ACES School of Electromagnetics
Online Lectures
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Microwave and Millimeter-wave Imaging in Real Time

Part 1: Applications and Data Acquisition Systems

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LECTURE OVERVIEW

Part 1: Introduction
- Applications of Microwave and mm-Wave Imaging (MMI)
- Components of MMI Systems and Their Requirements
- Data Acquisition Systems, Antennas and Antenna Arrays in MMI

Part 2: Models of Electromagnetic Scattering
- Data and State Equations
- Linearized Scattering Models

Part 3: Fourier-domain Direct Image-reconstruction Methods
- Core Concept: Data Point-spread Function (PSF)
- Quantitative Microwave Holography (QMH)
- Scattered Power Mapping (SPM)

Applications of Microwave and mm-Wave Imaging (MMI)

ADVANTAGES AND USES OF MICROWAVE OR MILLIMETER-WAVE IMAGING

- penetration into optically obscured objects (fog, clouds, foliage, soil, brick, concrete, drywalls, fabrics, living tissue…)
  - the lower the frequency the better the penetration
  - frequency bands from 300 MHz well into the mm-wave bands (≤300 GHz)
- compact relatively cheap electronics all the way up to ~80 GHz
- diverse suite of image reconstruction methods
- *long-range* (far-field) radars – well established technology used in weather, air-traffic, marine, automotive, satellite imaging (Earth and planetary observations)

Emerging New Technology: Close-range and Near-field MMI

whole body scanners

nondestructive testing

underground radar

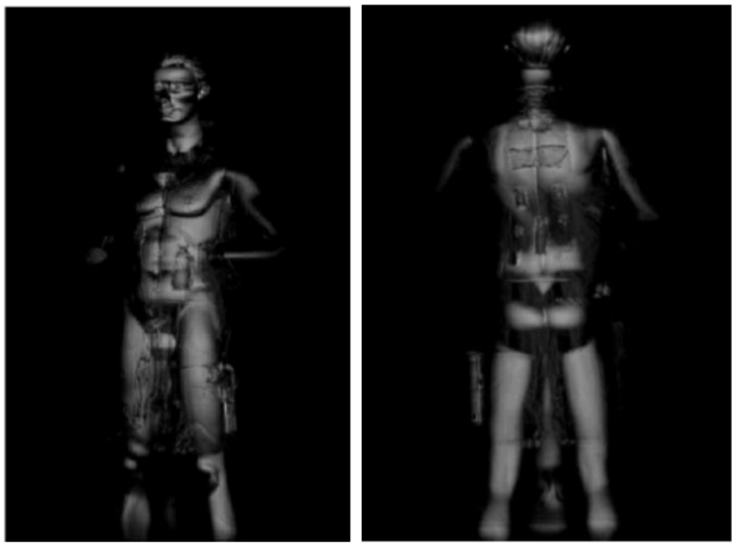
medical imaging

through-wall imaging

CLOSE-RANGE MMI SYSTEMS: WHOLE BODY SCANNERS

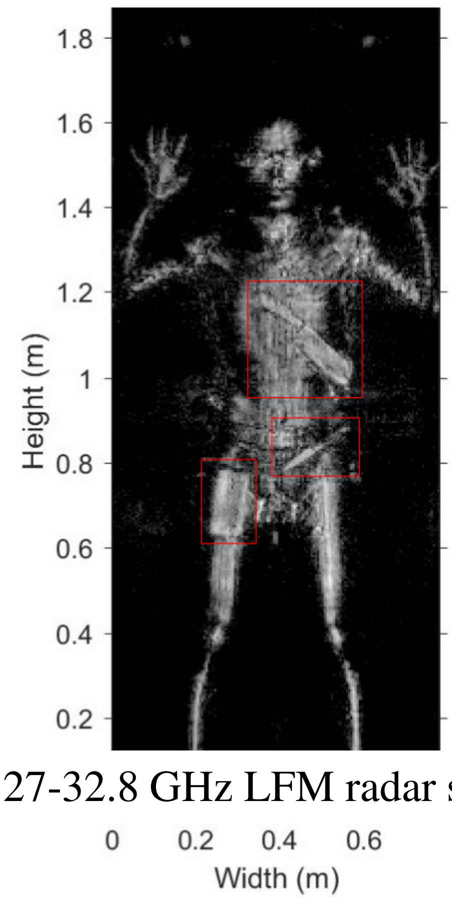
• stand-off distance to target is electrically large

[Sheen *et al.*, *Applied Optics* 2010]



40-60 GHz SFCW cylindrical scan

[Meng *et al.*, *IEEE Trans. MTT* 2020]



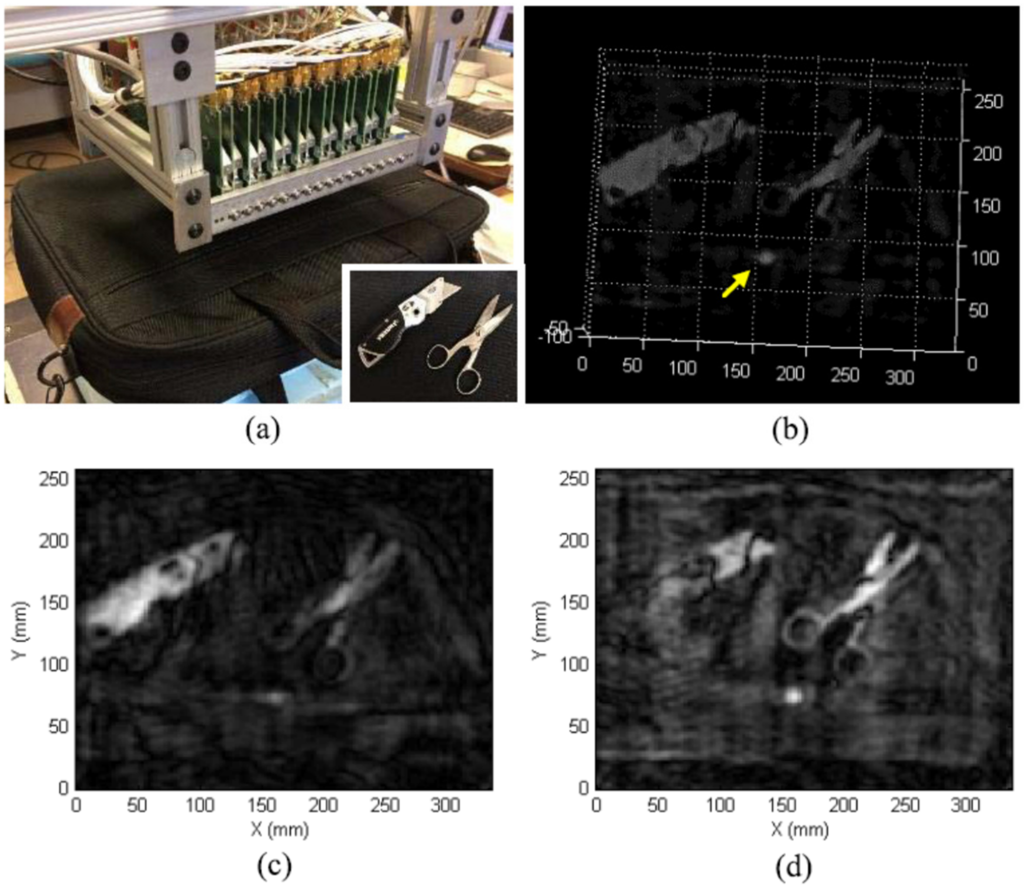
27-32.8 GHz LFM radar scan

• walk-through real-time whole-body scanners are now available

https://www.rohde-schwarz.com/us/knowledge-center/videos/revolutionizing-security-screening-with-the-qps-walk2000_251220-1500675.html

NEAR-FIELD MMI SYSTEMS: LUGGAGE INSPECTION

[Ghasr *et al.*, *IEEE Trans. AP*, 2017]



- stand-off distance to target is very small or zero

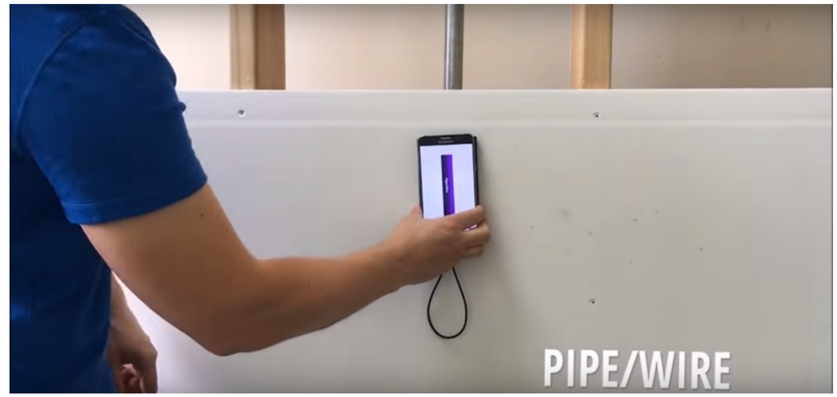
20 GHz to 30 GHz frequency range

Fig. 15. Example of video camera utility for imaging a box cutter and a pair of scissors inside a laptop bag. (a) Picture of laptop bag in front of the camera aperture with inset showing the objects inside the bag. (b) 3-D view. (c) 2-D image slice focused on the box cutter. (d) 2-D image slice focused on the pair of scissors.

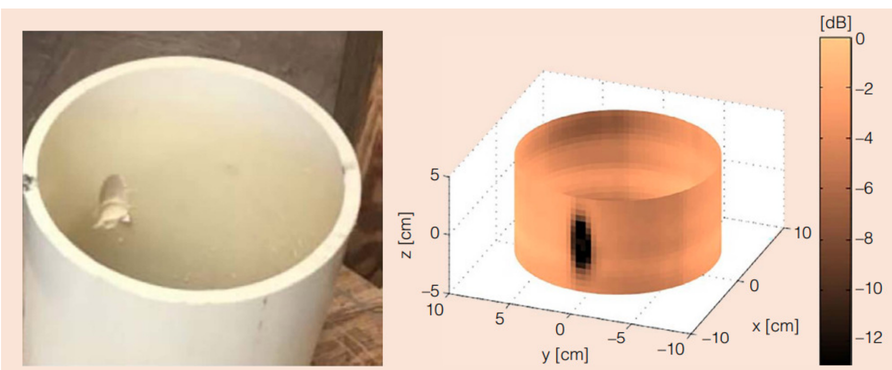
NEAR-FIELD MMI SYSTEMS: INFRASTRUCTURE INSPECTION

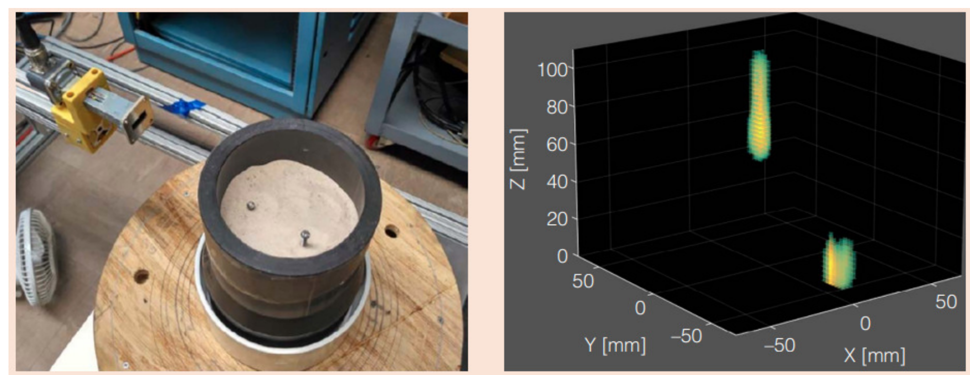
- through-wall and through-floor infrastructure inspection for contractors and home inspectors (UWB, 3 GHz to 8 GHz)
- inspection of pipes, pipelines, borehole assemblies (low-GHz range)

[https://walabot.com/diy]



[Amineh, *IEEE Instrumentation & Measurements Mag.* 2024]





8-12 GHz (X-band) SFCW cylindrical scans

NEAR-FIELD MMW IMAGING: MEDICAL DIAGNOSTICS

[Song *et al.*, *Nature Sci. Reports* 2017]

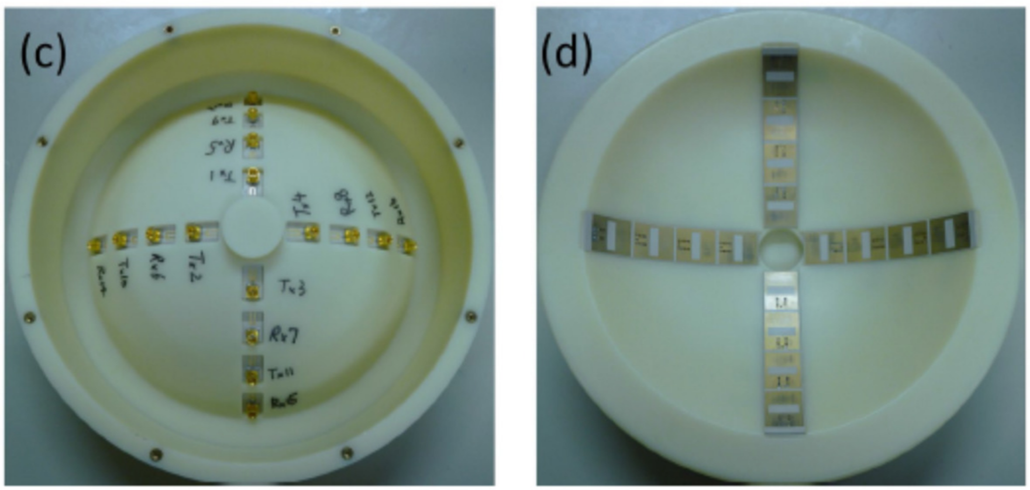


Figure 3. Dome antenna array design. (**a**) The top view of the antenna in *x*-*y* plane. (**b**) The side view of the antenna in *x*-*z* plane. (**c**) Top view photograph. (**d**) Bottom view photograph.

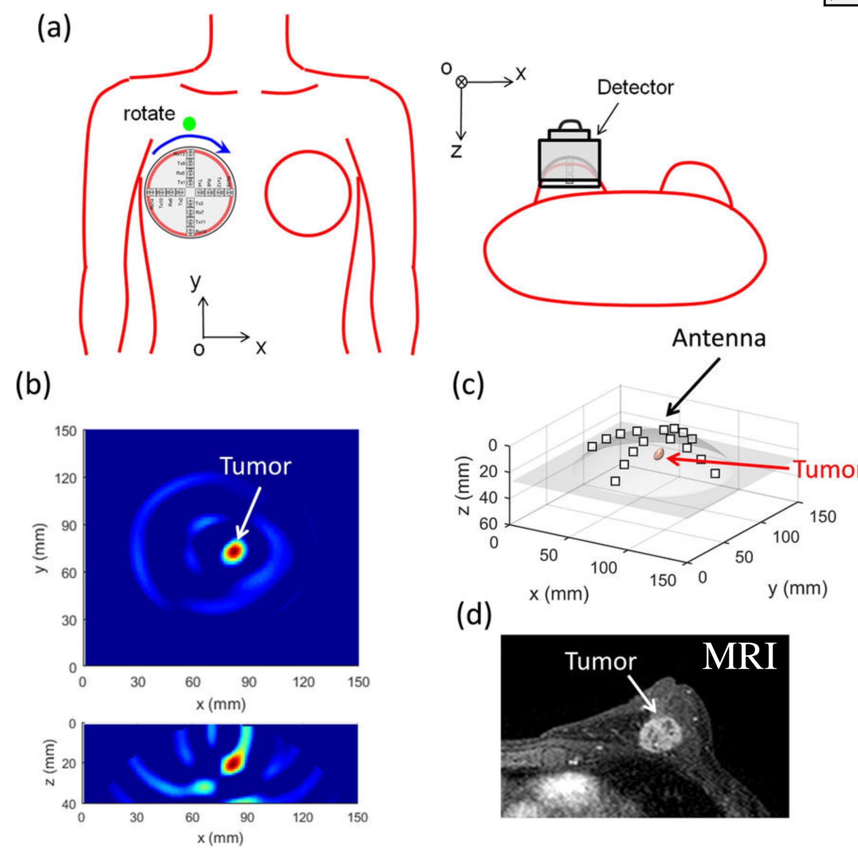
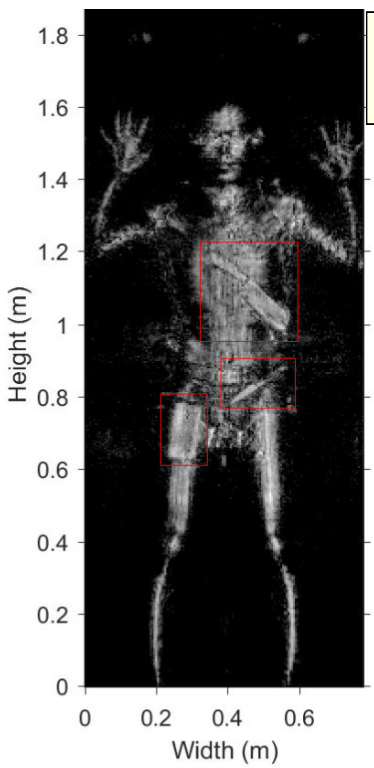


Fig. 7 in Song 2017

TYPES OF IMAGES: QUALITATIVE *vs*. QUANTITATIVE IMAGES

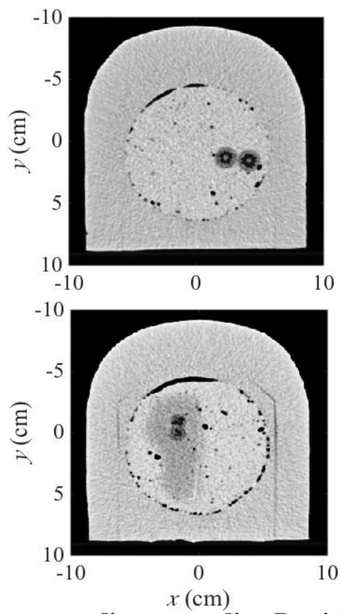
security scan with 27-32.8 GHz LFM radar

[Meng *et al.*, *IEEE Trans. MTT* 2020]



qualitative image of target reflectivity

CT Image Slices

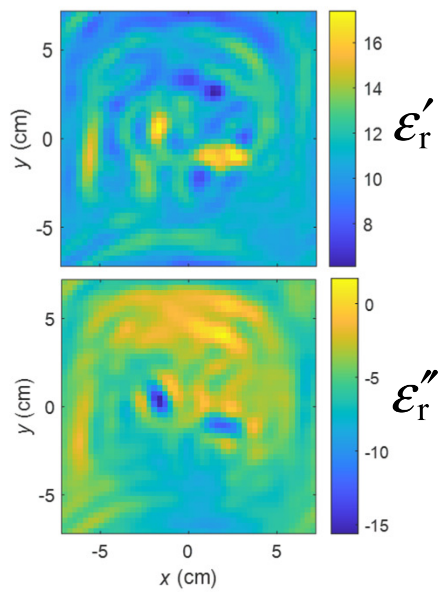


breast phantom scan (3-8 GHz SFCW radar)

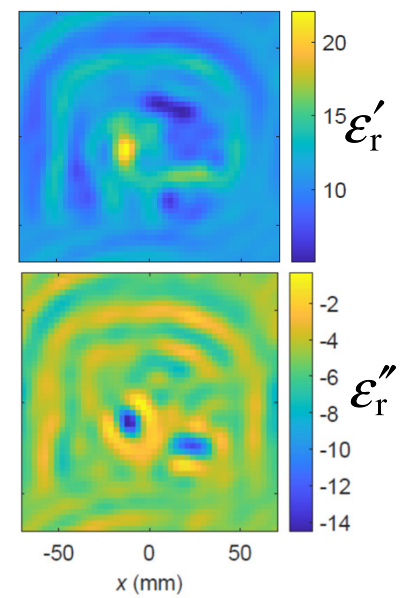
[Tajik *et al.*, *IEEE Trans. MTT* 2022]

quantitative images of complex permittivity

SPM 2D Images



QMH 2D Images



[image credits: Daniel Tajik, Romina Kazemivala]

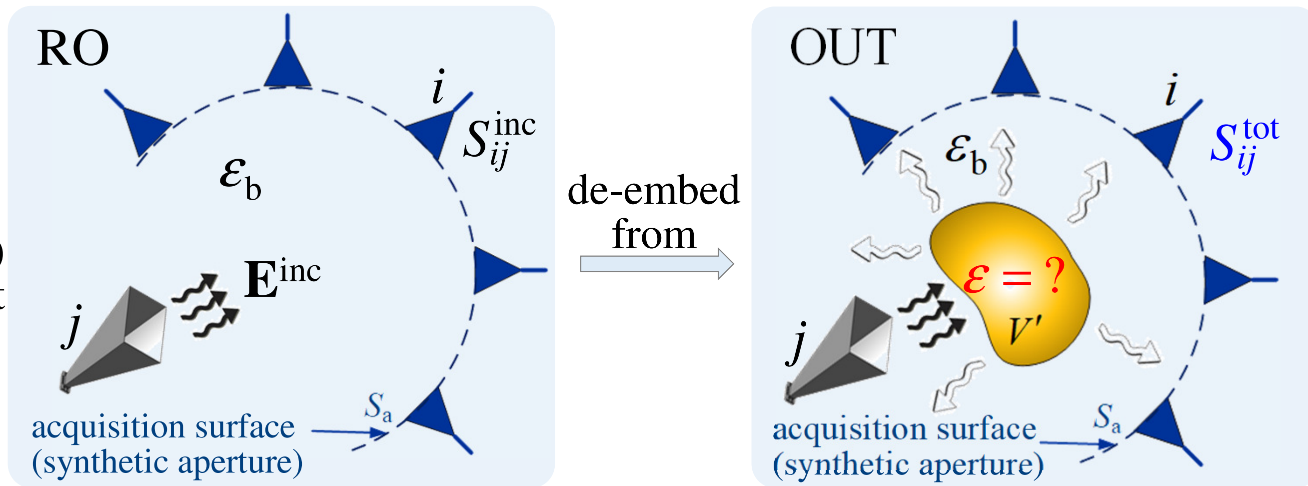
Components of the Microwave and Millimeter-wave Imaging Systems and Their Requirements

THE PRINCIPLE OF ACTIVE MICROWAVE IMAGING

- radiation penetrates and interacts with the imaged object under test (OUT)
- *scattered* waves are collected and processed to deduce the *EM property* distribution

TYPICAL BACKGROUND AND OUT MEASUREMENT PROCEDURE

background (incident-field) measurement



OUT (total-field) measurement

- scattered-field data must be extracted from total-field data (background de-embedding)

$$\underbrace{S_{ij}^{\text{sc}} = S_{ij}^{\text{tot}} - S_{ij}^{\text{inc}}}_{\text{data 1st order Born approx.}} \quad \text{or} \quad \underbrace{S_{ij}^{\text{sc}} = S_{ij}^{\text{inc}} \ln(S_{ij}^{\text{tot}} / S_{ij}^{\text{inc}})}_{\text{data 1st order Rytov approx.}}$$

[Tajik *et al.*, *PIER B* 2017]

COMPONENTS OF THE IMAGING PROCESS

MEASURED DATA: *d*

SFCW, LFM (chirp),
or pulsed radars, antennas

FORWARD MODELS:

$$\underbrace{\boldsymbol{F}(\boldsymbol{x}) = \boldsymbol{d}}_{\text{data equation}} \quad \underbrace{\mathcal{L}_{\text{ME}}\{\boldsymbol{x}, \boldsymbol{E}\} = \boldsymbol{E}}_{\text{state equations}}$$

analytical EM models
EM simulators

INVERSION STRATEGY:

$$\boldsymbol{x} = \boldsymbol{F}^{-1}\{\boldsymbol{d}\} \quad \text{subject to } \mathcal{L}_{\text{ME}}\{\boldsymbol{x}, \boldsymbol{E}\} = \boldsymbol{E}$$

linear and nonlinear solvers
deconvolution and optimization methods
sensitivity analysis

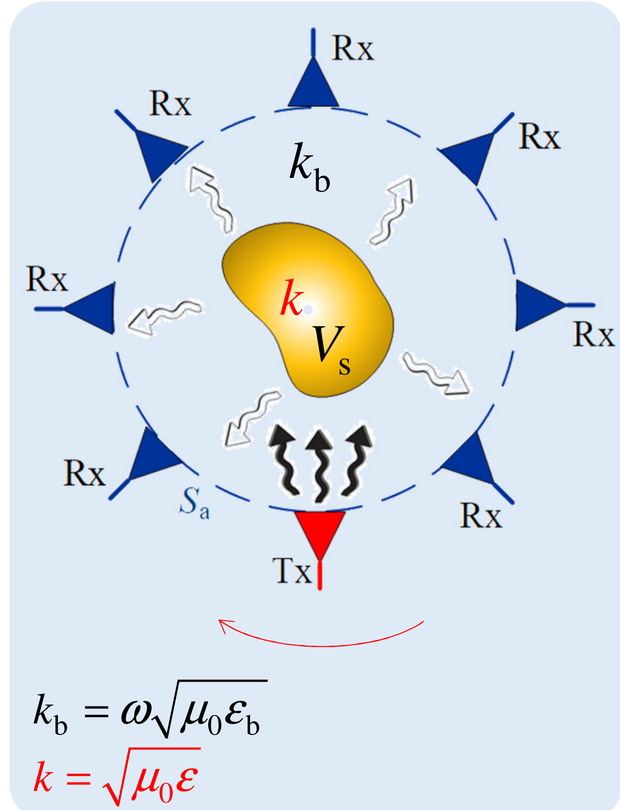
noise analysis & suppression
data filtering
image post-processing

imaging research is an intersection of engineering, math, material science and physics

DATA ACQUISITION: DATA ABUNDANCE AND DIVERSITY

Main Acquisition Requirement: **provide *abundant* and *diverse* data**

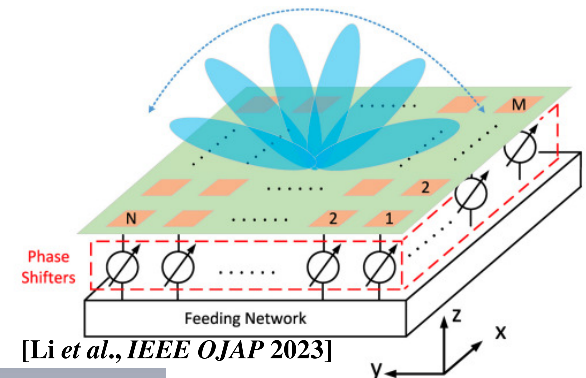
- data ***abundance*** in ($\mathbf{r}$,ω) or ($\mathbf{r}$,t) requires extensive measurements
  - ➢ illuminate target from various positions ($\mathbf{r}_{Tx}$)
  - ➢ receive at various positions ($\mathbf{r}_{Rx}$)
  - ➢ antenna scanning ($\mathbf{r}$) over aperture surfaces (planar, cylindrical, hemi-spherical): $\mathbf{r}_{Tx}(\mathbf{r})$, $\mathbf{r}_{Rx}(\mathbf{r})$
  - ➢ measure at many frequencies (ω) – wide bandwidth B



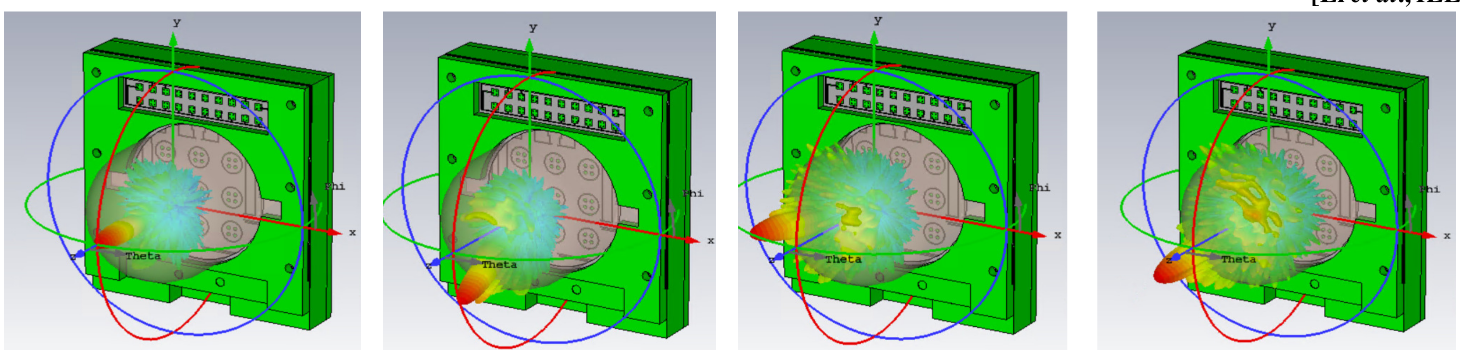
COMPARISON OF SCANNING APPROACHES

	mechanical scanning	electronic scanning
speed	low	HIGH
design complexity	LOW	high
flexibility in adjusting scan parameters	GREAT	limited

- **beam-steering (phased) arrays**: all antennas transmit or receive simultaneously under different feeding schemes – open-air measurements
- **beam-switched arrays**: antennas switched often behind a lens – open-air measurements



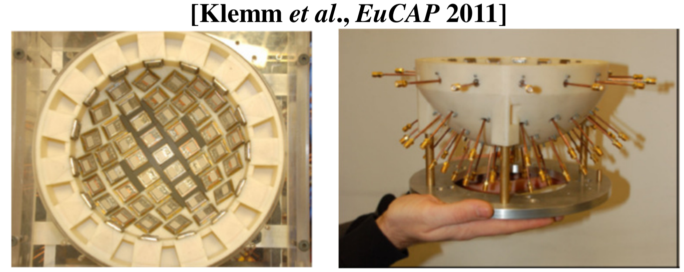
[Li *et al.*, *IEEE OJAP* 2023]



[image credits: Mohamed Akbari]

- high-density **switched arrays**: one antenna or group of antennas transmit or receive at any given measurement – near-field imaging (e.g., biomedical, NDT)

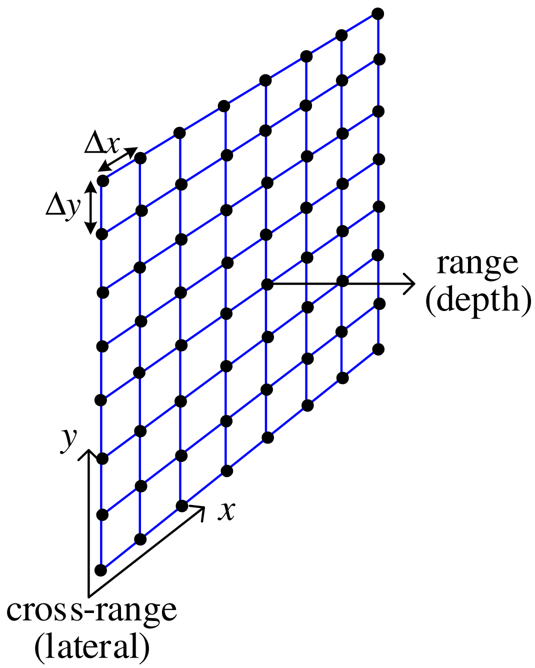
[Klemm *et al.*, *EuCAP* 2011]



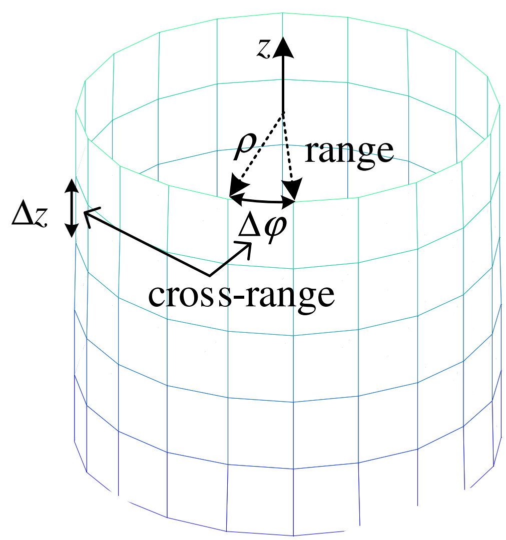
DATA ACQUISITION: SPATIAL SAMPLING OVER SYNTHETIC APERTURE

- apertures of canonical shapes with uniform grid enable fast processing through Fourier transform in *k* or *wavenumber* space

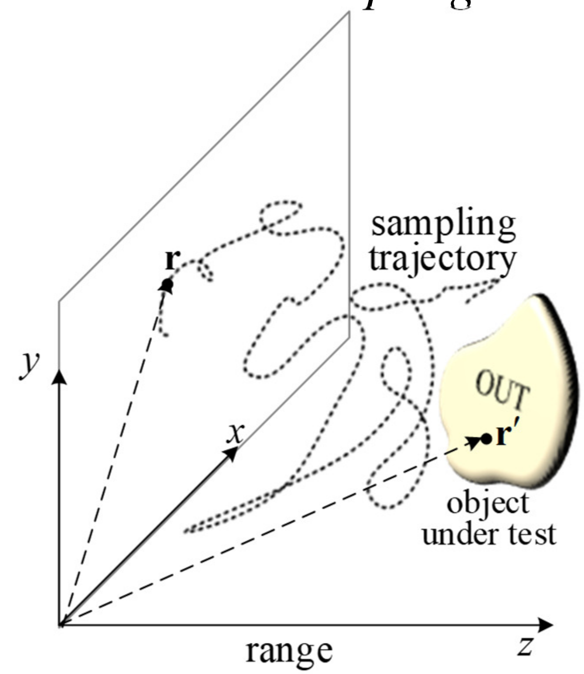
planar aperture



cylindrical aperture



random sampling



[Kazemivala *et al.*, *Sensors* 2025]

DATA ACQUISITION: SPATIAL SAMPLING

- each data sample must add independent information (diversity)
- *over-sampling* does not ensure diversity while it increases acquisition time
- *over-sampling* counteracts noise effectively in cross-correlation reconstruction methods
- *over-sampling* may lead to ill-posed inversion problem if systems of equations solved (linearly dependent data)

➢ stay below but close to the **maximum spatial sampling step** to ensure diversity

$$\Delta\xi \le \Delta\xi_{max} \approx \frac{\lambda_{min}}{4\sin\alpha}, \ \xi \equiv x, y$$

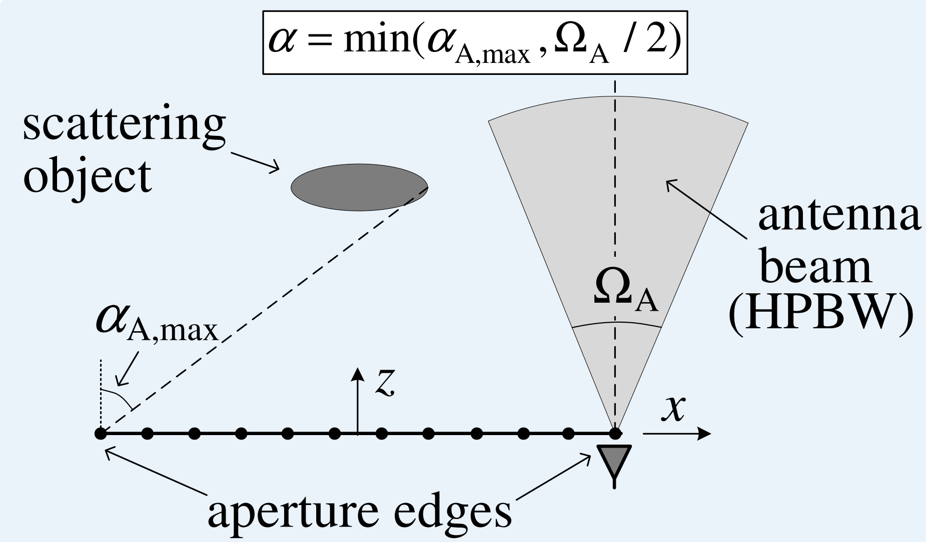


Illustration of Viewing Angle *α*

[Nikolova, *Introduction to Microwave Imaging*, 2017]

DATA ACQUISITION: FREQUENCY SAMPLING

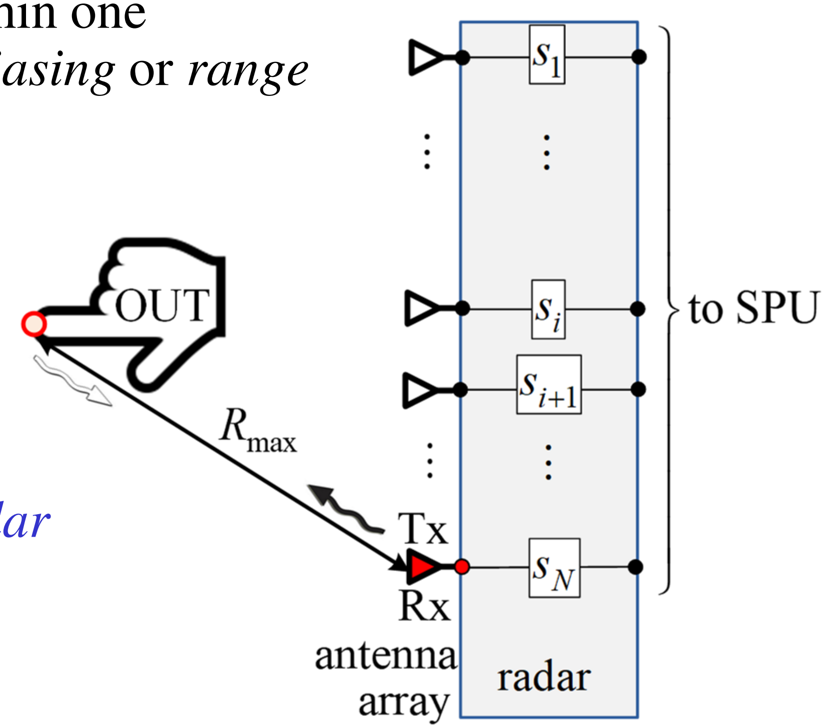
- frequency data diversity in frequency-domain measurements
  - stay below but close to the **maximum frequency sampling step** $\Delta f_{\max}$
  - $\Delta f_{\max}$ ensures that back-scattered signals from all targets within radar range $R_{\max}$ do not overlap within one observation period $[0, T_p]$ (avoids *range aliasing* or *range ambiguity*)

discrete FT relation

$$\Delta f \le \Delta f_{\max} = \frac{1}{T_p} \approx \frac{v_b}{2R_{\max}}$$

maximum range of radar

observation period



DATA ACQUISITION: TEMPORAL SAMPLING

- temporal sampling in time-domain (pulsed-radar) measurements
  - the **maximum time-sampling step** ensures that there are at least two samples within the shortest period $T_{\min}$ in the spectrum of the pulse (Nyquist sampling criterion)

$$\Delta t \le \Delta t_{\max} \approx \frac{1}{2\underbrace{f_{\max}}_{\sim B}} = \frac{T_{\min}}{2}$$

↑ *determines the image range resolution*

DATA ACQUISITION: SAMPLING RATES AND IMAGE SPATIAL RESOLUTION

[Nikolova, *Introduction to Microwave Imaging*, 2017]

- cross-range sampling steps (Δx, Δy) relate closely to the image lateral resolution (δ_x, δ_y), e.g., *Abbe's diffraction limit* with far-zone measurements

image cross-range resolution → $\delta_\xi \approx \Delta\xi_{\max} \approx \dfrac{\lambda_{\min}}{4\sin\alpha} \approx \dfrac{\lambda_{\min}}{2}, \; \xi \equiv x, y$

$\Delta\xi_{\max}$: *cross-range sampling step*; $\lambda_{\min}/2$: *rule of thumb*

- signal bandwidth B (Hz) limits the image range resolution δ_z, e.g., with back-scatter measurements

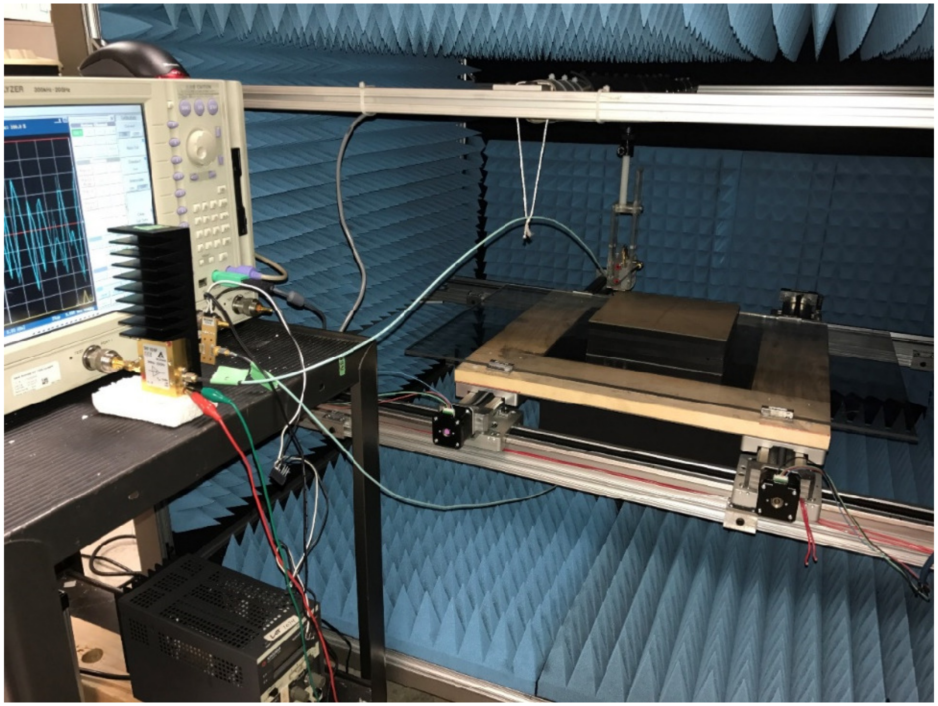
$$\delta_z \approx \frac{v_{\mathrm{b}}}{2B}$$

v_{b}: *speed of light in background*

Data Acquisition Systems, Antennas and Antenna Arrays in MMI
(with examples in breast-phantom measurements)

OUR FOCUS TODAY: REAL-TIME IMAGE RECONSTRUCTION METHODS

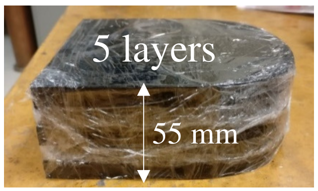
- today we will discuss fast (real-time) image reconstruction methods
  - ***quantitative microwave holography*** (QMH)
  - ***scattered power mapping*** (SPM)
- computational time for both methods ~1 s (without GPU acceleration or parallel computing) for target lateral size within ~100λ
- imaging time dictated by data acquisition (measurement scans), *not* image reconstruction ⇨



mechanical *xy* scan of a compressed-breast tissue phantom with 51×51 spatial samples and 51 frequency samples takes > 1 hour

NEAR-FIELD IMAGING OF COMPRESSED-BREAST PHANTOM (55 MM)

- proof-of-concept experiments toward microwave system for breast-cancer screening
- mechanical scan, 20×20 cm^2 ($\Delta_{x,y}$ =3 mm), 3 GHz - 8 GHz SFCW (Δ_f =100 MHz), S_{21}

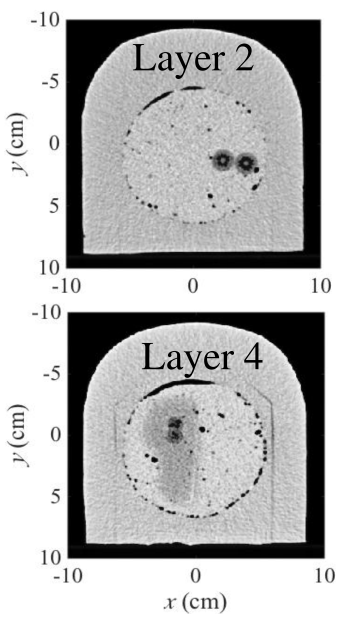


[Tajik *et al.*, *IEEE Trans. MTT* 2022]

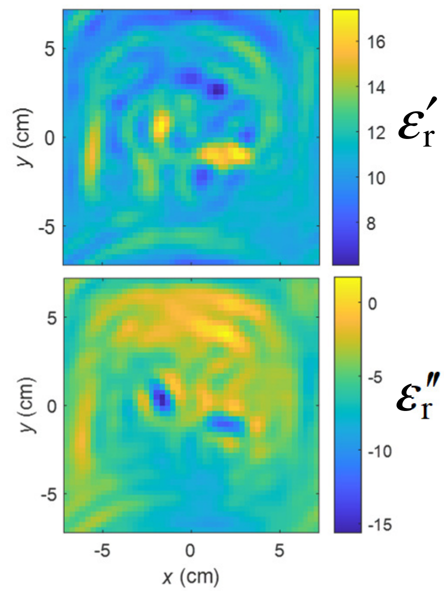
projection images of ***complex permittivity***

[image credits: Daniel Tajik, Romina Kazemivala]

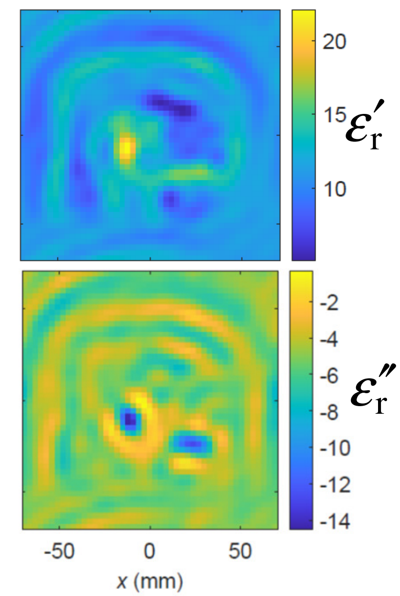
CT IMAGE SLICES



SPM 2D IMAGES

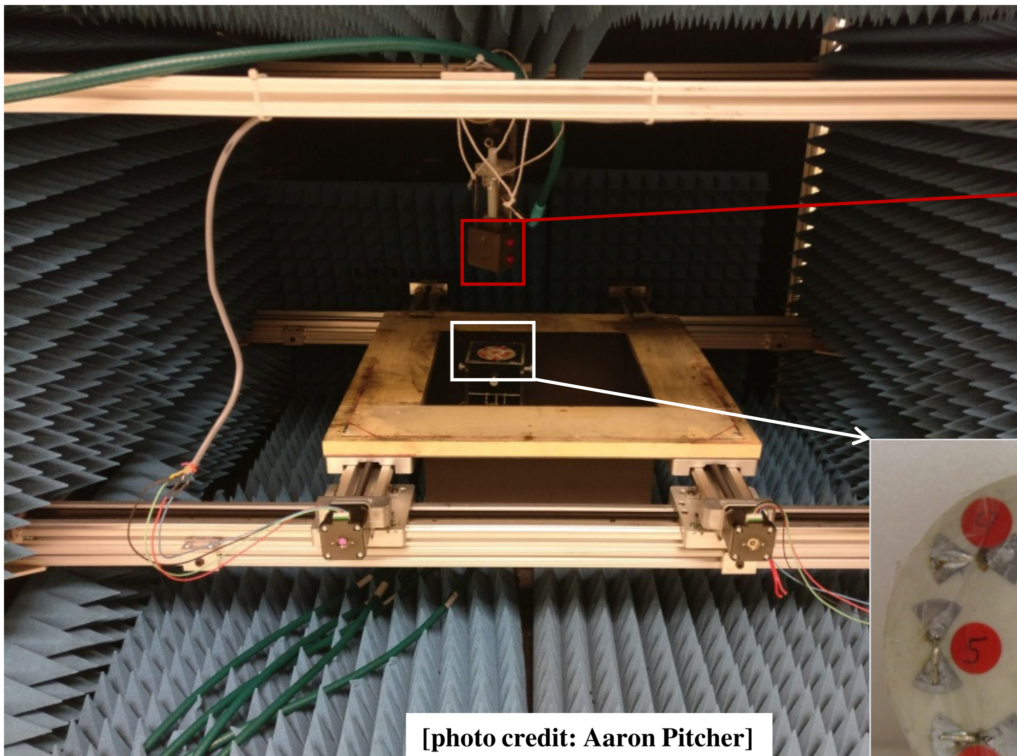


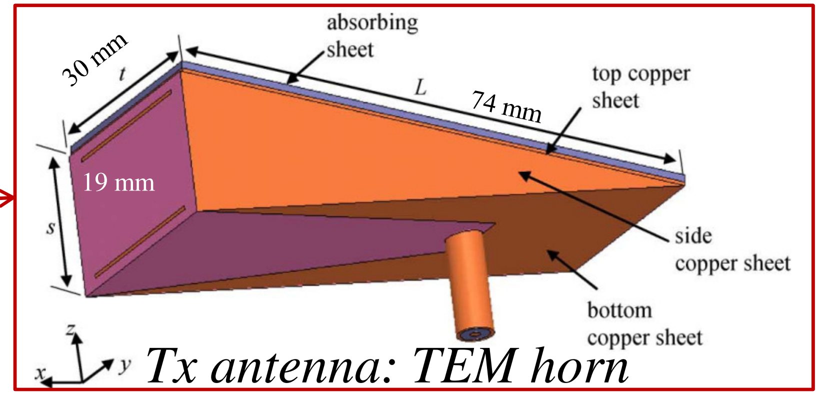
QMH 2D IMAGES



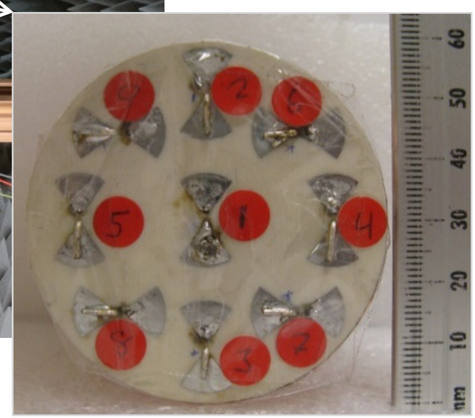
55-MM COMPRESSED-BREAST PHANTOM MEASUREMENTS: ANTENNAS

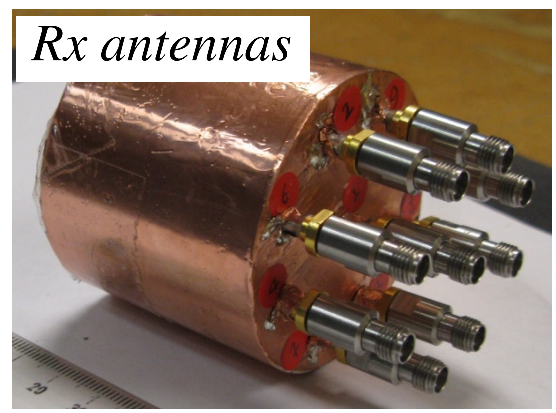
- **mechanical scanner**: easy to set up, adjustable, and allowing for large antennas
- BUT it is slow (acceptable at R&D stage)





[R.K. Amineh *et al.*, *IEEE Trans. Antennas Propag.*, 2011]

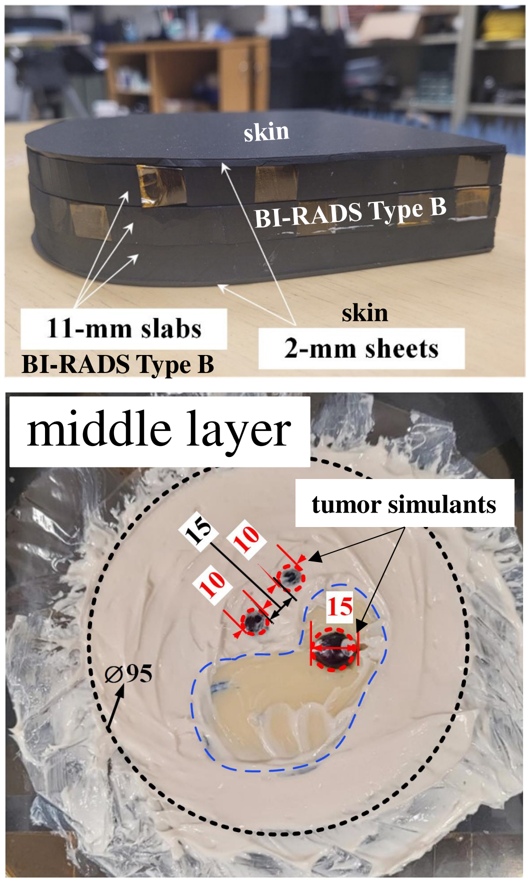


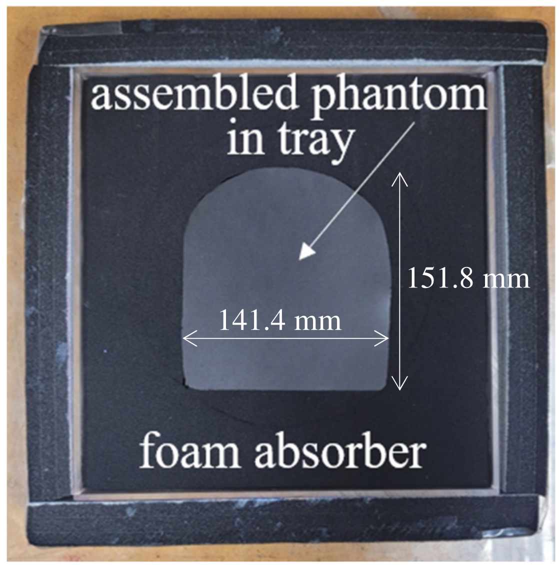


[R.K. Amineh *et al.*, *IEEE Trans. Instrum.&Meas.*, 2015]

NEAR-FIELD IMAGING OF COMPRESSED-BREAST PHANTOM (35 MM)

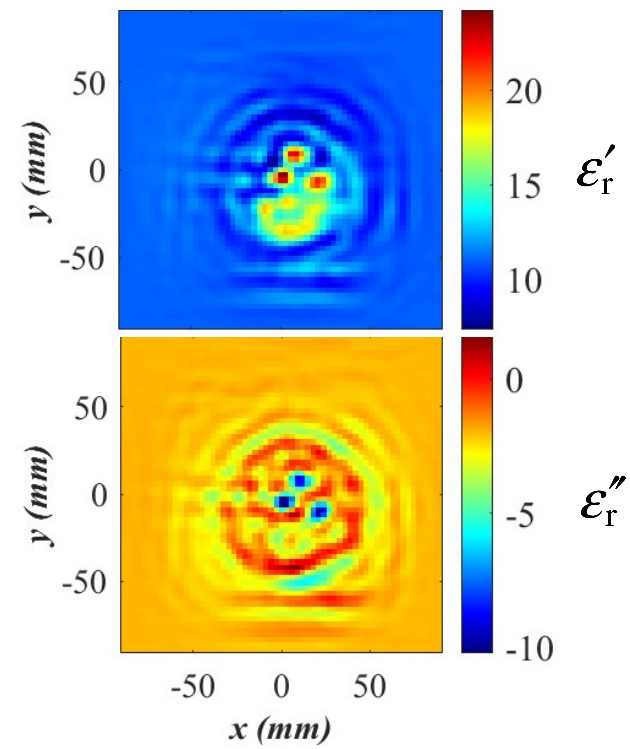
- mechanical scan, 18×18 cm^2 ($\Delta_{x,y}$ = 3 mm), 3 GHz - 8 GHz SFCW (Δ_f =100 MHz), S_{21}





projection images of ***complex permittivity***

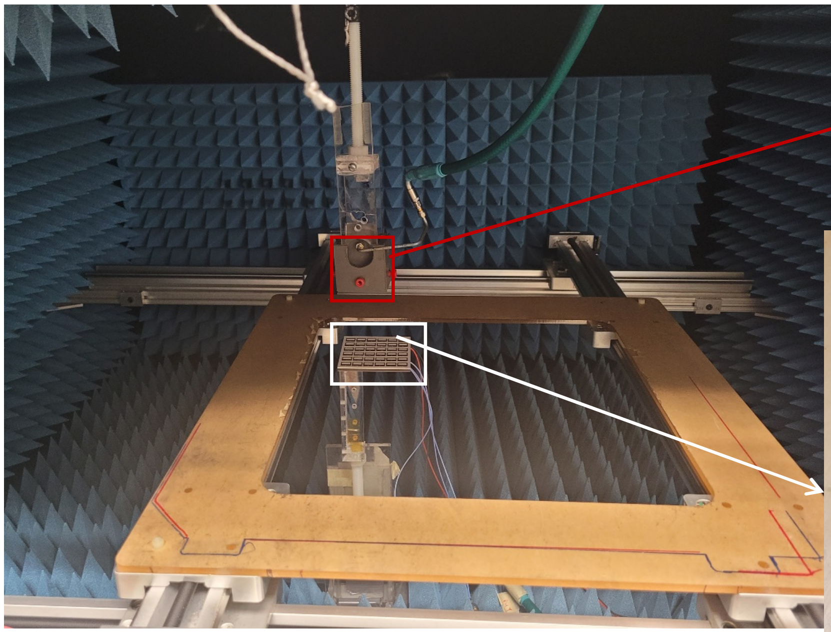
[image credits: Romina Kazemivala]



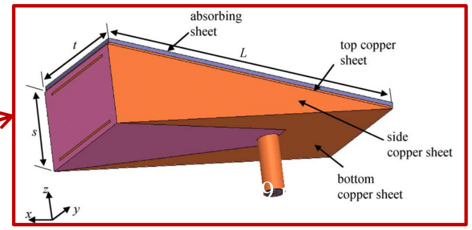
[N. Shahmirzadi *et al.*, *IEEE Trans. AP.*, 2023]
[R. Kazemivala *et al.*, *Sensors.*, 2024]

35-MM COMPRESSED-BREAST PHANTOM MEASUREMENTS: ANTENNAS

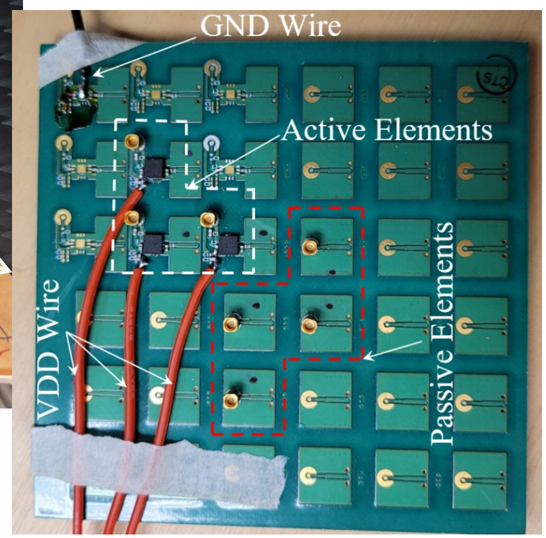
active Rx array prototype: LNA-integrated antennas

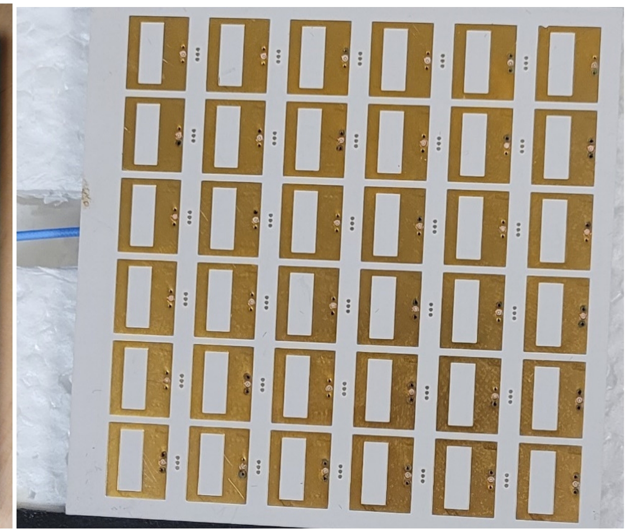


[photo credit: Nooshin V. Shahmirzadi]
[N.V. Shahmirzadi *et al.*, *IEEE Trans. Antennas Propag.*, 2023]



Tx antenna (TEM horn)





*Rx array prototype with **active** slot-antenna elements of 12×12 mm² inter-element spacing*

NEAR-FIELD QUANTITATIVE IMAGING OF THE COMPRESSED-BREAST

- proof-of-concept experiments confirm feasibility of microwave imaging of the breast with spatial resolution of ~1 cm, sufficient for the purpose of breast-cancer screening

HOWEVER

- advancement to clinical trials and clinical practice hinges on developing fast electronic scanners (*aka* imagers) with
  - high-density antenna arrays
  - low Rx noise floor and high signal dynamic range
  - MIMO capability
  - enclosures ensuring low radar clutter

SUMMARY OF PART 1

- MMW imaging serves to visualize optically obscured targets
- images may be ***qualitative*** (reflectivity images) or ***quantitative*** (permittivity images)
- imaging measurements are very different from device measurements as they realize extensive sampling in space and frequency (or time)
- sampling criteria must be observed in the design of the acquisition system

lateral sampling step

$$\Delta\xi_{\max} \approx \frac{\lambda_{\min}}{4\sin\alpha}, \ \xi \equiv x, y$$

frequency sampling step

$$\Delta f \le \Delta f_{\max} = \frac{1}{T_{\mathrm{p}}} \approx \frac{v_{\mathrm{b}}}{2R_{\max}}$$

time sampling step

$$\Delta t \le \Delta t_{\max} \approx \frac{1}{2f_{\max}} = \frac{T_{\min}}{2}$$

- lateral sampling rates and aperture size limit the image lateral resolution whereas the bandwidth B limits the image range resolution

$$\delta_{\xi} \approx \Delta\xi_{\max} \approx \frac{\lambda_{\min}}{2}, \ \xi \equiv x, y$$

$$\delta_{z} \approx \frac{v_{\mathrm{b}}}{2B}$$

SUMMARY OF PART 1, cont.

- over-sampling should be used only if it benefits the image-reconstruction algorithm (typically for noise and clutter suppression); it extends measurement time and may result in an ill-posed inverse problem
- spatial sampling is realized by mechanical or electronic scanning (or combination of the two)
- mechanical sampling is versatile and allows for large antennas
- electronic scanning is fast, but requires custom electronics and high-density arrays of miniature antenna elements

QUESTIONS?

REFERENCES

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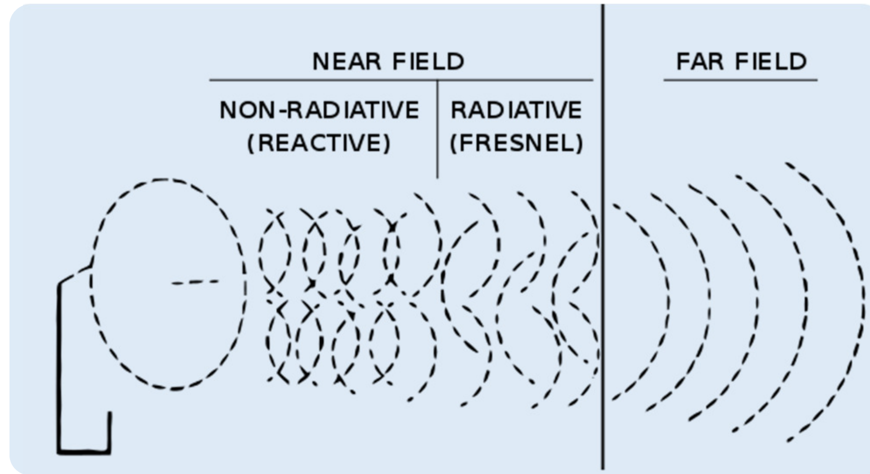
BE AWARE OF NEAR-FIELD EFFECTS IN DATA

any one of the conditions below implies near-field imaging

$$r \le \frac{2D_{\text{A,max}}^2}{\lambda}, \; r \le D_{\text{A,max}}$$

$$r \le \frac{2D_{\text{OUT,max}}^2}{\lambda}, \; r \le D_{\text{OUT,max}}$$

$$r \le \lambda$$



Goran M Djuknic - commons.wikimedia.org/w/index.php?curid=20417988

- OUT is in Tx/Rx antennas' near field
- antennas are in the OUT's near field
- <u>implication *A*</u>: ***multiple scattering & coupling between antennas and OUT***

$$S_{ik} \neq S_{ik}^{\text{inc}} + S_{ik}^{\text{sc}}$$

not valid!

- <u>implication *B*</u>: ***incident antenna fields do not conform to free-space far-zone model***

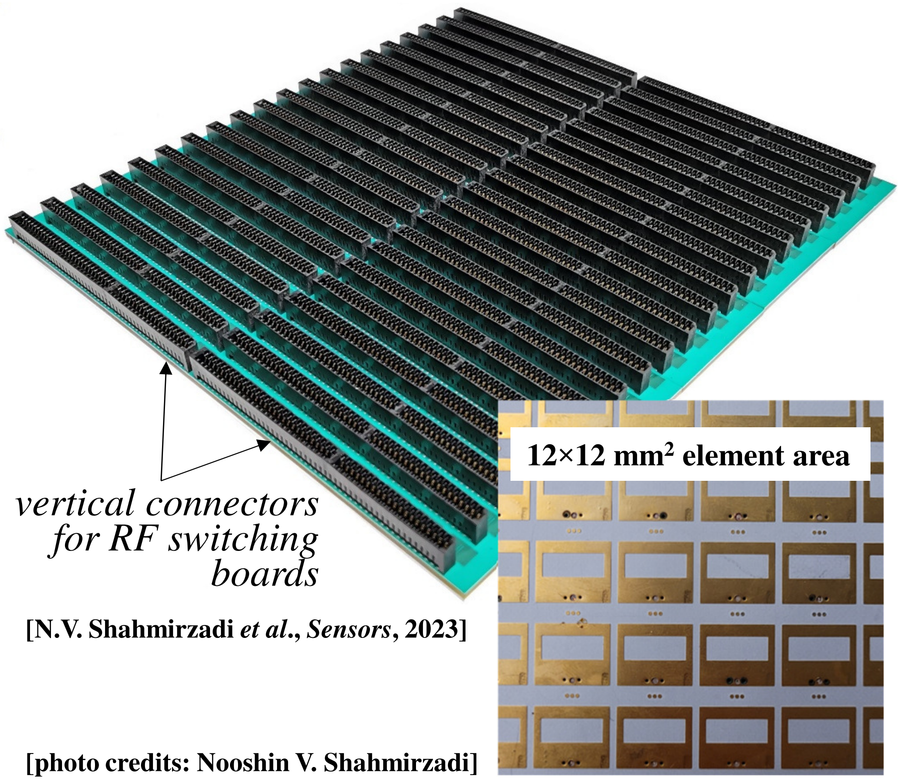
$$\mathbf{E}^{\text{inc}}(\mathbf{r}') \sim \hat{\mathbf{p}} G(\theta,\varphi) \frac{e^{-\mathrm{i}k_{\mathrm{b}} r}}{r}$$

← *not valid!*

ELECTRONICALLY SWITCHED ARRAYS FOR BREAST-CANCER SCREENING

- 3 GHz - 8 GHz antenna panels (motherboards): high-density antenna arrays (12×12 mm^2, 8×8 mm^2) connectorized with high-speed vertical connectors

16×16 3-8 GHz Tx/Rx antenna array (passive) for compressed breast imaging

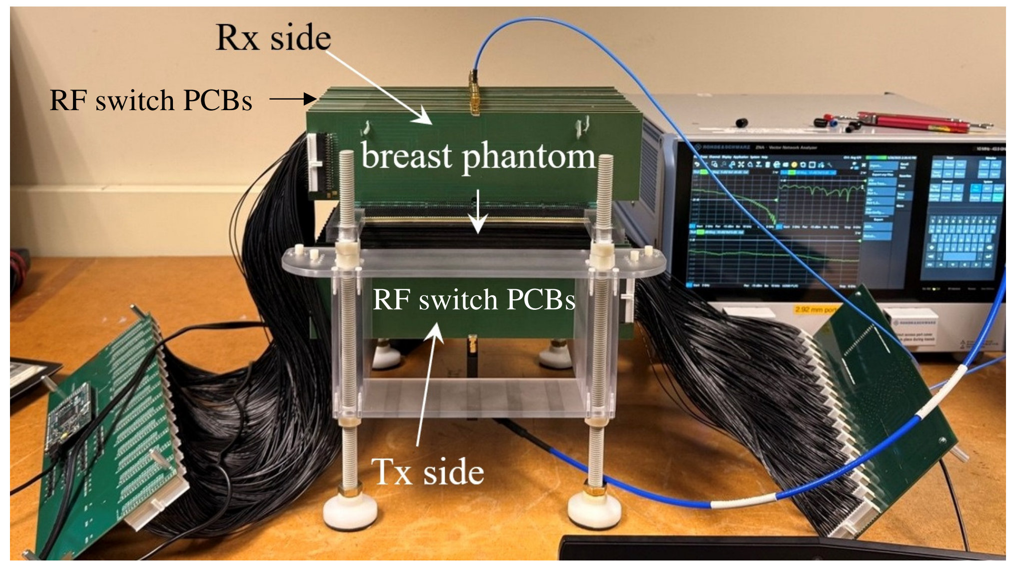


[N.V. Shahmirzadi *et al.*, *Sensors*, 2023]

[photo credits: Nooshin V. Shahmirzadi]

side facing tissue

RF-switched imager prototype



[N.V. Shahmirzadi *et al.*, *IEEE Trans. Antennas Propag.*, 2025]