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Microwave Near-field Imaging of Human Tissue: Hopes, Challenges, Outlook

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Outline

microwave imaging – emerging modality in medical imaging

imaging approaches

- **reconstruction approaches**
- **experimental setups**

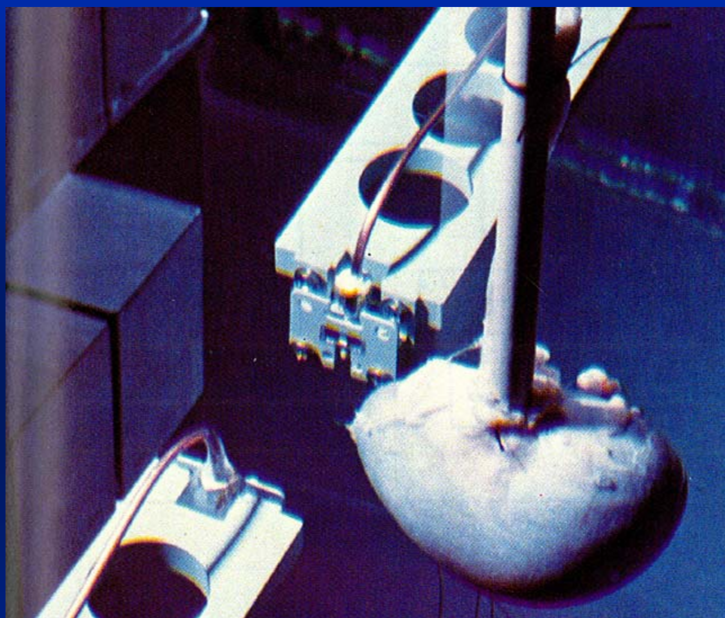
recent developments

- **sensors and phantoms**
- **data acquisition via aperture scanning**
- **real-time reconstruction approaches**

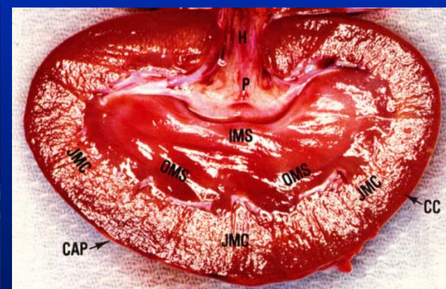
looking forward

Microwave Imaging – Emerging Modality

first systematic studies date back to 1978
[Larsen & Jacobi eds. 1986]

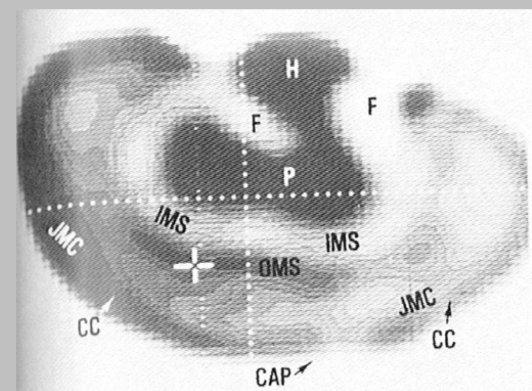


canine kidney scan in water
[Jacobi 1978]

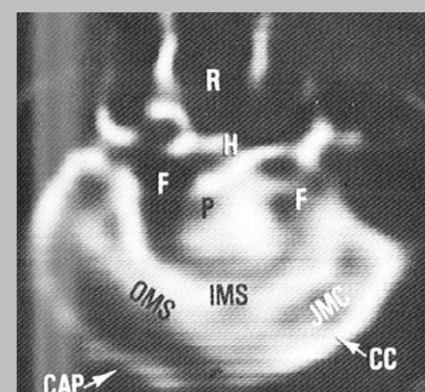


dissection

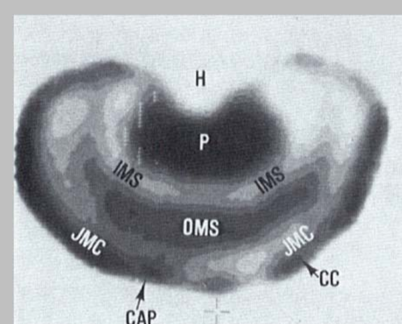
S_{21} scan, 3.9 GHz



$|S_{21}|$ co-pol



$|S_{21}|$ cross-pol



chirp-radar scan
(500 MHz to 2 GHz)

Microwave Imaging: Conclusions from Early Experiments

- resolution on the order of a centimeter
- coupling microwave energy into tissue improved by *coupling liquids*
- significant tissue heterogeneity
- significant tissue dissipation
- compromise between penetration depth (better at low frequencies) and resolution (better at high frequencies)
- optimal frequency range: 2 GHz to 8 GHz **[Lin 2005]**, 0.5 to 3 GHz **[Li 2004, Semenov 2005]**

microwaves hold promise for early-stage breast cancer diagnostics
[Sepponen 1987]

Microwave Imaging: Some Facts about Breast Cancer

[www.breastcancer.org]

- the 2nd largest cause of female cancer deaths in the US; annually: over 280,000 diagnosed, about 39,500 dying; incidence among women: 1 in 8 [ACS 2011]
- early-stage (below 1.5 cm) detection is crucial (> 90% survival rate)
- current modalities are not satisfactory
  - mammography: the standard, high false-negative rate (~15%), ionizing, discomfort due to compression
  - MRI: not suitable for mass screening, high false-positive rate, contrast agent required
  - ultrasound: low specificity, operator dependent

Advantages of Microwave Imaging

advantages of microwave technology in cancer diagnostics

- safe: non-ionizing and very low SAR (frequent check-ups)
- no need for significant breast compression
- relatively cheap compact technology (deployment in GP offices)

other applications of near-field microwave imaging

- security surveillance (concealed weapon detection)
- underground surveillance
- nondestructive testing and evaluation

cnn.com

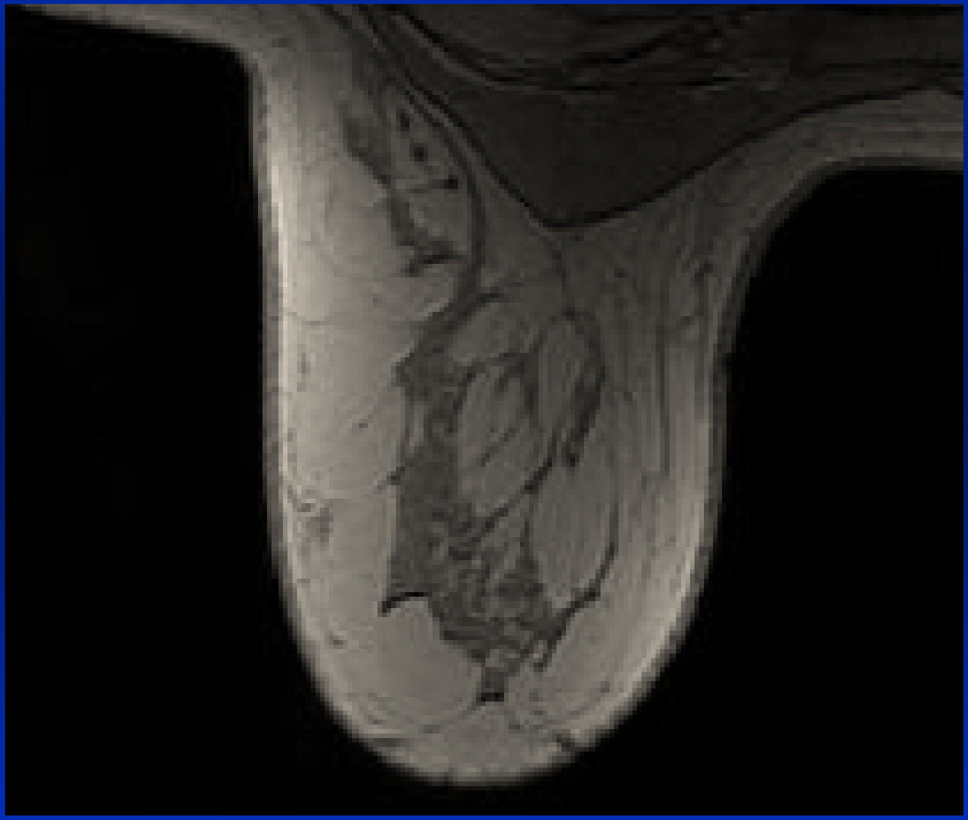
Breast Tissue Constitutive Parameters

[Lazebnik 2007, Halter 2009]

- 5 major tissue types: skin, muscle, adipose (fat), fibro-glandular (FG), cancerous (benign, malignant)
- adipose tissue features the lowest ε_r and σ ($\varepsilon_r \approx 4$ to 6 and $\sigma \approx 0.2$ S/m @ 3 GHz) while tumors feature the highest values ($\varepsilon_r \approx 44$ to 59 and $\sigma \approx 2.5$ to 3 S/m @ 3 GHz)
- low contrast between FG tissue and tumors ($\approx$ 10% in ε_r, up to 100% in σ, still under investigation); FG tissue is the place where most cancers appear **[Lazebnik 2007, Poplack 2007, Halter 2009]**
- significant frequency dispersion

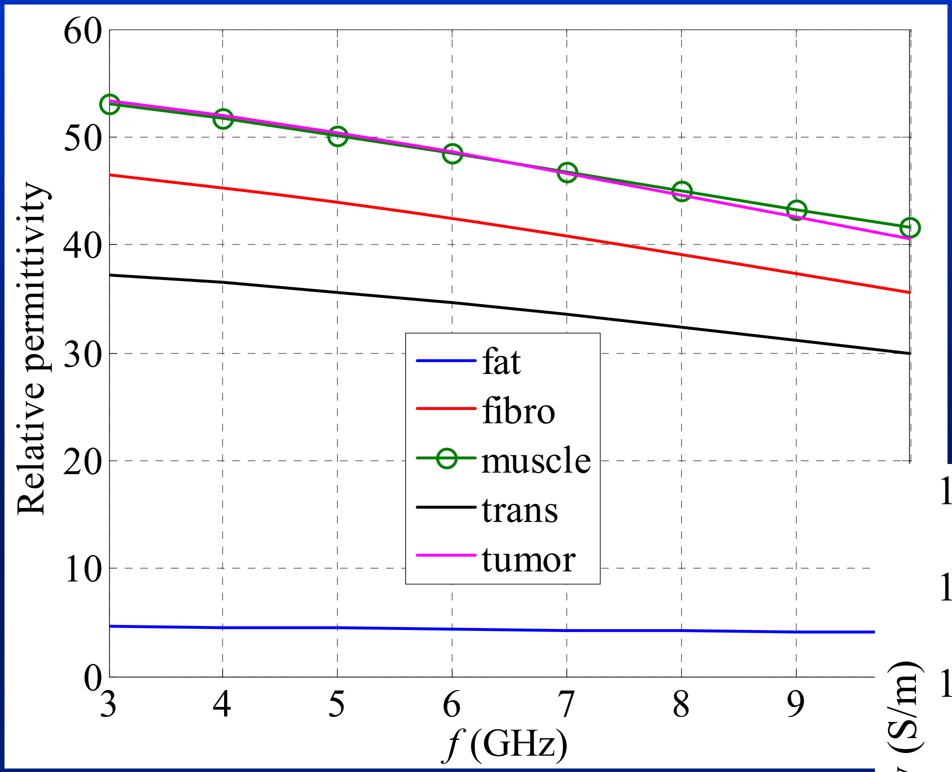
Breast Tissue Heterogeneity

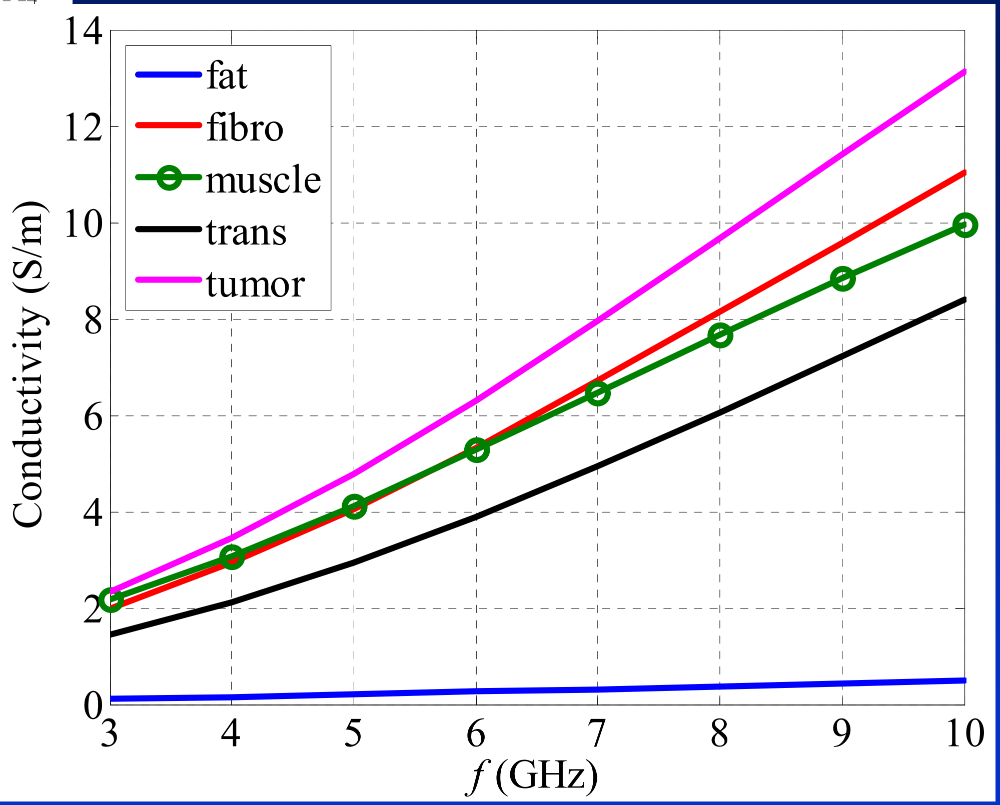
a slice of a T_1 weighted MR breast image in the transverse plane



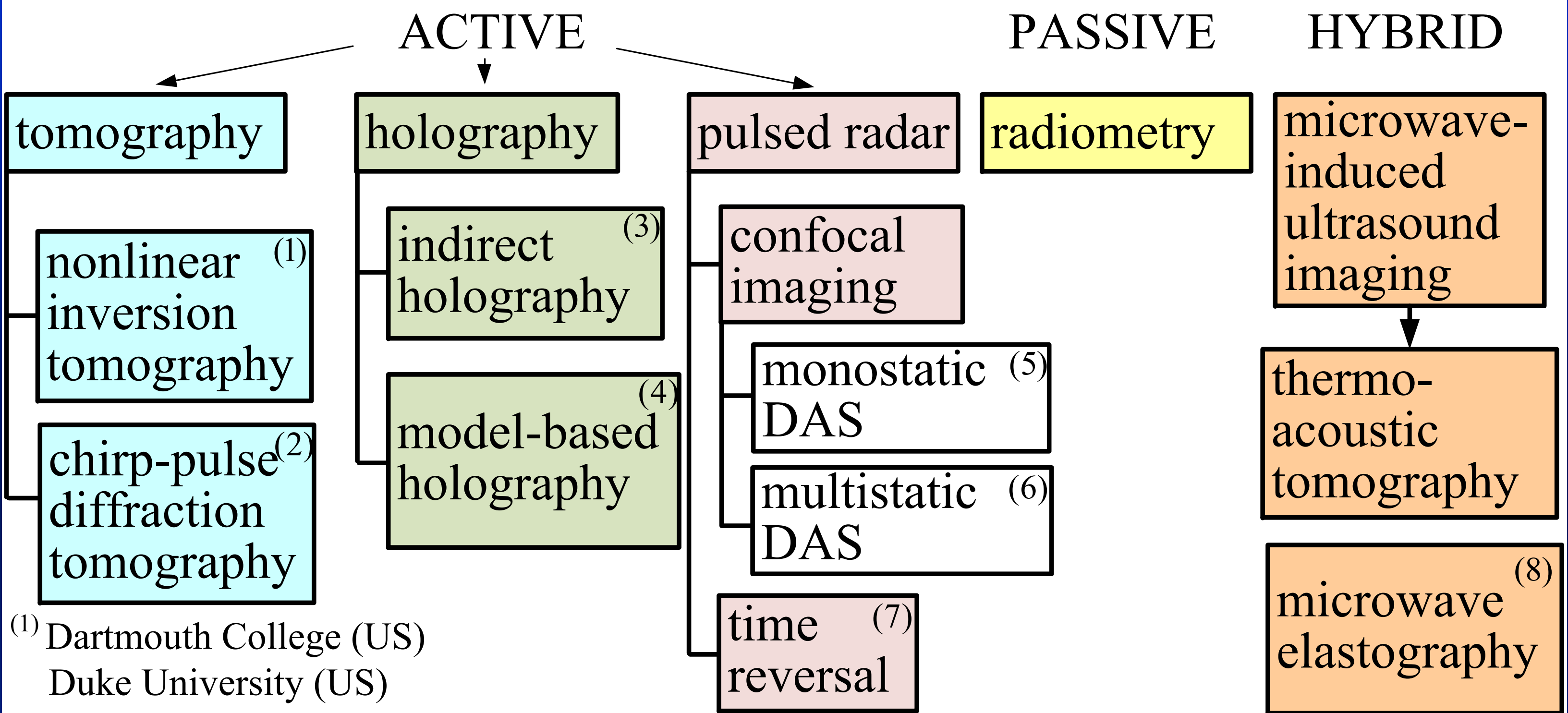
Breast Tissue Constitutive Parameters – Illustration

[Trehan 2009]





Microwave Imaging Approaches in Breast-cancer Research



(1) Dartmouth College (US)
Duke University (US)
Carolinas Medical Center (US)
Delft University of Technology (the Netherlands)
Université de Nice-Sophia Antipolis (France)
(1),(2) Chalmers University of Technology (Sweden)
(2) University of Genoa, Niigata University

(3) Northumbria University (UK)
(4) McMaster University (Canada)

(8) University of Queensland (AU)

(5) University of Calgary (Canada)
McGill University (Canada)
University of Wisconsin-Madison (US)
(6) University of Bristol (UK)
(7) Northeastern University (US)
University of Technology Sydney (AU)

Reconstruction Approaches

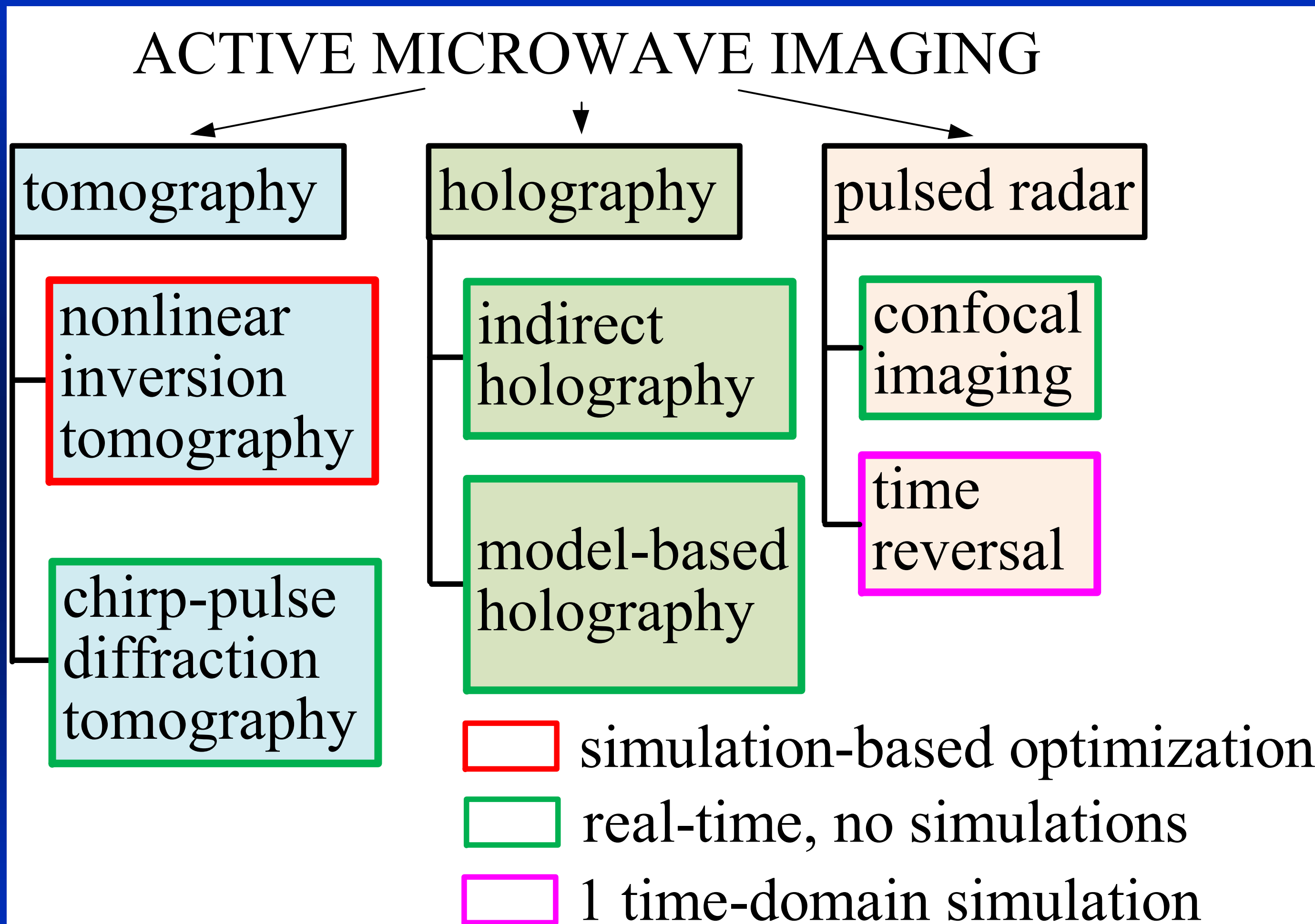
linear (direct) inversion

- approximations in forward model (e.g. Born or Rytov) produce closed-form inverse operator
- real-time performance
- subject to diffraction limit with far-zone measurements

nonlinear inversion

- nonlinear optimization procedures
- forward model is iteratively updated to match measurements
- fidelity of EM forward models is low esp. at high frequencies
- time consuming, cannot perform in real time
- convergence not guaranteed; local minima are a problem
- can achieve super-resolution even with far-zone measurements **[Chew 1998]**

Reconstruction Approaches in Tissue Imaging

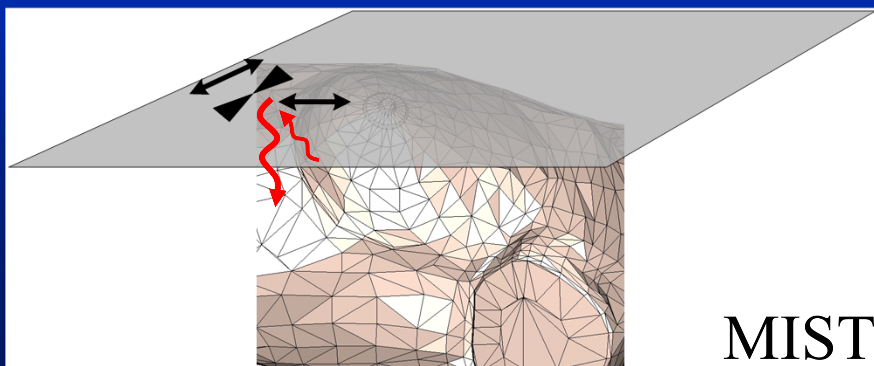


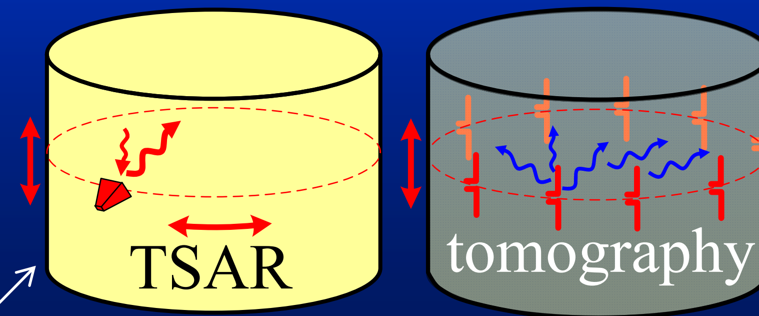
Experimental Setups: Data-acquisition Arrangements

may use co-pol and cross-pol interrogation in time or frequency domains

planar scan – supine

cylindrical scans – prone

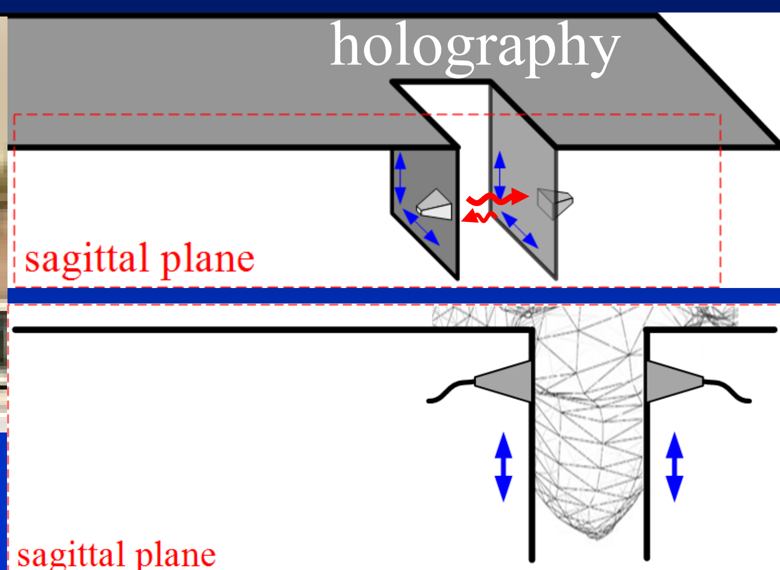


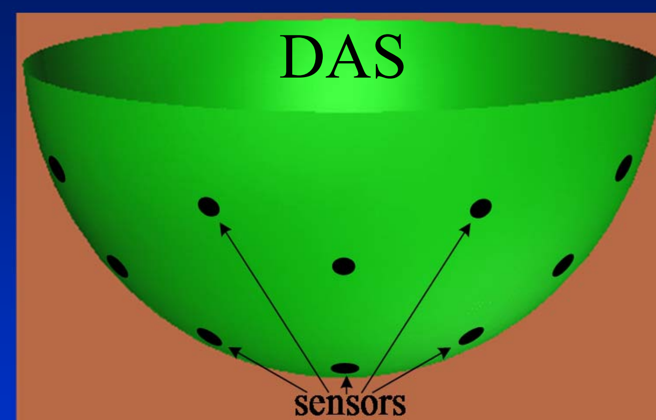


confocal imaging

planar scan – prone

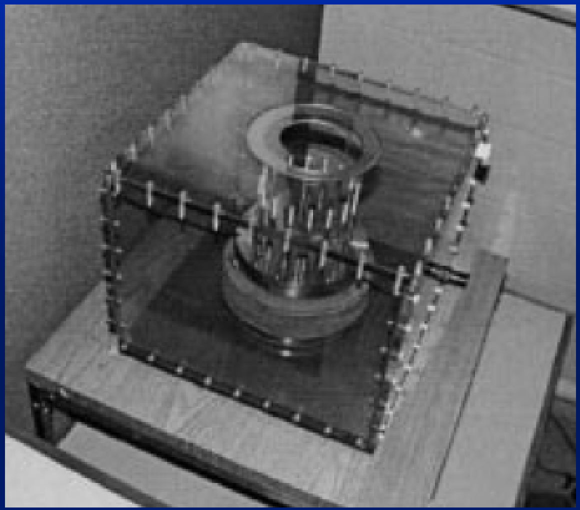
multi-static array – prone



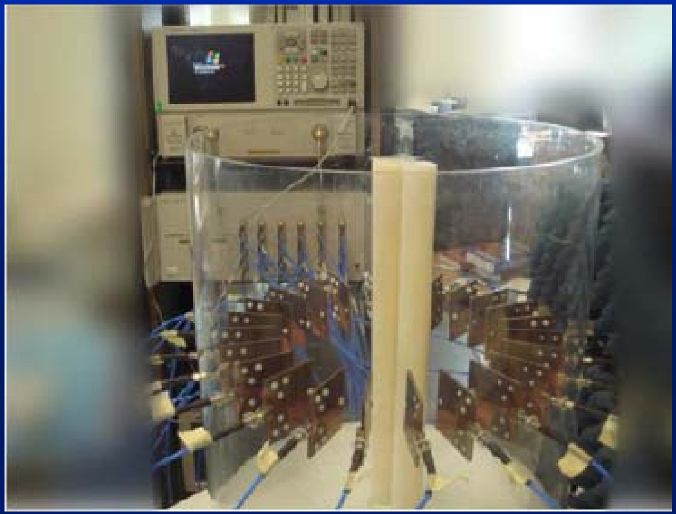


Experimental Setups Using Coupling Liquids

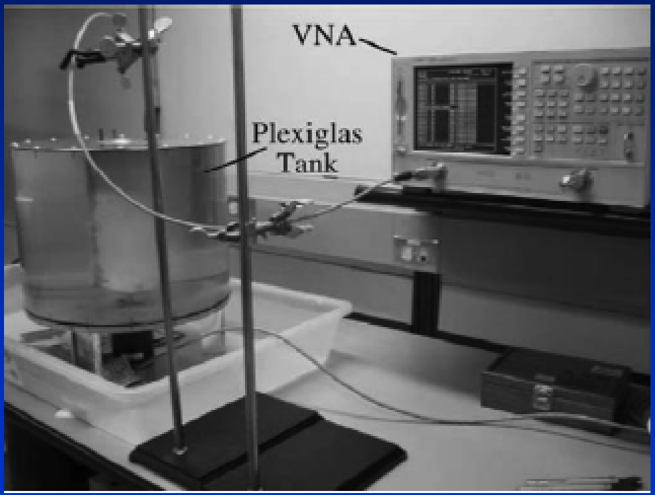
tanks of *coupling liquids* typically used to improve energy coupling into tissue



Dartmouth C [Meaney 2000]



U of Manitoba [Zakaria 2010]

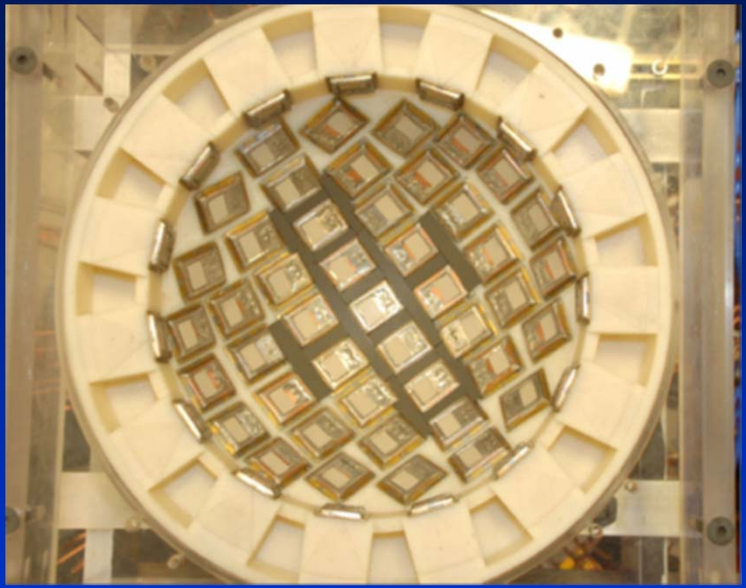


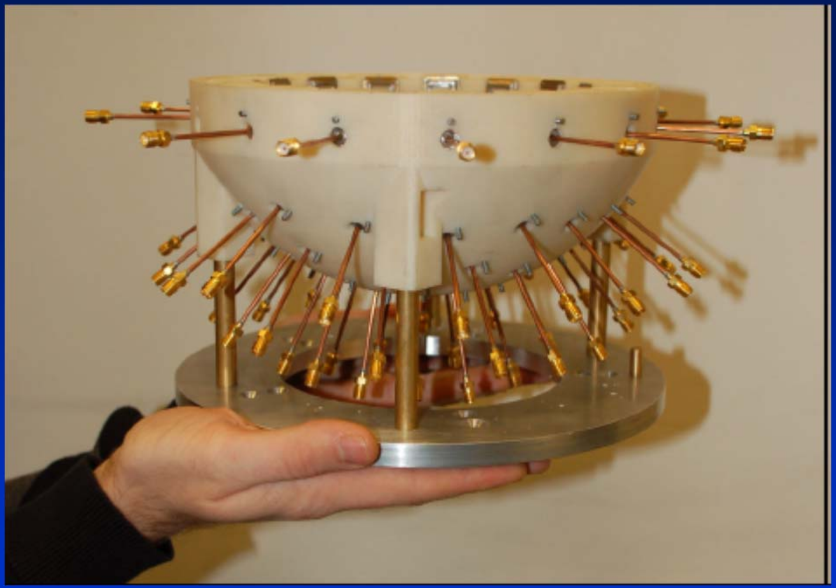
U of Calgary [Sill 2005]

Liquid-free Experimental Setups: Sensor Arrays

recent trend toward liquid-free setups (gels may be used)

- easy maintenance
- no danger of contamination
- contact with tissue through thin layers of protective coating & gel
- challenging sensor design





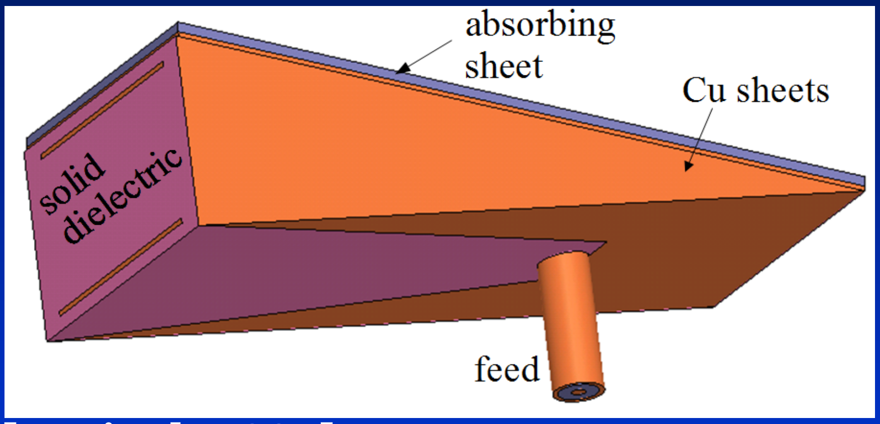
[Klemm 2010, 2011]

Sensors for Liquid-free Scanning

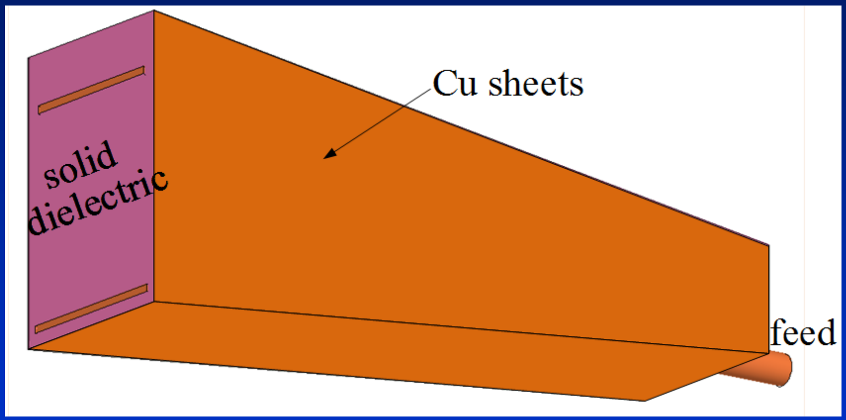
design requirements for aperture-scan sensors

- no coupling liquids
- frequency range within UWB (3.1 GHz to 10.6 GHz)
- $20\log_{10}|S_{11}| \leq -10$ dB
- coupling efficiency ≥ 80% → $e_c = \dfrac{P_{\text{tissue}}}{P_{\text{in}}}$
- small front aperture

<u>shielded dielectric-filled TEM horns</u>



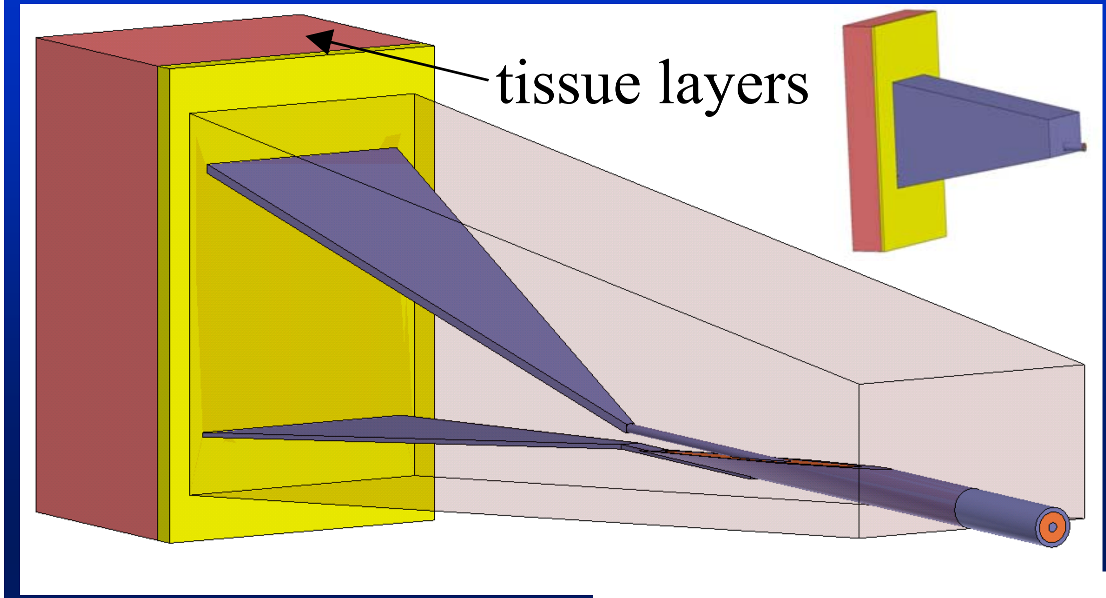
[Amineh 2009]



[Moussakhani 2010]

Fully Shielded Dielectric-filled TEM Horn Sensor

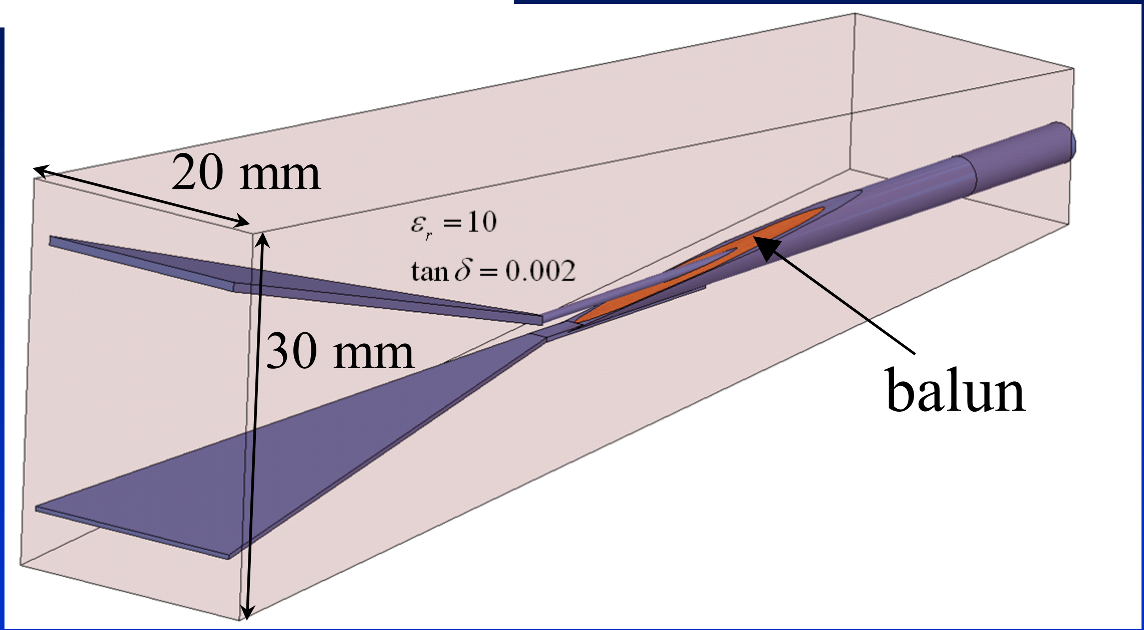
[Moussakhani 2010]



dielectric material

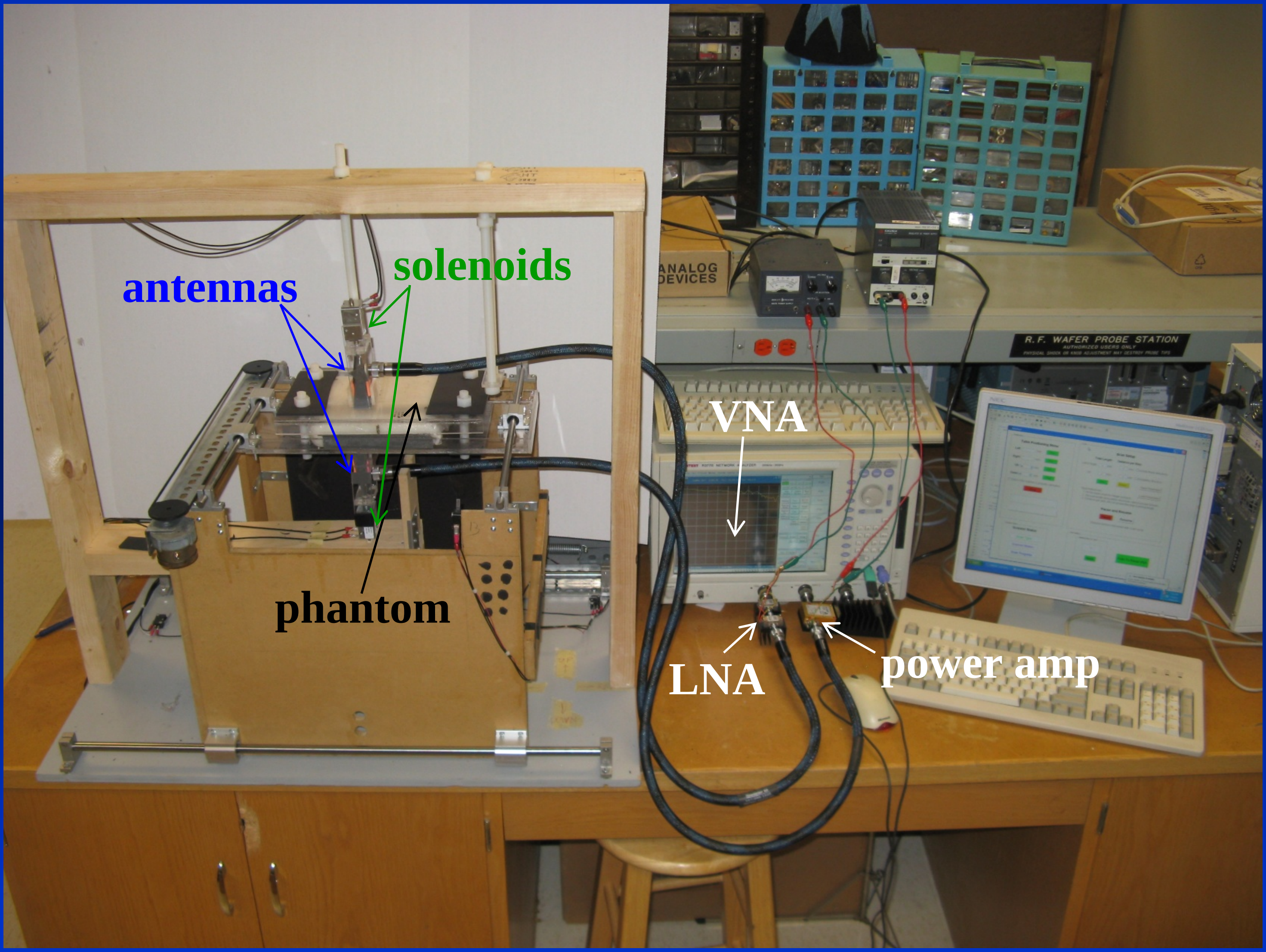
$\varepsilon_r \approx 10$
$\tan\delta \approx 0.002$

[ECCOSTOCK®, Emmerson&Cuming Microwave Products]



Raster Scanning: Experimental Setup

2-port *S*-parameter measurement



Raster Scanning: Measurement Procedure

1. Calibrate VNA
2. Measure reference phantom

   $$S^{\mathrm{r}}_{jk}(x,y),\quad j,k=1,2$$

3. Measure object under test

   $$S^{\mathrm{o}}_{jk}(x,y),\quad j,k=1,2$$

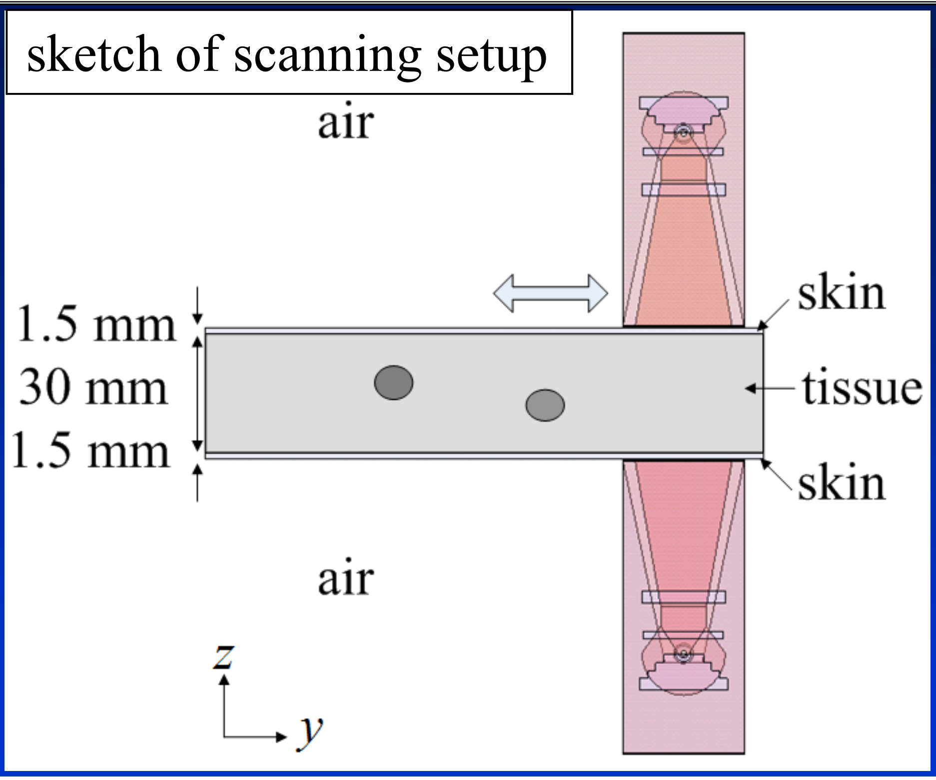
4. Calculate calibrated scattering parameters

   $$S^{\mathrm{c}}_{jk}(x,y)=S^{\mathrm{o}}_{jk}(x,y)-S^{\mathrm{r}}_{jk}(x,y),\quad j,k=1,2$$

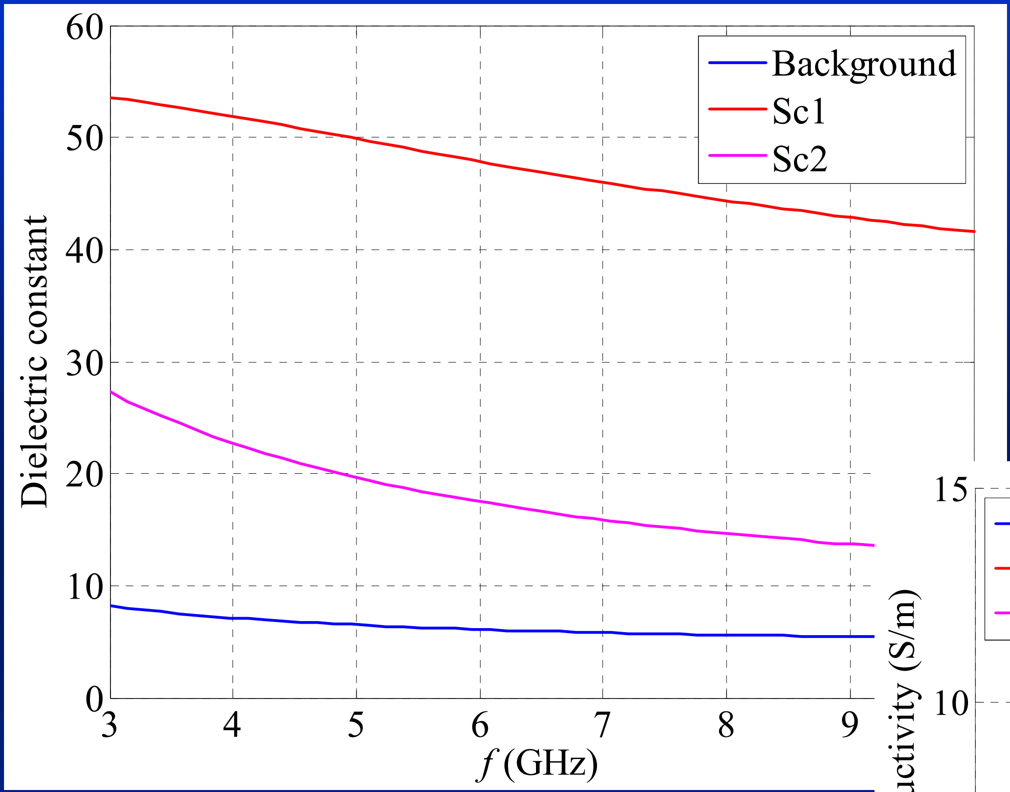
Raster Scanning: 2-D Images of *S*-parameter Magnitude

EXAMPLE 1:
MEASUREMENT OF TWO SCATTERERS IN A 3-CM THICK PHANTOM

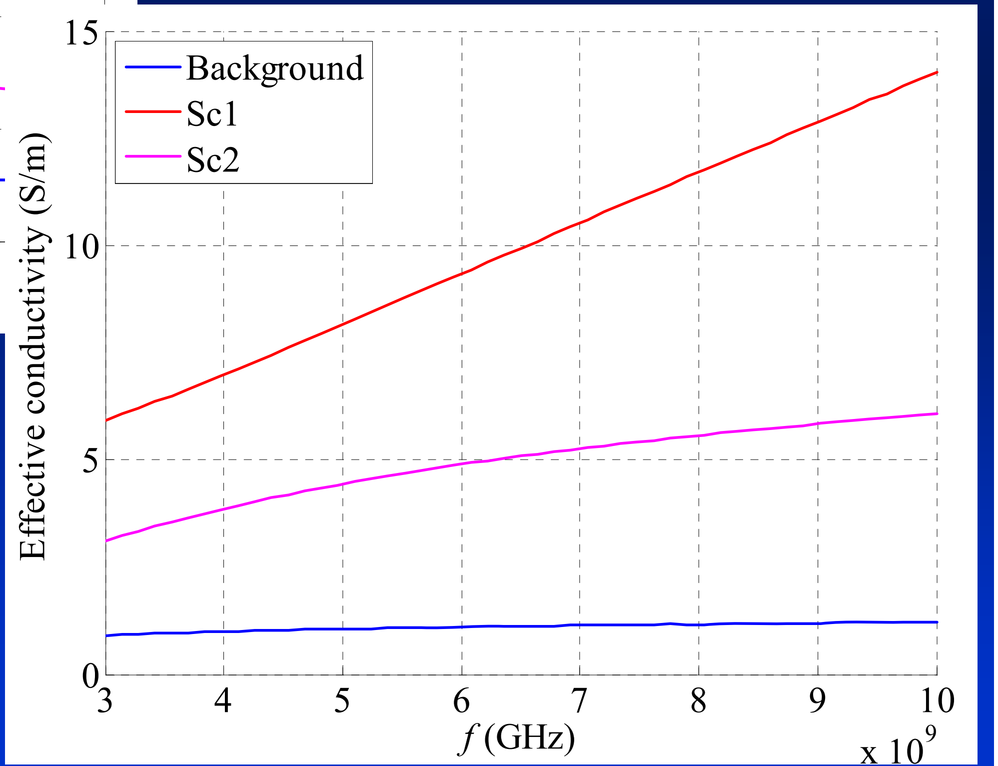
Scatterer	Position (mm)	Size (mm)	Material
Sc1	(−4, 25)	10×10×10 [before diffusion]	alginate powder
Sc2	(9, −25)	15×15×15	glycerin



Raster Scanning: 2-D Images of *S*-parameter Magnitude (2)

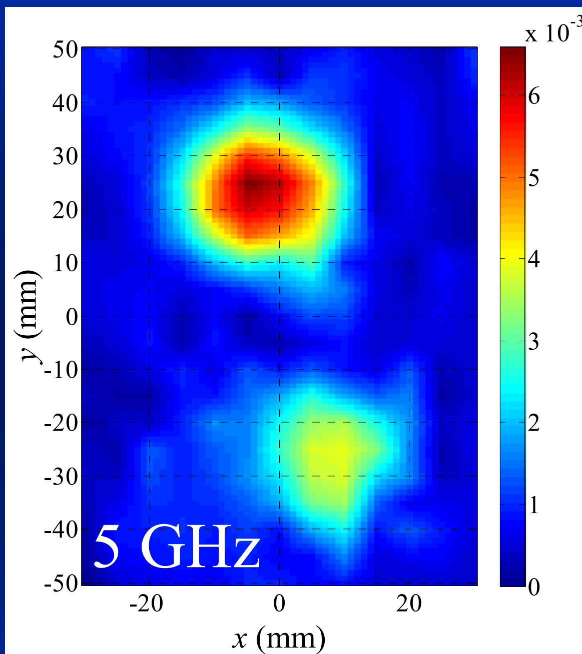


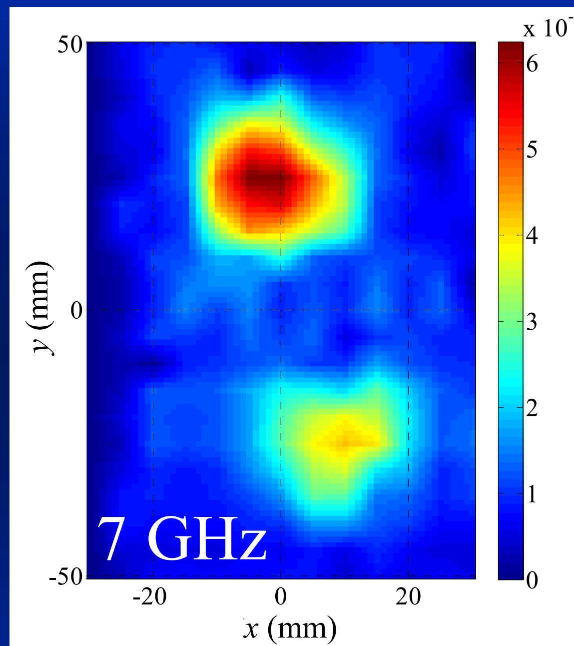
phantom electrical properties

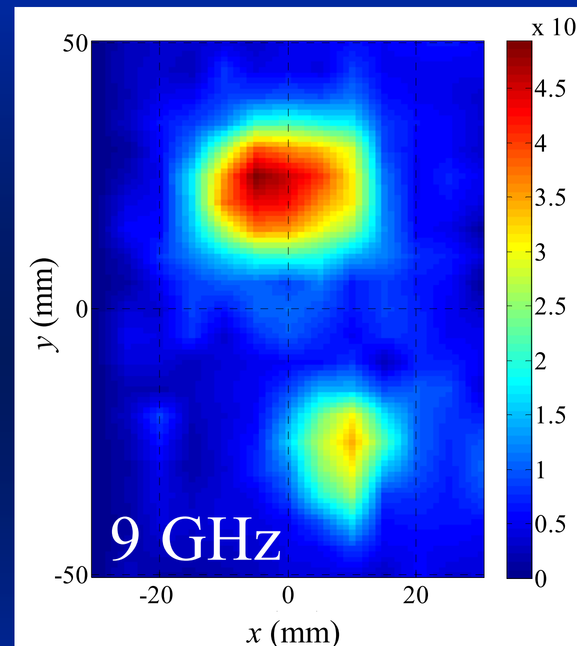


Raster Scanning: 2-D Images of *S*-parameter Magnitude (3)

Example 1: $|S_{21}^{c}|$ images





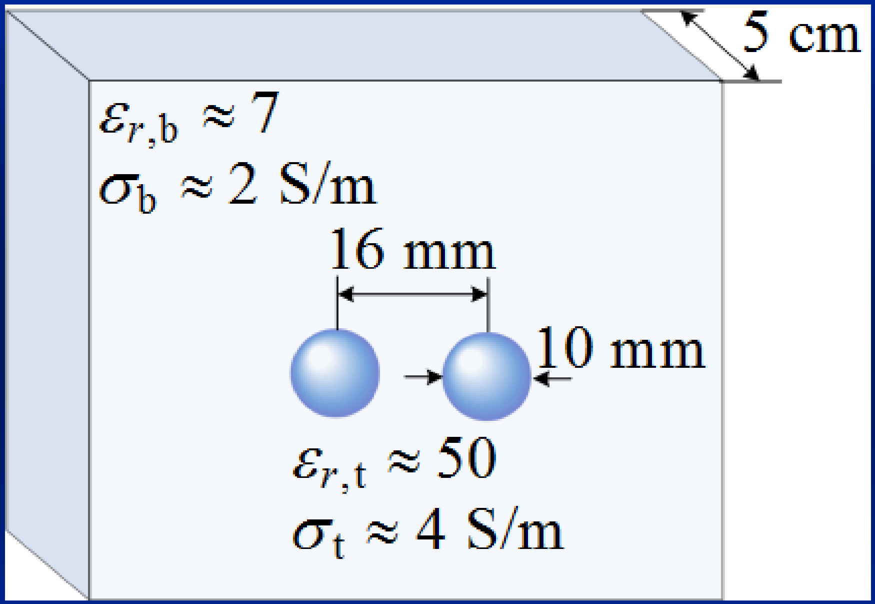


<u>VNA settings</u>
averaging: 10
bandwidth: 1 kHz
smoothing: 5%

sampling rate along *x* and *y*: 5 mm

Raster Scanning: 2-D Images of *S*-parameter Magnitude (4)

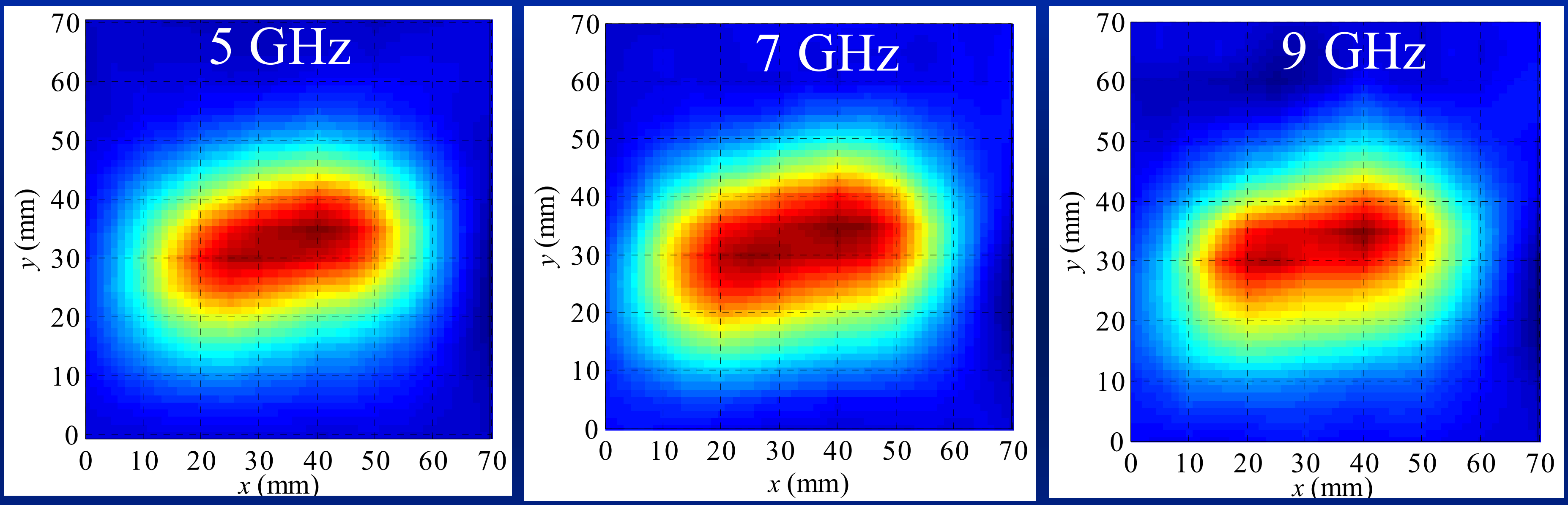
EXAMPLE 2:
MEASUREMENT OF TWO SCATTERERS IN A 5-CM THICK HOMOGENEOUS PHANTOM



two identical tumor simulants made of alginate powder (electrical properties at 5 GHz shown in figure)

Raster Scanning: 2-D Images of *S*-parameter Magnitude (5)

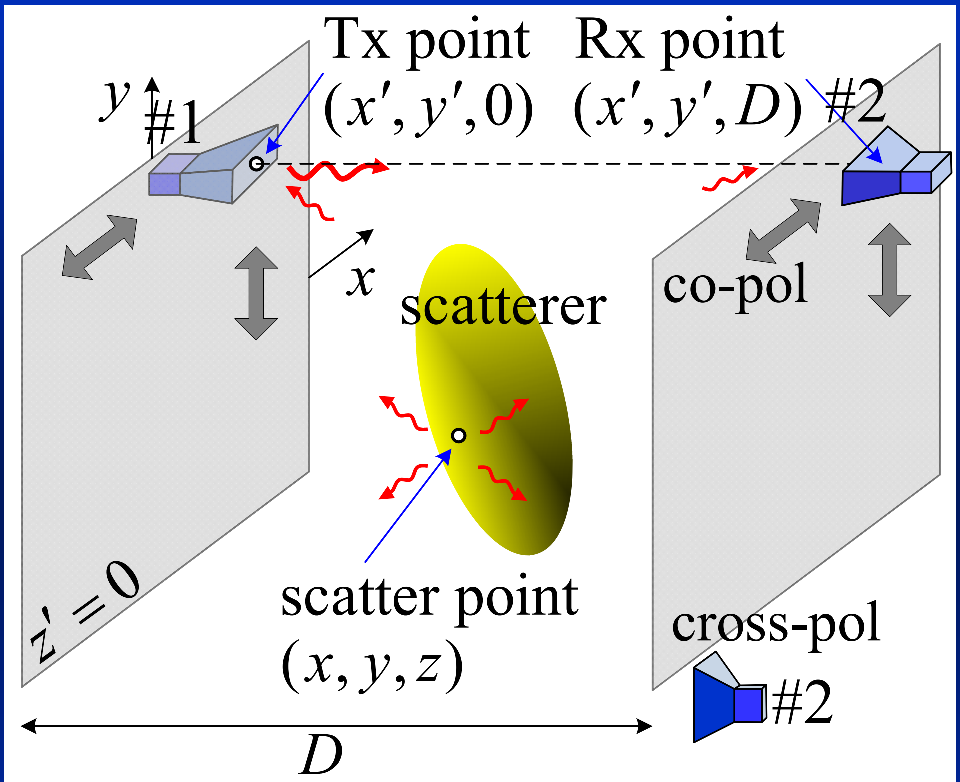
Example 2: $|S_{21}^{c}|$ images after resampling and smoothing



- image quality is low – the two targets are fused together
- due mainly to integrating property (low-pass filtering) of the relatively large sensor aperture

Holography Reconstruction with Raster Scanning Data

[Amineh 2010, 2011]



type of measurement	number of signals $S_{ij}(x', y')$
co-pol X-X	4xN_ω
co-pol Y-Y	4xN_ω
cross-pol X-Y	4xN_ω
cross-pol Y-X	4xN_ω
TOTAL	16xN_ω

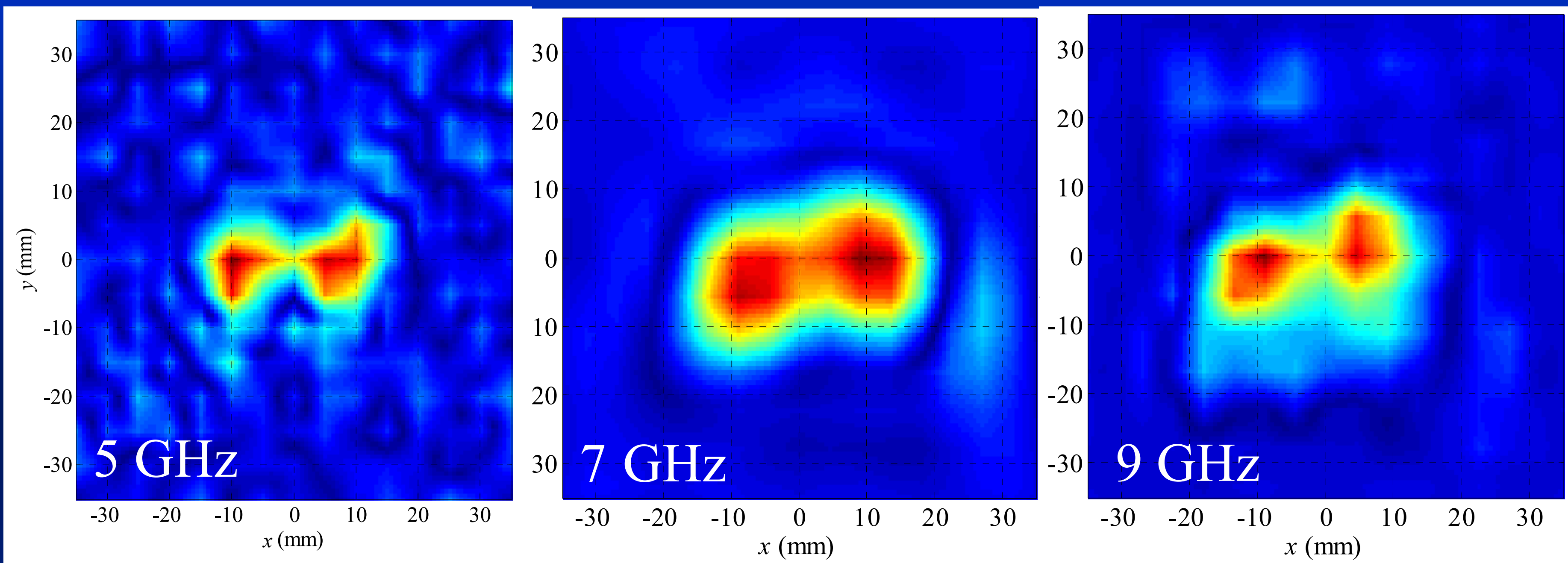
acquired scattered signals (magnitude and phase)

- reflected signals: S_{11}, S_{22}
- transmitted signals: S_{21}, S_{12}

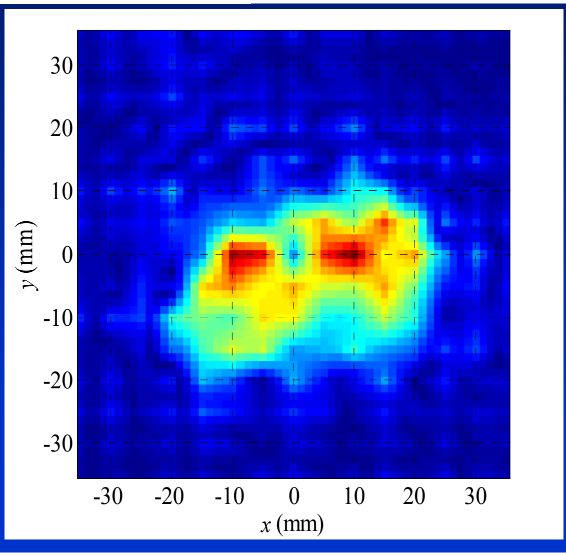
(both) functions of $(x', y', \omega_m), m = 1, \ldots, N_\omega$

Holography Reconstruction: Measurement Example

Example 2: images after holography reconstruction



all frequency samples from 5 GHz to 9 GHz



Recent Advances: Sensitivity-based Imaging

[Liu 2010][Zhang 2011]

objective: identify locations in the object under test (OUT) where the electrical parameters differ from those in the reference object (RO)

input

- **RO data:** acquired (simulation or measurement) prior to measurements; part of system calibration; independent of OUT

$$\rightarrow \mathbf{E}_k^{\mathrm{r}(m)}(\mathbf{r}),\ i=1,\ldots,N_p;\ m=1,\ldots,N_f$$ (RO field distributions)

$$\rightarrow S_{jk}^{\mathrm{r}(m)},\ j,k=1,\ldots,N_p;\ m=1,\ldots,N_f$$ (RO responses)

- **OUT data**

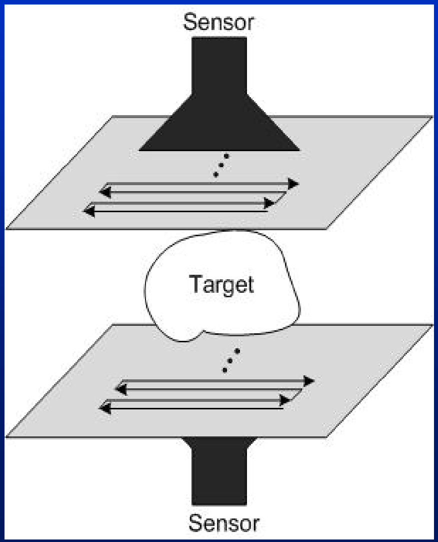
$$\rightarrow S_{jk}^{\mathrm{o}(m)}(x',y'),\quad j,k=1,2;\ m=1,\ldots,N_f$$ (OUT responses)

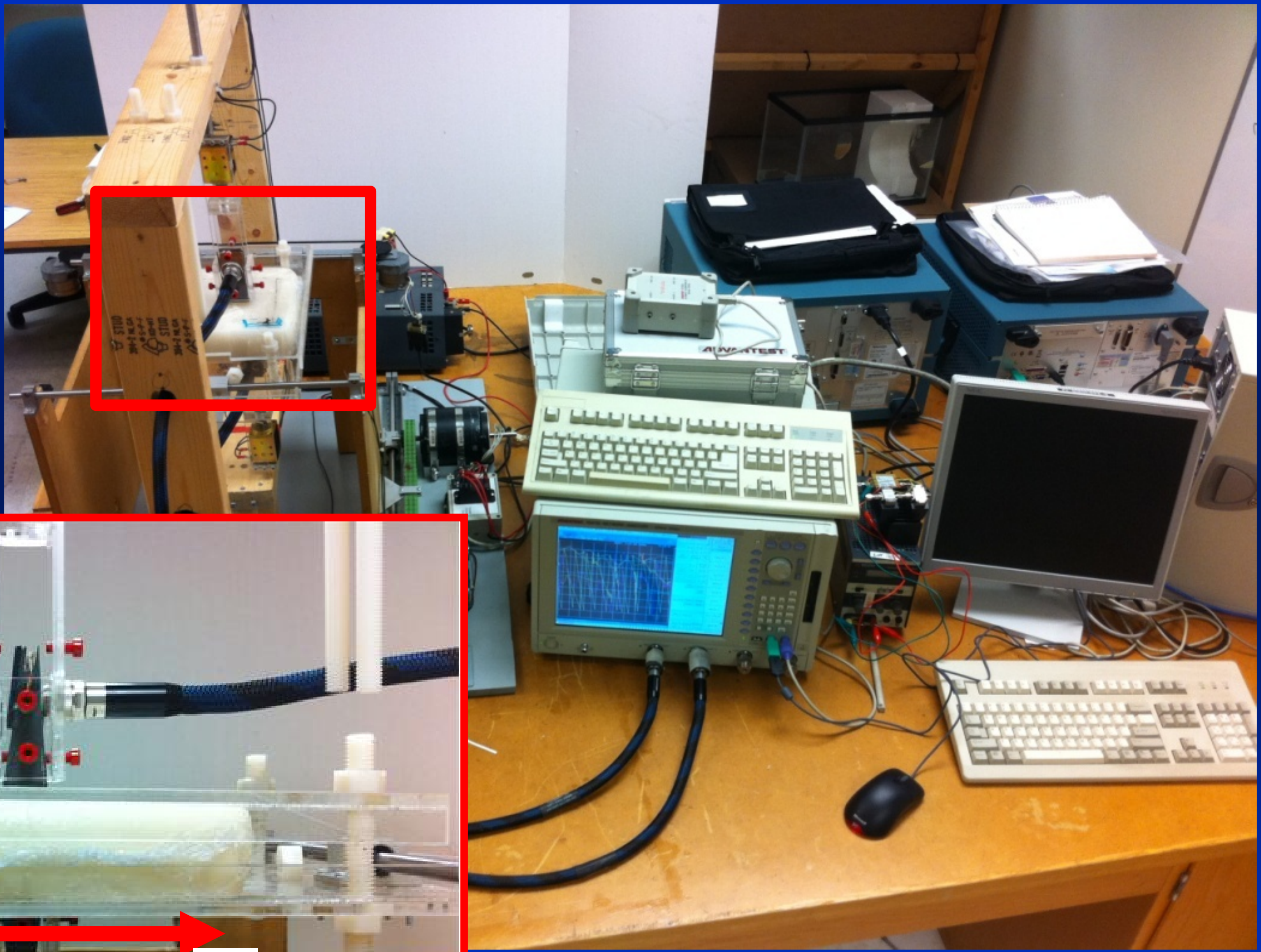
output

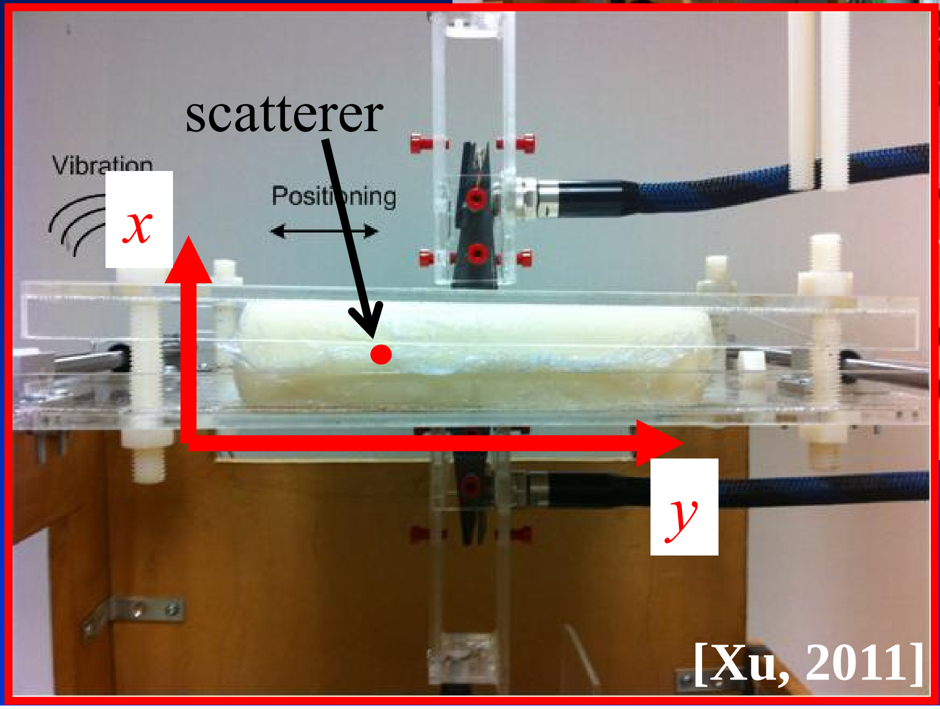
image is a measure of the difference between the electrical parameters of the RO and the OUT

Sensitivity-based Imaging: Single Target Example

[Zhang 2011]

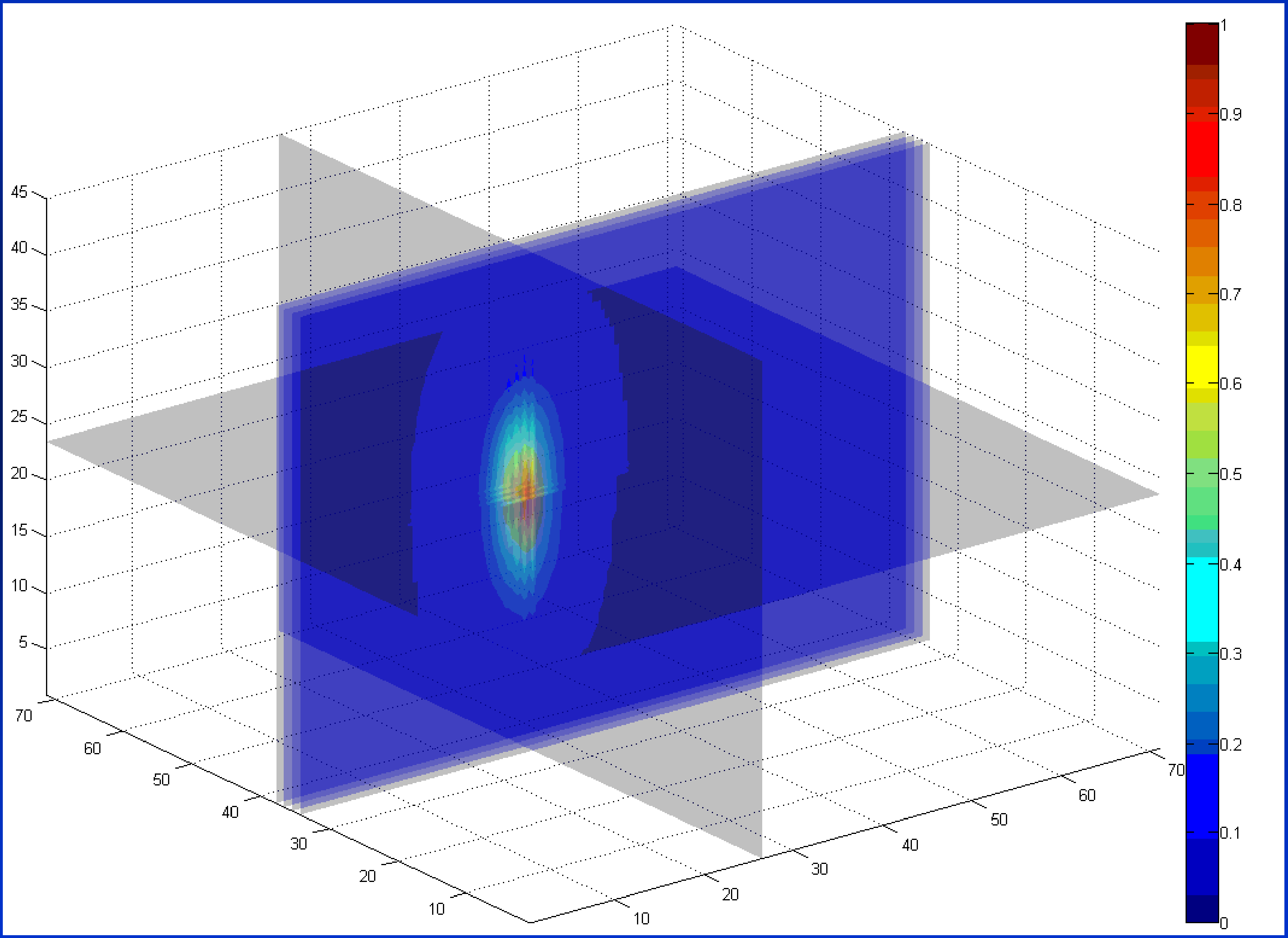






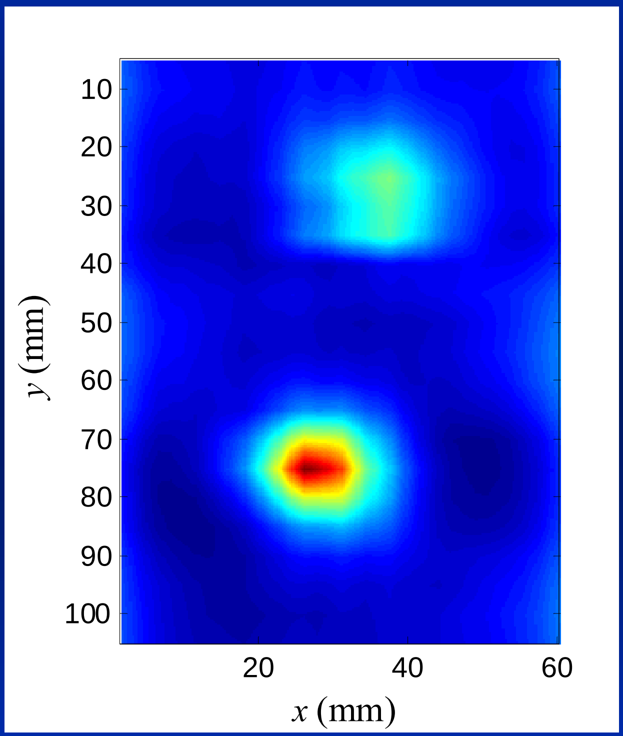
Sensitivity-based Imaging: Single Target Example (3)

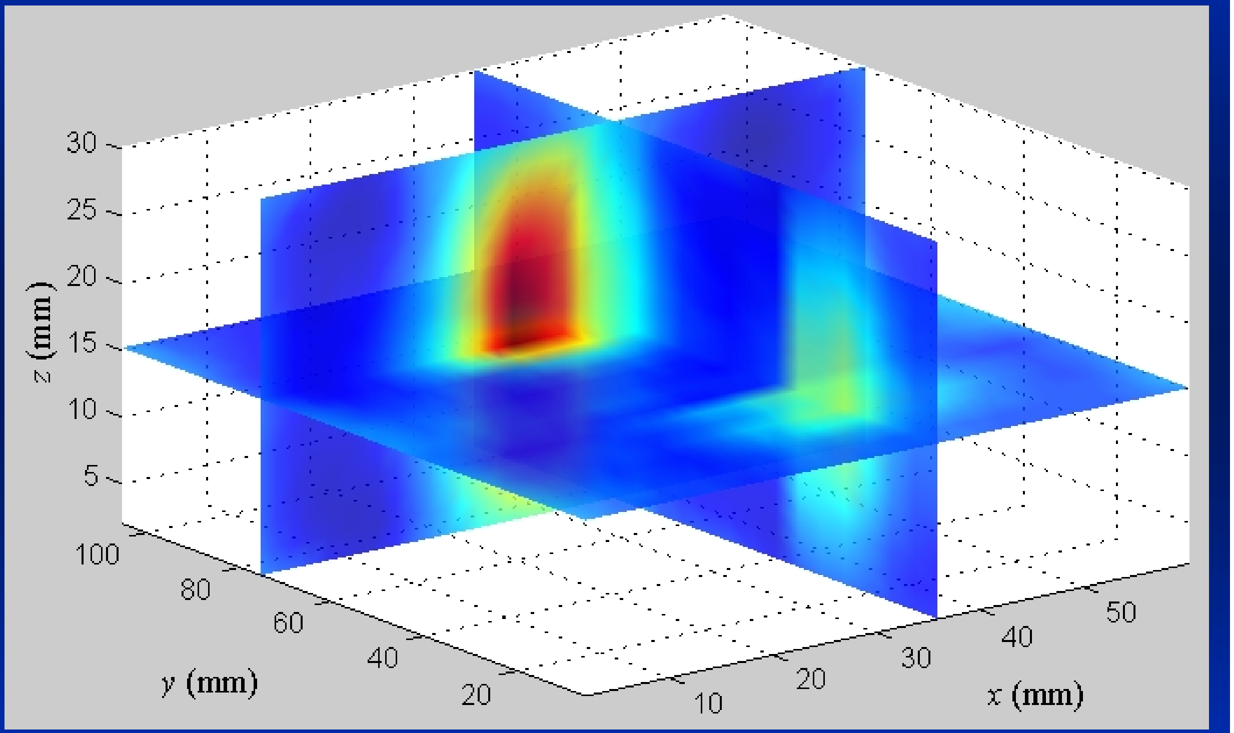
final 3-D image (all frequencies)



Sensitivity-based Imaging: Double Target Example

[Zhang 2011]





Looking Forward

software

⇨ new advancements in imaging algorithms

- image reconstruction using response sensitivities **[Song 2008, Liu 2010, Zhang 2011]**
- iterative update schemes combining model-based holography and sensitivity-based imaging

hardware

⇨ improving sensors, sensor arrays } co- and cross-pol interrogation

⇨ improving scanning apparatus } co- and cross-pol interrogation

⇨ time-domain interrogation (chirp waveforms for improved focusing)

⇨ contrast agents for microwave imaging (carbon and magnetic nanoparticles)

This talk is the basis of an overview paper by the same title in the *IEEE Microwave Magazine*, Dec. 2011.

Thank you!

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