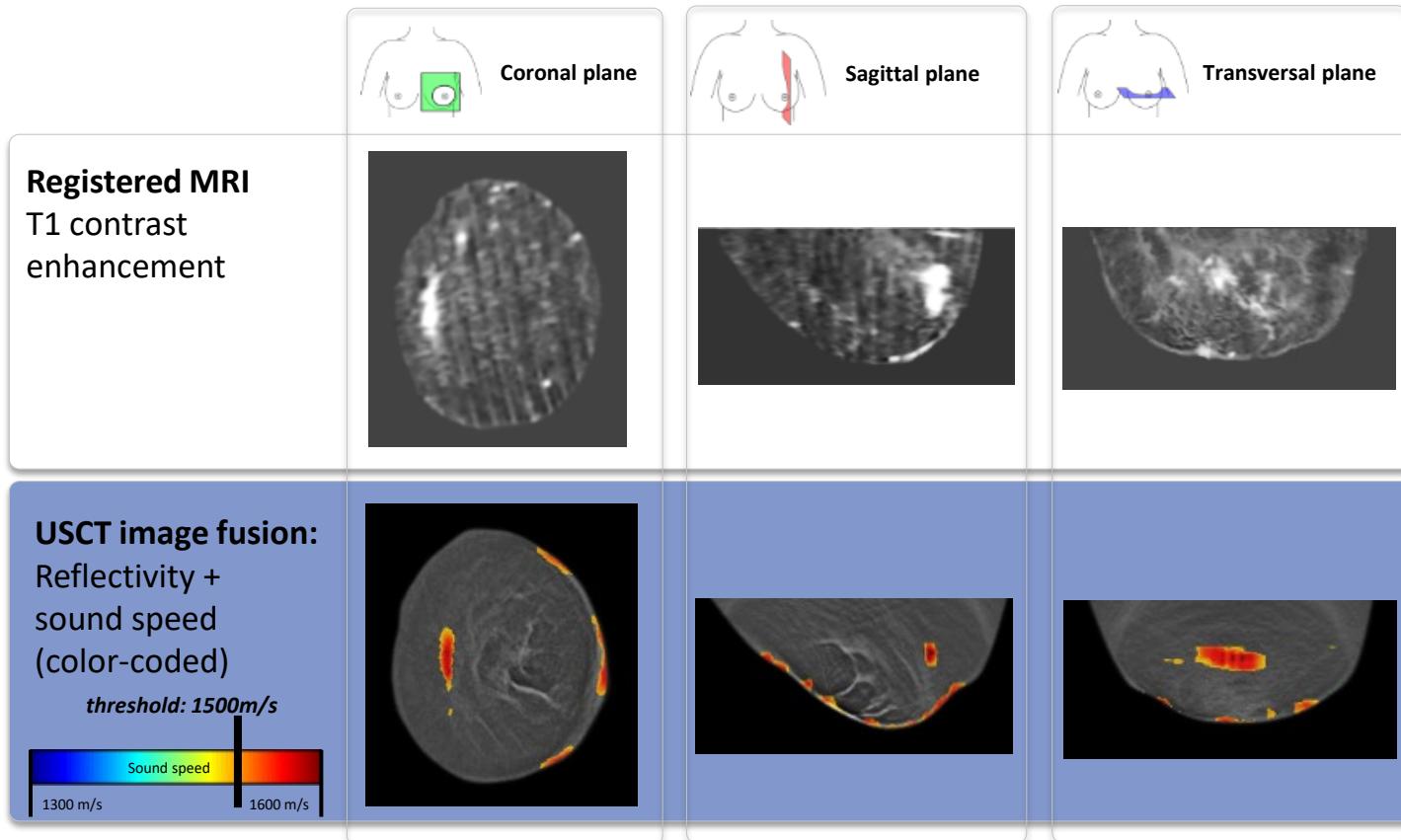


Coronal plane





Results: Clinical use case: Multicenter carcinoma



KIT 3D USCT: Status – finished?

- Not in market yet
- Collaborations and ongoing work

European
Innovation
Council



瑞康医药股份有限公司
Realcan Pharmaceutical Co., Ltd.



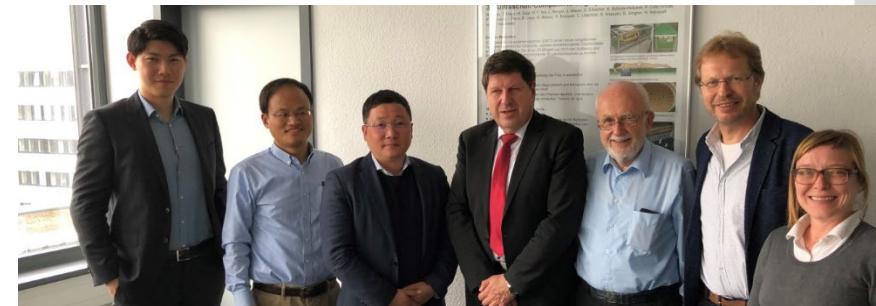
- EIC QusTom: Kick off February 2024
 - Open goals:
 - Showing clinical viability of the method
 - Showing viability of full waveform image reconstruction methods
- Equilibrium 9 Technology Transfer project (2024-25)
 - Open goals:
 - Passing chinese regulatory process and entering the Chinese Market
 - Showing viability via Multicenter study

USCT 2024: USCT Technology transfer project

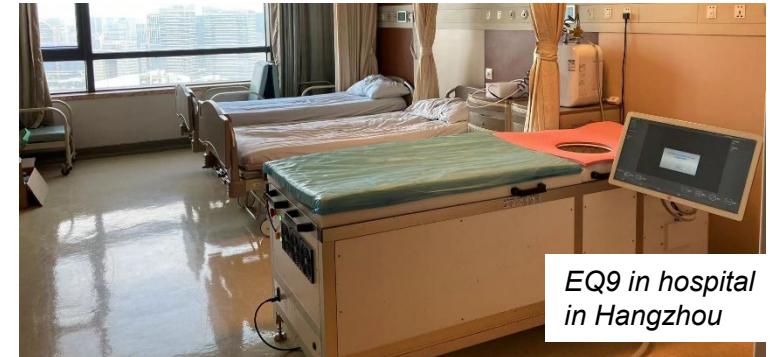


瑞康医药股份有限公司
Realcan Pharmaceutical Co., Ltd.

- Aim: 3D USCT for multi-center study in China, five USCT III, approx. 1000 patients
- Current status: Technology transfer finished (end 2023), first pre-trial in Hangzhou
- In-process 2024:
 - CFDA approval and fabrication site in Hangzhou (near Shanghai)
 - KIT supports EQ9 for study and built up of USCTs and commercialization



Zhejiang Equilibrium Nine Medical Equipment Co., Ltd



EQ9 in hospital
in Hangzhou

Status USCT 2024: QusTom Project

European
Innovation
Council



Imperial College
London



FrontWave Imaging



■ EIC Pathfinder Grant: QusTom

- Aim: 60 patient study for full 3D wave inversion reconstruction imaging
- Status: Preparations for „Kick off in Hospital“: Crunch from Nov. 23 to 9th of Feb. 2024



Preparation and packaging for transport to Spain, Barcelona

Status: QusTom Project

- Kick off: Arrival at Barcelona: 13th February 2024
 - Handover at 15th of February



Transportbox arrives at Val'd Hebron



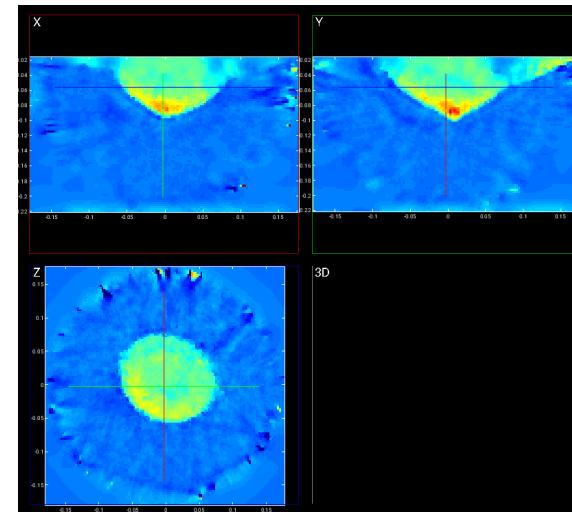
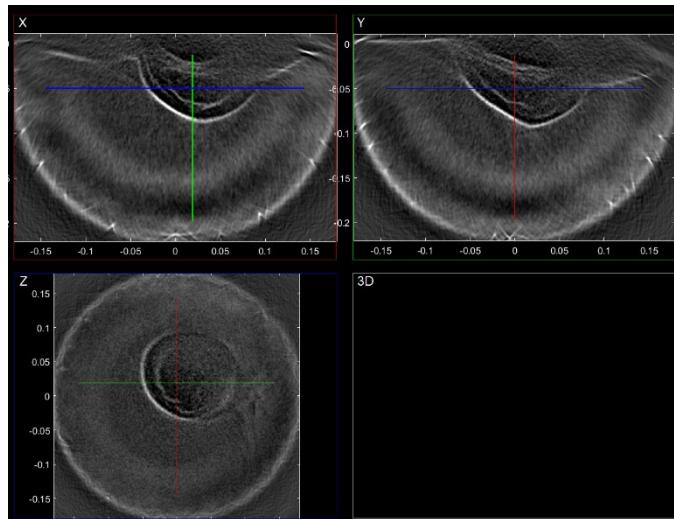
Built up and commissioning of the system



Handover to the hospital and trial coordinators

KIT 3D USCT: Status

- Current project status
 - Realizability?
 - Done
 - Clinical Viability?
 - Measurement time: 5-20min,
 - Imaging time : 30min
 - Ongoing patient & hospital studies
 - Fully realized imaging potential?



Left: 2D cuts of reflectivity imaging, Right: soundspeed of healthy volunteer P1 (2023)

Image reconstruction: Future

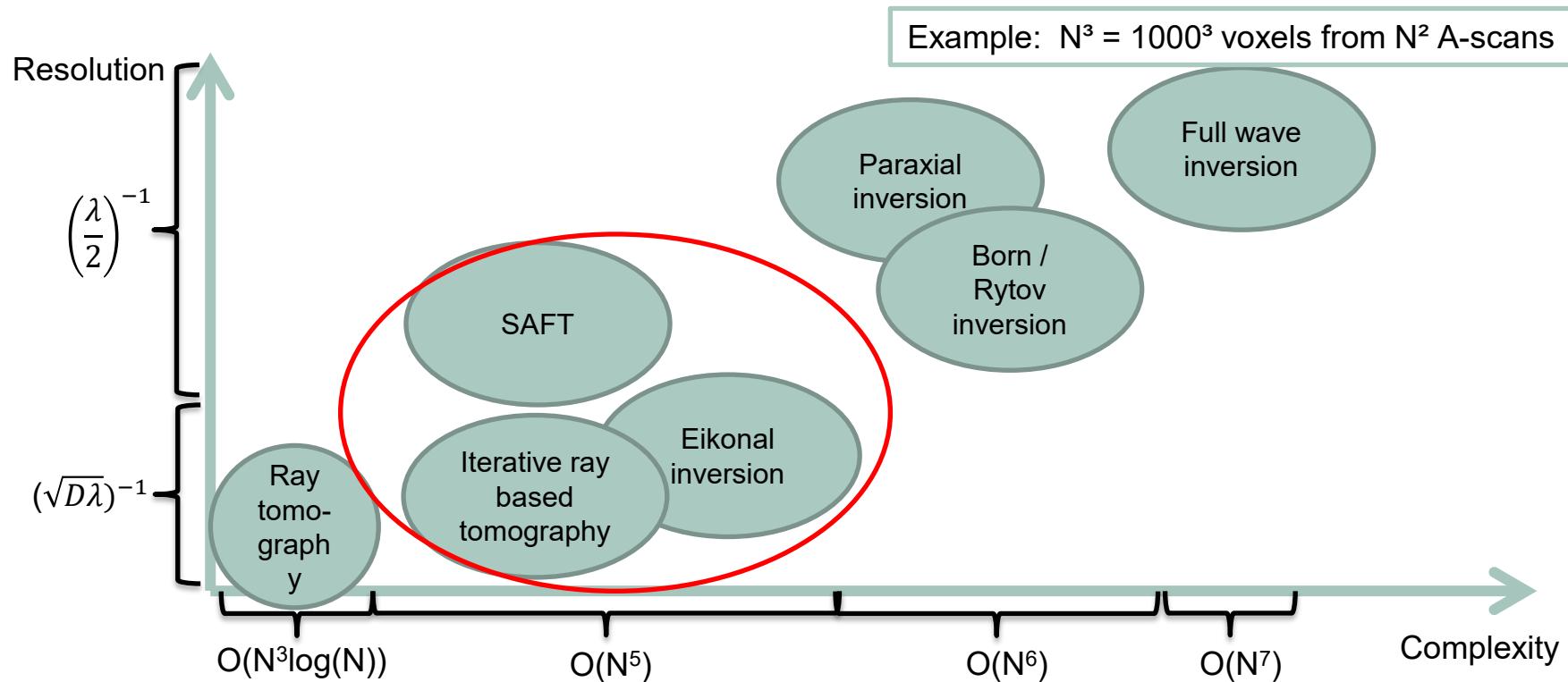


Image reconstruction: Future

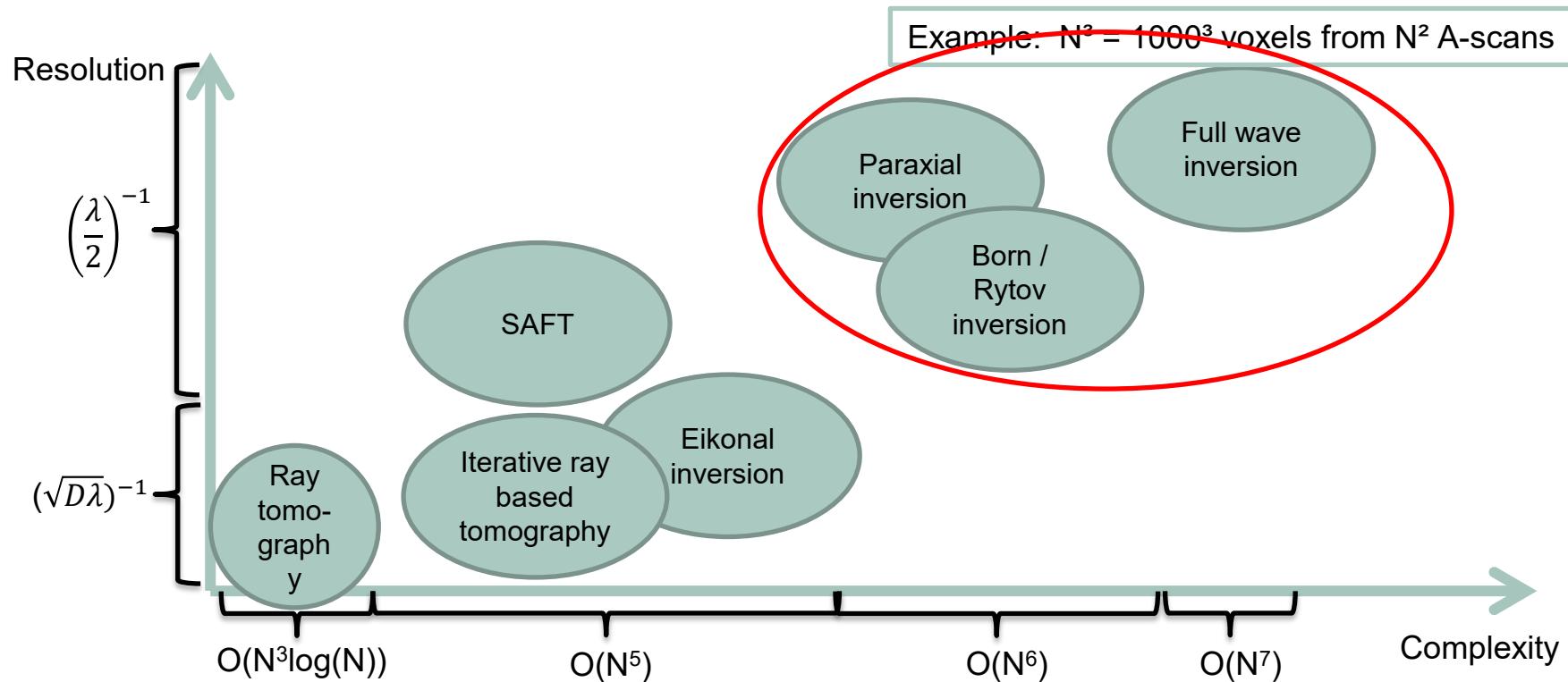
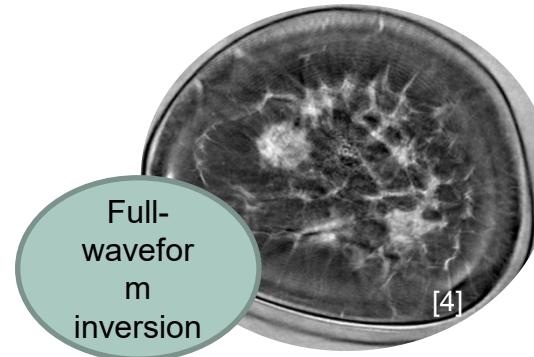
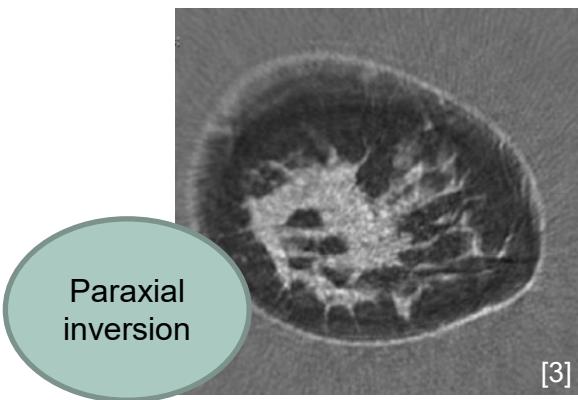
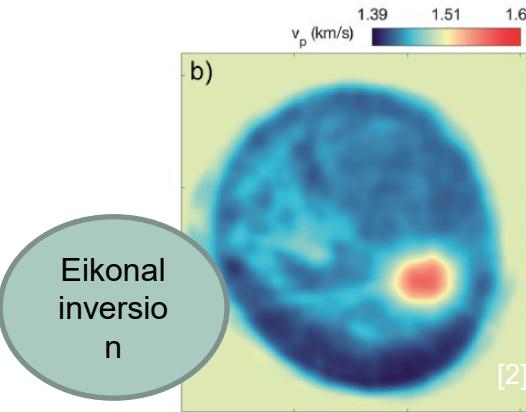
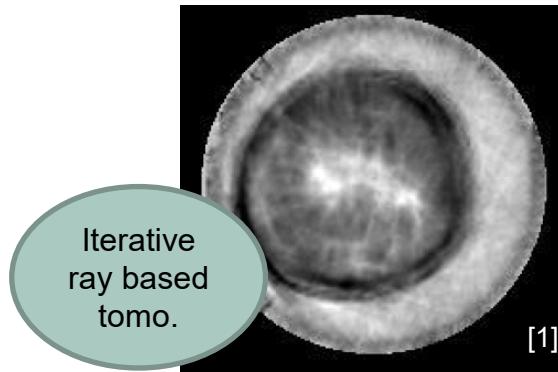




Image reconstruction: Future: 2D Speed of Sound

- More advanced methods...for quantitative imaging
 - Examples from 2D systems



[1] Li et al. Proc. SPIE Medical Imaging, 2008
[2] Agudo, et al. *Proc. of MUST*, 2017

[3] Wiskin et al. Proc. SPIE Medical Imaging, 2020
[4] Littrup, Duric, et al. *Proc. of MUST*, 2017.

Image Reconstruction: Full wave form inversion – paraxial approximation

- The spherical wave in the forward direction can be approximated by a plane wave.

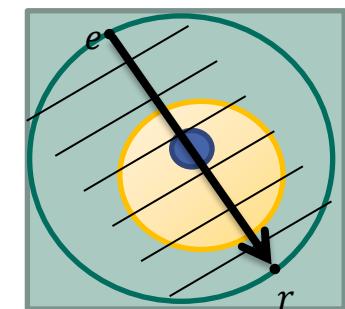
$$p = \frac{e^{-ikr}}{r}$$

$$r = \sqrt{x^2 + y^2 + z^2} = z \sqrt{1 + \frac{x^2+y^2}{z^2}}$$

Taylor series: $\sqrt{1+b} = 1 + \frac{1}{2}b + O(b^2)$

$$\Rightarrow r \approx z + \frac{x^2+y^2}{2z} \approx z \quad \text{for } x, y \ll z$$

$$\Rightarrow p_{\text{paraxial}} = \frac{e^{-ikr_{\text{paraxial}}}}{r_{\text{paraxial}}} \approx \frac{e^{-ikz}}{z}$$



M :	system matrix
e :	emitter position
r :	receiver position
c :	sound speed
t :	time of flight

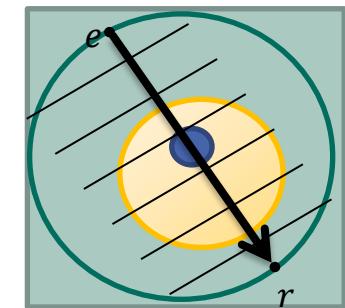
Approximation: Up to an angle of 25° between wave vector and z-axis the deviation for the amplitude is under 10 %.

Image Reconstruction: Full wave form inversion – paraxial approximation (2)

- Iterative method

$$p(x, y, z + \Delta z) = e^{-i k_0 \eta \Delta z} \ F^{-1} \left\{ e^{-ik_0 \sqrt{1 - \frac{\xi_{x,y}^2}{k_0^2}} \Delta z} \ F\{p(x, y, z)\} \right\}$$

[phase] [propagator]



- Forward model, backward, update...
- Initial pressure p_0 can be calculated analytical in homogeneous medium:

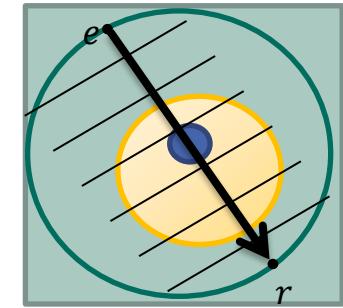
spherical wave, piston model, ...

<i>M</i> : system matrix <i>e</i> : emitter position <i>r</i> : receiver position <i>c</i> : sound speed <i>t</i> : time of flight
--

Image Reconstruction: Full wave form inversion – paraxial approximation (3)

- Iterative Scheme, sequential (not trivial parallelizable):

- Per emission, per frequency,
 - forward projection 2D plane, along Z, to receiver
 \Rightarrow Many fourier transformations
 - Per emitter: Rotation & interpolation of image domain
 \Rightarrow many rotations in image domain required
 - Matrix Inversion



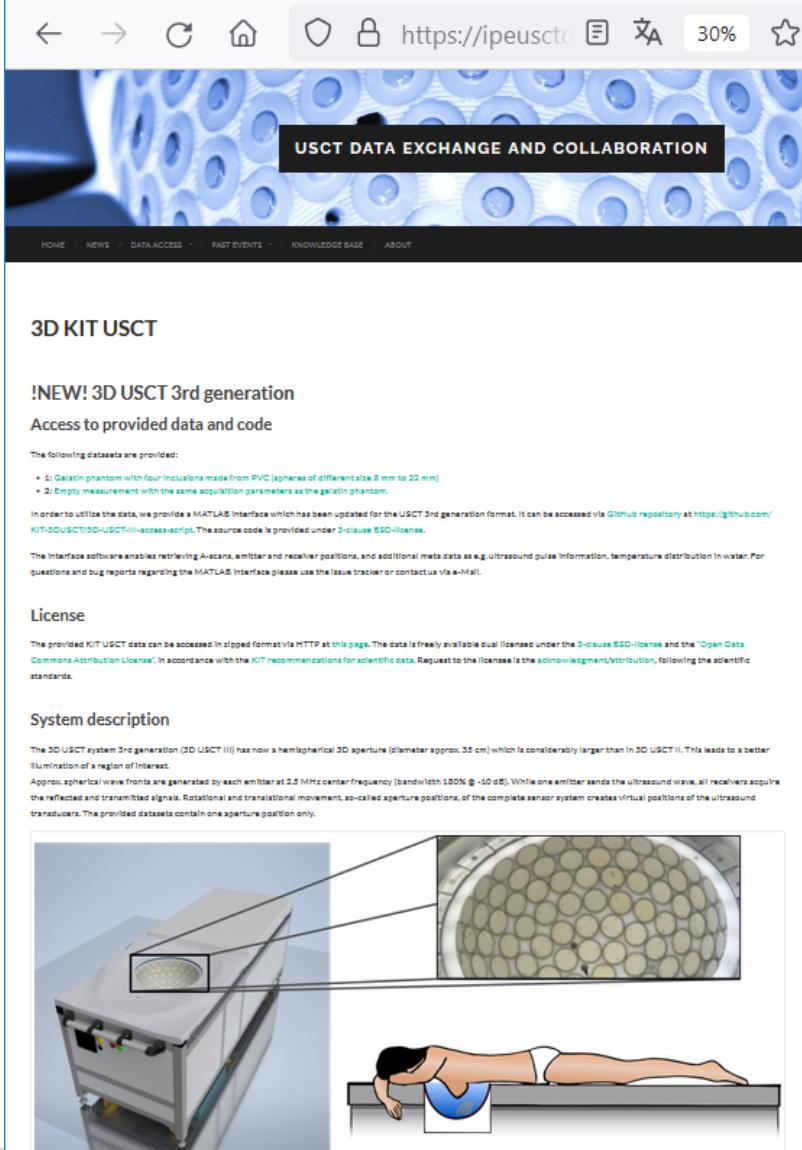
M : system matrix
 e : emitter position
 r : receiver position
 c : sound speed
 t : time of flight

- Applicability:
 - Runs for 2D subsets and < 1MHz center frequency ~ 30min
 - 3D not realized, applicability currently limited by: Memory, bulk calculation time in the many fourier transformations & rotations

Solution: Open data and open access to 3D USCT data

■ 3D KIT USCT – USCT data exchange and collaboration

- A MATLAB script with some reference imaging and visualization code:
- „3D-USCT-III-access-script“ [KIT-3DUSCT/3D-USCT-III-access-script \(github.com\)](#)
- The following datasets are provided:
 1. Gelatin phantom with four inclusions made from PVC (spheres of different size 8 mm to 22 mm)
 2. Empty measurement with the same acquisition parameters as the gelatin phantom.



The screenshot shows a web browser window displaying the "USCT DATA EXCHANGE AND COLLABORATION" page. The URL is https://ipeuscto. The page features a blue header with the title and a navigation bar with links for HOME, NEWS, DATA ACCESS, PAST EVENTS, KNOWLEDGE BASE, and ABOUT. Below the header is a large image of a gelatin phantom with four inclusions. The main content area is titled "3D KIT USCT" and includes sections for "NEW! 3D USCT 3rd generation" and "Access to provided data and code". It provides details about the datasets (Gelatin phantom with four inclusions and an empty measurement) and a GitHub repository for the MATLAB interface. The "System description" section contains a diagram showing a 3D USCT system emitting waves into a phantom containing spheres, and a patient lying on a table. A detailed caption explains the system's architecture and transducer distribution.

3D KIT USCT

NEW! 3D USCT 3rd generation

Access to provided data and code

The following datasets are provided:

- 1: Gelatin phantom with four inclusions made from PVC (spheres of different size 8 mm to 22 mm)
- 2: Empty measurement with the same acquisition parameters as the gelatin phantom.

In order to utilize the data, we provide a MATLAB Interface which has been updated for the USCT 3rd generation format. It can be accessed via [GitHub repository at https://github.com/KIT-3DUSCT/3D-USCT-III-access-script](#). The source code is provided under 3-clause BSD-license.

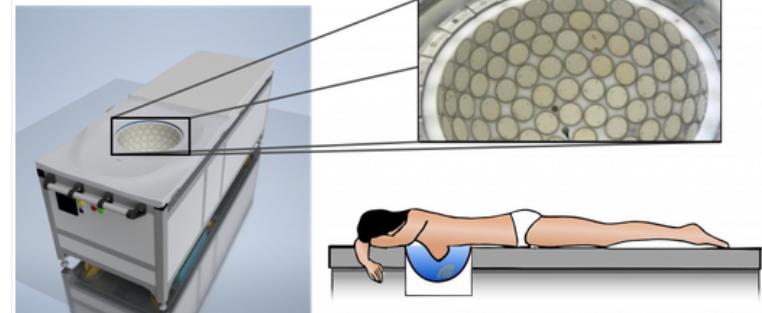
The Interface software enables retrieving A-scans, emitter and receiver positions, and additional meta data as e.g. ultrasound pulse information, temperature distribution in water. For questions and bug reports regarding the MATLAB Interface please use the issue tracker or contact us via e-Mail.

License

The provided KIT USCT data can be accessed in zipped format via [HTTP](#) at this page. The data is freely available dual licensed under the 3-clause BSD-license and the "Open Data Commons Attribution License", in accordance with the KIT recommendations for scientific data. Request to the license is the [acknowledgment/attribution](#), following the scientific standards.

System description

The 3D USCT system 3rd generation (3D USCT III) has now a hemispherical 3D aperture (diameter approx. 35 cm) which is considerably larger than in 3D USCT II. This leads to a better illumination of a region of interest. Approx. spherical wave fronts are generated by each emitter at 2.5 MHz center frequency (bandwidth 120% @ -10 dB). While one emitter sends the ultrasound wave, all receivers acquire the reflected and transmitted signals. Rotational and translational movement, so-called aperture positions, of the complete sensor system creates virtual positions of the ultrasound transducers. The provided datasets contain one aperture position only.



The system consists of 2304 individual transducers which are operated both as emitters and receivers. 10 transducers are grouped together including pre-amplifier and control electronics in so-called Transducer Array Systems (TAS), similar to USCT II. Each of the 128 TAS contains a temperature sensor for tracking the temperature distribution similar to USCT II. The transducers inside the TAS are pseudo-randomly positioned. The TAS are positioned with random rotation, leading to an overall pseudo-random distribution of transducers in the aperture.

The raw data does not contain the bandpass filtering applied in USCT II and thereby contains significantly more frequency content below 1.6 MHz. The emitters are excited with a coded excitation signal, e.g. frequency coded chirps can be applied to increase the signal-to-noise ratio of the data. Also the gain of the receiving channels is set individually based on a pre-

Meet us at MUST 2024

- Workshop on Medical Ultrasound Tomography (MUST) at 10-12 June 2024, in Amsterdam, Amsterdam Science Park, Centrum Wiskunde & Informatica (CWI)
- <https://www.cwi.nl/en/events/must-2024/>

International Workshop on Medical Ultrasound Tomography

Amsterdam, 10-12 June 2024

CWI TU/e Radboudumc university medical center



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The 4th International Workshop on Medical Ultrasound Tomography (MUST 2024)

Location: Amsterdam, NL

Dates: 10-12 June 2024

Type: In-person event

The forth edition of the International Workshop on Medical Ultrasound Tomography will be held in Amsterdam from 10th to 12th June 2024. The conference will be hosted by the [Centrum Wiskunde & Informatica \(CWI\)](#), the national research institute for mathematics and computer science in the Netherlands

MUST brings together research groups from around the globe that are engaged in the development of ultrasound tomography (UST) – an emerging medical imaging technique with immense clinical potential. The workshop is designed to be interactive and intimate, allowing for discussion, exchange of new ideas and fostering collaboration between researchers working on all parts of the development chain of UST, from mathematical modeling over image reconstruction, processing and analysis to instrumentation, clinical applications and commercialization.

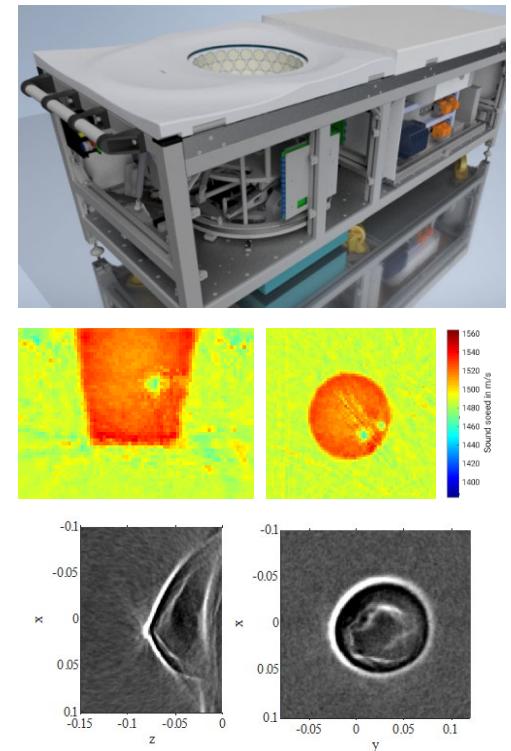
Invited Speakers

[Yonina Eldar](#) [Ben Cox](#) [Christian Böhm](#) [Richard Lopata](#)

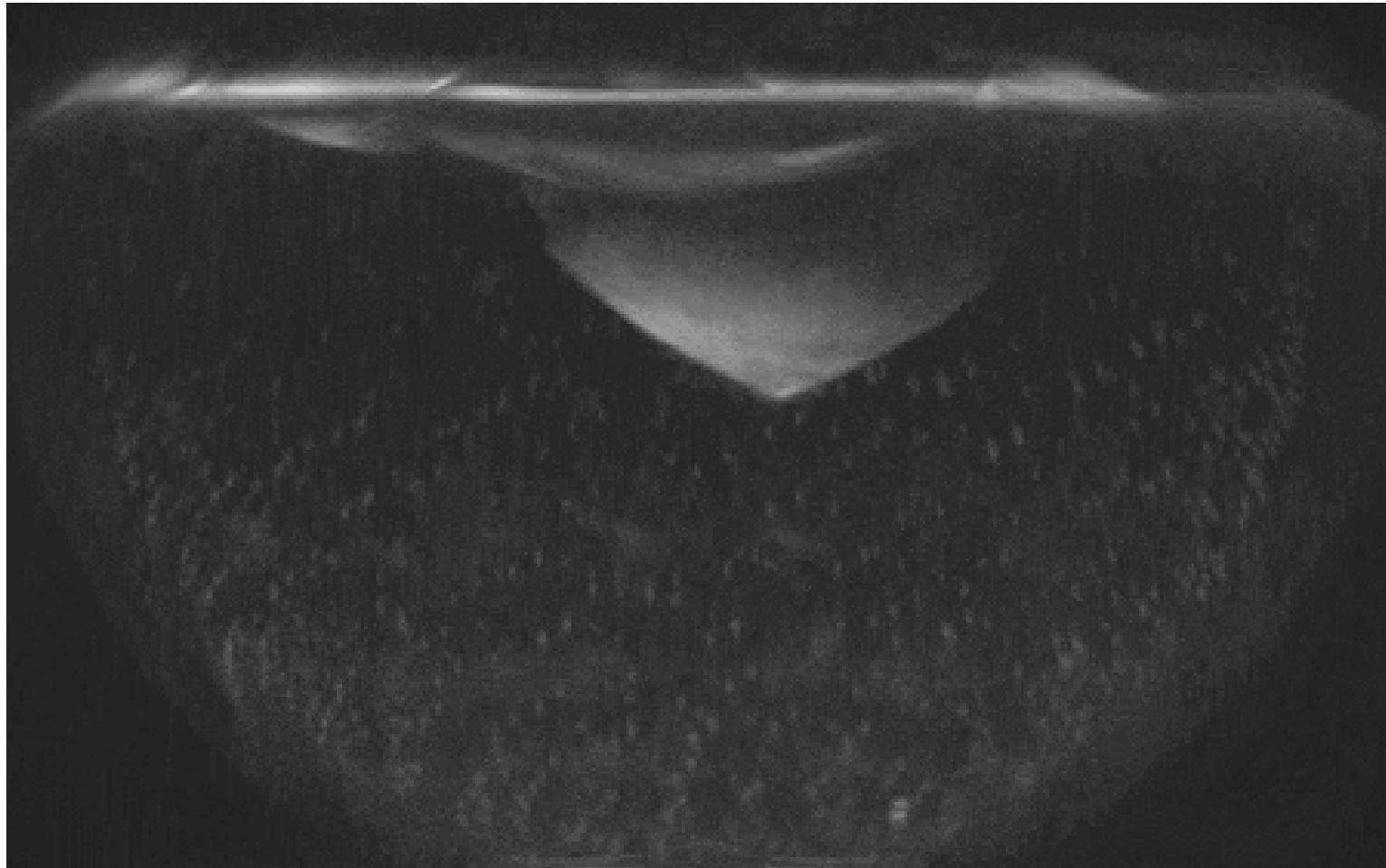


Summary

- Realizability:
 - Successful realization of KIT 3D USCT III as full 3D and multimodal ultrasound computertomography device
- Clinical viability:
 - Promising first images with phantoms and volunteers
 - Measurement time: 5-20min
 - Imaging time: 30min
 - Ongoing multicenter study
 - Ongoing steps into Chinese and European market
- Full realization of imaging potential:
 - Computational and ressource wise challenging due to **3D approach and high frequency system**
 - Paraxial currently 30min (2D), to days (3D) with low frequencies (<1MHz)



Join our data challenge!



<http://ipeusctdb1.ipe.kit.edu/~usct/challenge/>
or contact me: **michael.zapf@kit.edu**