Microwave Tomography: Clinical Success and Why So Many Efforts Fail

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Abstract: There has been a wide range of hype surrounding microwave imaging for a number of decades. Much of the interest has centered in academia and especially in the numerical modeling realm. The major motivations are that tissue dielectric properties can be remarkably specific and that microwave radiation is nonionizing. For instance, breast tumors generally have higher dielectric properties than normal breast tissue - a possible mechanism for cancer detection. In addition, recent studies show that bone dielectric properties change with bone density – a possible alternate to x-ray densitometry for monitoring bone loss. Blood properties are different than those for brain tissue – possible applications in stroke diagnosis. These are only a few potential medical applications. The Dartmouth Microwave Imaging Group is the only group in the world to have an actual working tomography system in the clinic. A large part of this success is related to the unconventional and counterintuitive antenna array we use. Our development has been a unique synergism of hardware and software expertise which has allowed us to perform over 500 patient breast exams along with a small pilot study looking at bone screening.

I will briefly discuss some of the more daunting implementation challenges and how we’ve addressed them. This will include our unique algorithmic approach, which now allows us to reconstruct images from exams in only a few minutes compared to hours to days for other modeling groups. In addition, this approach has allowed us to apply a fairly simple hardware configuration that keeps the number of antennas and transmit/receive pairs to a minimum and dramatically impacts the overall system cost. Complementing this design, we’ve also directly addressed multi-path signal interference problems which plague most system implementations. More importantly, we have developed a strategy for recovering images that is not subject to convergence to local minima or unwanted solutions which plagues most current approaches.

I will show a broad array of images from our clinical system including a variety of breast cancer detection and therapy monitoring examples. In addition, I will also show some of the more recent bone results as an example of where this technology can have important healthcare impact.

Keywords: microwave tomography, breast cancer imaging, multi-path signals, unique solution log transform
References:


Dr. Paul Meaney received AB’s in Electrical Engineering and Computer Science from Brown University in 1982. He earned his Masters Degree in Microwave Engineering from the University of Massachusetts in 1985 and worked in the millimeter-wave industry at companies including Millitech, Aerojet Electrosystems and Alpha Industries. He received his PhD from Dartmouth College in 1995 and spent two years as a postdoctoral fellow including one year at the Royal Marsden Hospital in Sutton, England. His research has focused mainly on microwave tomography which exploits the many facets of dielectric properties in tissue and other media. His principle interest over the last decade has been in the area of breast cancer imaging where his group was the first to translate an actual system into the clinic. The Dartmouth group has
published several clinical studies in various settings including: (a) breast cancer diagnosis, (b) breast cancer chemotherapy monitoring, (c) bone density imaging, and (d) temperature monitoring during thermal therapy. He has also explored various commercial spin-off concepts such as detecting explosive liquids and non-invasively testing whether a bottle of wine has gone bad. He has been a Professor at Dartmouth since 1997, a professor at Chalmers University of Technology, Gothenburg, Sweden since 2015, and is also President of Microwave Imaging System Technologies, Inc. which he co-founded with Dr. Keith Paulsen in 1995. Dr. Meany holds 10 patents, has co-authored over 60 peer-reviewed journal articles, co-written one textbook and presented numerous invited papers related to microwave imaging.

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Earliest System
1993-95

Very Large Tank
Lossy Liquid - Saline

Water-Filled Waveguide Antennas
Monopole Antennas
Bench Top System – Circa 1995-98
First Clinical System – Circa 1998-2002
Second Clinical System – Circa 2003-2008
Current System

Clinical Interface

Illumination Tank
Example – Microwave Imaging in an MR System
Latest System – In Development
Perspective on Numerical Simulation in the Microwave Imaging World


The relative paucity of field data on geological flows presents a mis-match with the power and sophistication of modern digital computers. With few exceptions, numerical simulations of geological flows have little measured data input, or quantitative comparison between the computer output and field measurements. Parameters can be chosen without observational or experimental basis, but simply to make the output “seem reasonable,” i.e. to be in accord with preconceptions. Though often presented as factual, and generating their own air of reality, these simulations are often quite misleading, and no more than digitally precise renditions of a mostly imaginary world.
1) Why has the microwave imaging field struggled to get anything into the clinic?
   1) Technology limitations?
   2) Politics?
   3) Stubbornness? – People have been at it for a long time

2) Summary of our counterintuitive approach in the context of “prevailing wisdom”
Two Fundamental Challenges

Are you interrogating the tissue with your signal?

Can you recover an image without knowing the image beforehand?

Pretty basic questions
Misconceptions in the Field

Is there contrast between dielectric properties of normal breast tissue and tumor?

What part of the frequency range has the most information and why?

Before jumping on “ultrawideband” bandwagon, think first about where the valuable information is
Obviously the microwave signal will penetrate into the body.

The question is, is there part of the original signal that takes an alternate route and overwhelms your desired signal?

Multi-path signals

Alternate route

Thru signals
For me, interrogating the tissue means that the signals going thru the target are substantially greater than those going around. It’s very much a matter of degree.
Interplay Between Illumination Zone Challenge & Measurement System Requirements

Two major conflicts

A) Suppressing multi-path signals

B) Simplifying the measurement system

I’ll contend that this is harder

Easier to buy one if you don’t know how to build one.
Multi-Path Signals

Multi-path signals in near field systems are excited along feedlines and various structures.

If you find yourself working in an imaginary world, these problem signals can be eliminated by simply ignoring them (i.e. don’t include them in the model).

The Keysight VNA’s would be perfect for this because they would have adequate dynamic range.
Multi-Path Signals

Radio Transmission

Tomography System

Monopole Antennas
Multi-Path Signals

Not Noise

End result can be just as debilitating

Multi-Paths

Illumination chamber

Reflections off of surfaces

Surface waves

Microwave electronics

Cross-channel leakage
Surface Waves

Beam patterns as a function of bath conductivity (S/m)

- \( \sigma = 0.0 \) Planar modes
- \( \sigma = 0.2 \) Coaxial modes
- \( \sigma = 0.5 \) Well behaved
Multi-Path Signals

If you find yourself working in the real world, you might want to consider a lossy coupling bath to suppress unwanted signals.

However, this requires a larger dynamic range than the Keysight systems can typically deliver.

Possible solutions – (a) Rohde & Schwarz system (b) custom system

Alternatively, develop synthetic strategies for compensating for unwanted signals – easier said than done.
Alternative Compensation Techniques

Time Domain – Pulse

Time gating doesn’t work well when there are multiple reflections – you see this effect when working with circuits – it’s the same phenomenon.

University of Bristol’s technique of shifting the array slightly and doing a subtraction. My impression is that this basically assumes that the field propagation problem is linear. I’m guessing it tends to fall apart in higher contrast situations.
LoVetri – U Manitoba

Liquid coupled – Vivaldi Antennas - VNA for the measurements

Ground planes would keep the antenna active region away from chestwall

Small dynamic range translates to a small imaging zone
LoVetri – U Manitoba

Their “solution”:

An air coupled system – uses a VNA

Multi-path signals will kill them
Need as Many Measurements as # of Pixels

Problem – The amount of data gets extreme

EMTensor (Austria – Semenov)
  Stroke detection
  VNA’s alone cost over $300K
Roger Stancliff (Keysight)
  pushing this approach

Many modalities disobey this “rule”

Adding measurements doesn’t always add “information”
  Just look at the singular value decomposition (SVD) – We did
Difference Minimization Non-Uniqueness

Minimization Paths

Computed

Measured

A

B
Image Reconstruction Problem

We don’t need a priori information
  This really only exists as a figment of a numerical modeler’s imagination
  People quote times ranging from many hours to days

We can do this fast – and without converging to non-meaningful solutions
  DDA – discrete dipole approximation
Alternative Breast Imaging Program Project

Microwave Imaging Development

Integrated Technology
- Hardware Development
- Algorithm Development
- Patient Comfort/Safety

Dartmouth Medical Center

> 500 Patients Imaged

MR Elastography
Impedance Imaging
Initial Clinical Results
Pathology

Computational Core
Near IR Imaging
Statisticians
Radiology
Forward Solution

Monopole Source

Scattering Object

Antenna Array & Imaging Configuration
Gauss-Newton Iterative Algorithm

$$\min \left\| E^m - E^c(\mathbf{k}^2) \right\|^2$$

Nothing fancy

Ideal for nonlinear parameter estimation problems

Turns out the popular “Distorted Born Approximation” is mathematically equivalent

Extensive literature in the Probability & Statistics domain
Log Transformation – Box & Cox

Adopted from NIR Area – Ideally suited for cases where power levels differ over many orders of magnitude

\[
\text{min} \left( \left\| \Gamma^m - \Gamma^c (k^2) \right\|^2 + \left\| \Phi^m - \Phi^c (k^2) \right\|^2 \right)
\]

- Emphasizes greatest relative amplitude and phase projections
- Does have to deal with the phase at microwave frequencies
- Used extensively in optical coherence tomography
Patient 1915 – Fatty Breast – Position 3, Left Breast

1300 MHz
Interpretation of the Phase

For near infrared tomography, modulation frequency is low (typically 100 MHz) so phase wrapping never occurs.

For microwave tomography, wavelength is small:
- Phase has to be monitored.
- Turns out phase is the primary reason for local minima convergence.
- Some data is simply on the wrong Riemann sheet.

Unwrapping is challenging:
- Measurement data – unwrap as function of freq.
- Computed data – unwrap as function of iteration.
Measurement “Projections”

Log Magnitude

Phase

What Riemann sheet are these on?
Discrete Dipole Approximation
(Developed by Tomasz Grzegorczyk)

Requires medium to be purely dielectric
Works well for optical imaging applications (DOT)
Can be used with metallic scatterers but loses efficiency

Monopole antennas & a lossy coupling medium
The previous criterion is essentially met

2D recons – 2-5 seconds  3D recons – 5-15 minutes
Running Matlab on a Mac laptop
Fatty - Large Fibroglandular

Magnitude

Phase

Smoothed image

Starting guess

2 - step image
Smoothed algorithm

Euclidean distance regularization
Coronal Image Slice Orientation
Speculations on Why the 2D Algorithm is So Good

Placement of antennas close to the target

More closely emulates cylindrical geometry – almost true TM mode

Lossy medium

Severely attenuates signals out of plane

Specific to our implementation
Patient 2025

Pennsylvania State University
September 29, 2016

$\varepsilon_I$  $\sigma$
MR Images of Skin Thickening

Patient 1914 – Heterogeneously Dense Breast – 36 Years Old

T2  T1 – Gad Enhanced  Subtraction

Skin Thickening  Tumor
Patient 1914

Right Breast - Start Chemo  

Left Breast

Thickened Skin

Tumor
Patient 1914

Right Breast - Start Chemo

Right Breast - After 2nd Cycle

\( \varepsilon_r \)

\( \sigma \)

Tumor

Thickened Skin
Patient 1914

Right Breast - Start Chemo

Right Breast - After 4th Cycle

Thickened Skin
MR Images After Therapy

Patient 1914 – Heterogeneously Dense Breast – 36 Years Old

T2  T1 – Gad Enhanced  Subtraction

Skin Thickening (Reduced)  Tumor - Treated
Bone Imaging

Optical Surface Scanning