One Dimensional FDTD in Dispersive Media for Biomedical Imaging Applications

Rachel Lumnitzer, rachelgottlieb@mymail.mines.edu
Allison Tanner, tanner@mymail.mines.edu
Atef Elsherbeni, aelsherb@mines.edu

ELECTRICAL ENGINEERING
COLORADO SCHOOL OF MINES

Project Motivation

- MRI tradeoffs
- Need for investigation of SAR safe exposure limits at higher frequencies for biomedical imaging
- Simulations necessary to support validity of cutting edge technology

(MRI Brain Scan for Cancer Detection)

Image Shown: Carlisle Regional MRI Brain Scan 6/6/2019

Project Stages

- Stage 1
  - Analyzed the relative permittivity and conductivity of over 45 biological tissues using the Debye Model
- Stage 2
  - Used the Debye coefficients obtained in Stage 1 to analyze a Multiphysics model of the head using one dimensional finite difference time domain (FDTD) method
- Project focused on 100 MHz to 100 GHz in line with biomedical imaging applications

Tissue Properties - Numerical Data Acquired

Aorta Tissue
100 MHz – 2 GHz

Frequency (GHz)	Relative Permittivity ϵ'	Conductivity [S/m]
0.100	59.780	0.462
0.499	46.230	0.586
1.00	44.558	0.729
1.50	43.745	0.924
2.00	43.089	1.171

Brain Grey Matter Tissue
2 GHz – 20 GHz

Frequency (GHz)	Relative Permittivity ϵ'	Conductivity [S/m]
2.00	49.692	1.511
5.01	45.138	4.106
10.00	**38.111**	**10.311**
15.01	31.866	16.875
20.00	22.732	26.834

Muscle Tissue
20 GHz – 100 GHz

Frequency (GHz)	Relative Permittivity ϵ'	Conductivity [S/m]
20.00	30.951	24.673
35.00	20.423	39.649
50.00	15.037	48.688
75.00	10.698	**57.388**
100.00	8.631	62.499

- [1] http://niremf.ifac.cnr.it/tissprop/ [Online website 2020].

Debye Model for Dispersive Media Properties

- Many models for frequency-dependent permittivity
- Debye Model appropriate for dispersive media such as biological tissues

- Debye coefficients: $\Delta\varepsilon_k$, τ_k, ε_∞
- ε_∞: relative permittivity at infinite frequency.
- $\Delta\varepsilon_k$: relative permittivity.
- τ_k: relaxation time
- K: number of poles

$$\epsilon_r^*(\omega) = \epsilon_\infty + \sum_{k=1}^{N} \frac{\Delta\epsilon_k}{1 + j\omega\tau_k}$$
$$= \epsilon' - j\epsilon''$$

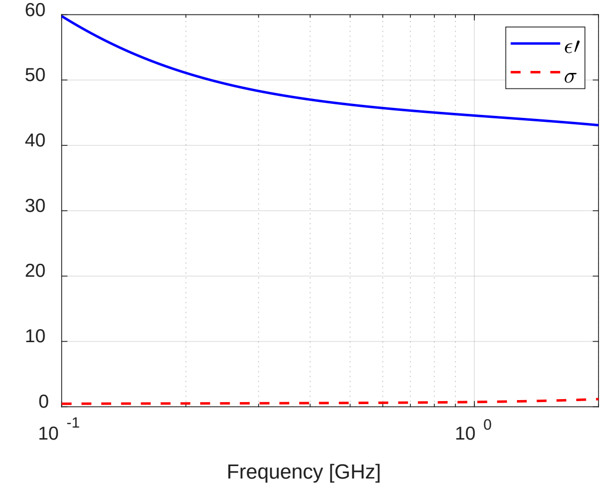
- Parameters such as conductivity and relative permittivity can be measured at several frequencies
- With set of experimental permittivity, Debye parameters can be obtained.

Debye FDTD Formulation: A. Elsherbeni and Veysel Demir, “The Finite-Difference Time-Domain Method for Electromagnetics with MATLAB Simulations”, 2nd edition

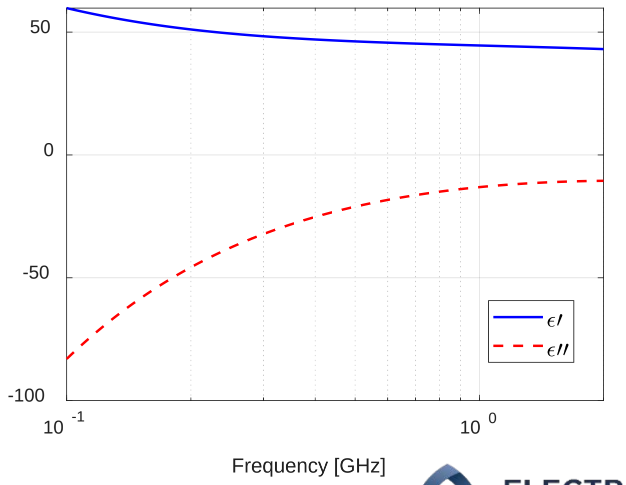
Dielectric Properties and Debye Model

Aorta
100 MHz-2GHz

Real Part of Permittivity and Conductivity

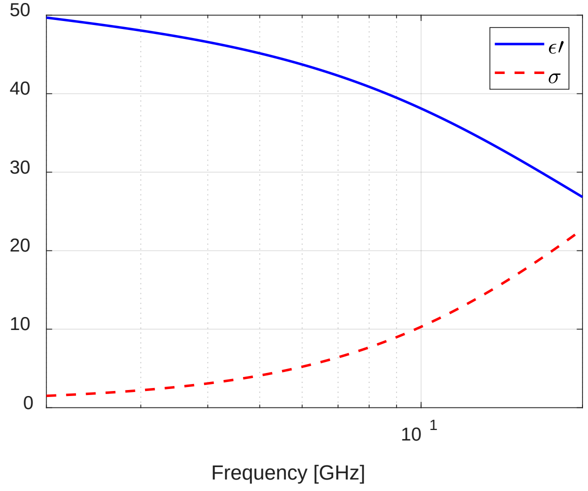


Real and Imaginary Parts of Permittivity

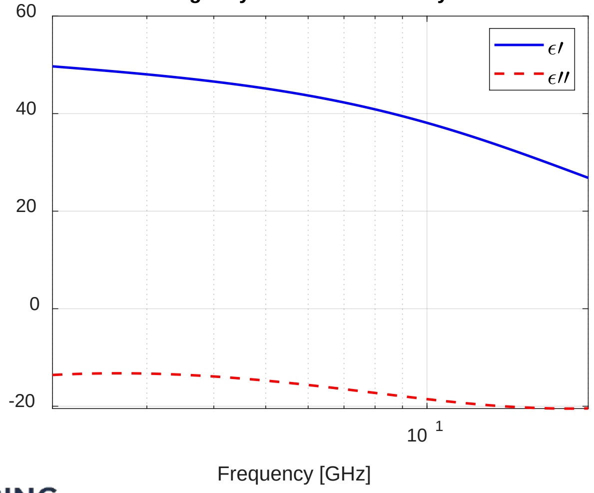


Brain Grey Matter
2 GHz-20GHz

Real Part of Permittivity and Conductivity

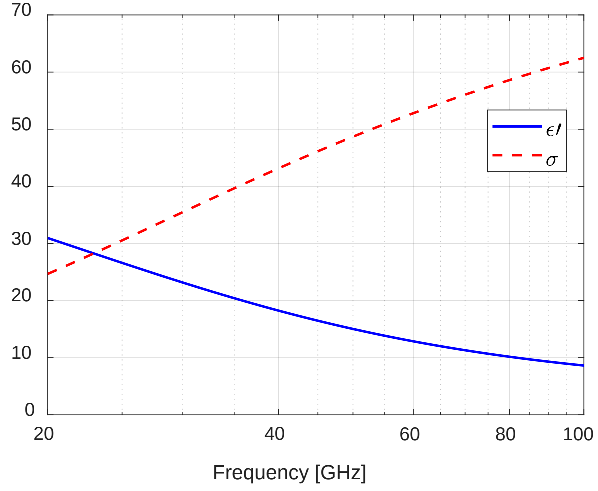


Real and Imaginary Parts of Permittivity

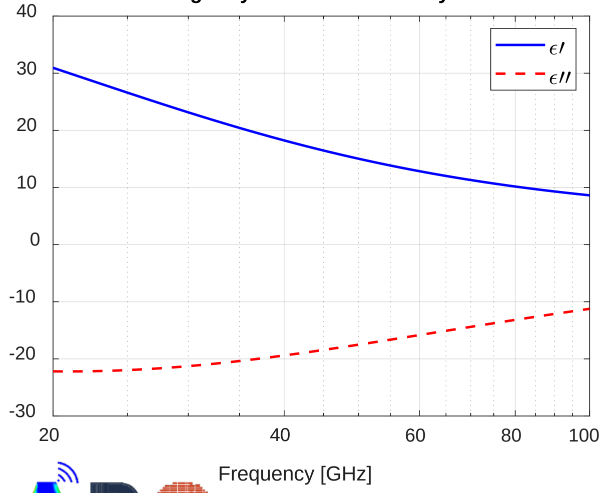


Muscle
20 GHz-100GHz

Real Part of Permittivity and Conductivity



Real and Imaginary Parts of Permittivity



ELECTRICAL ENGINEERING
COLORADO SCHOOL OF MINES

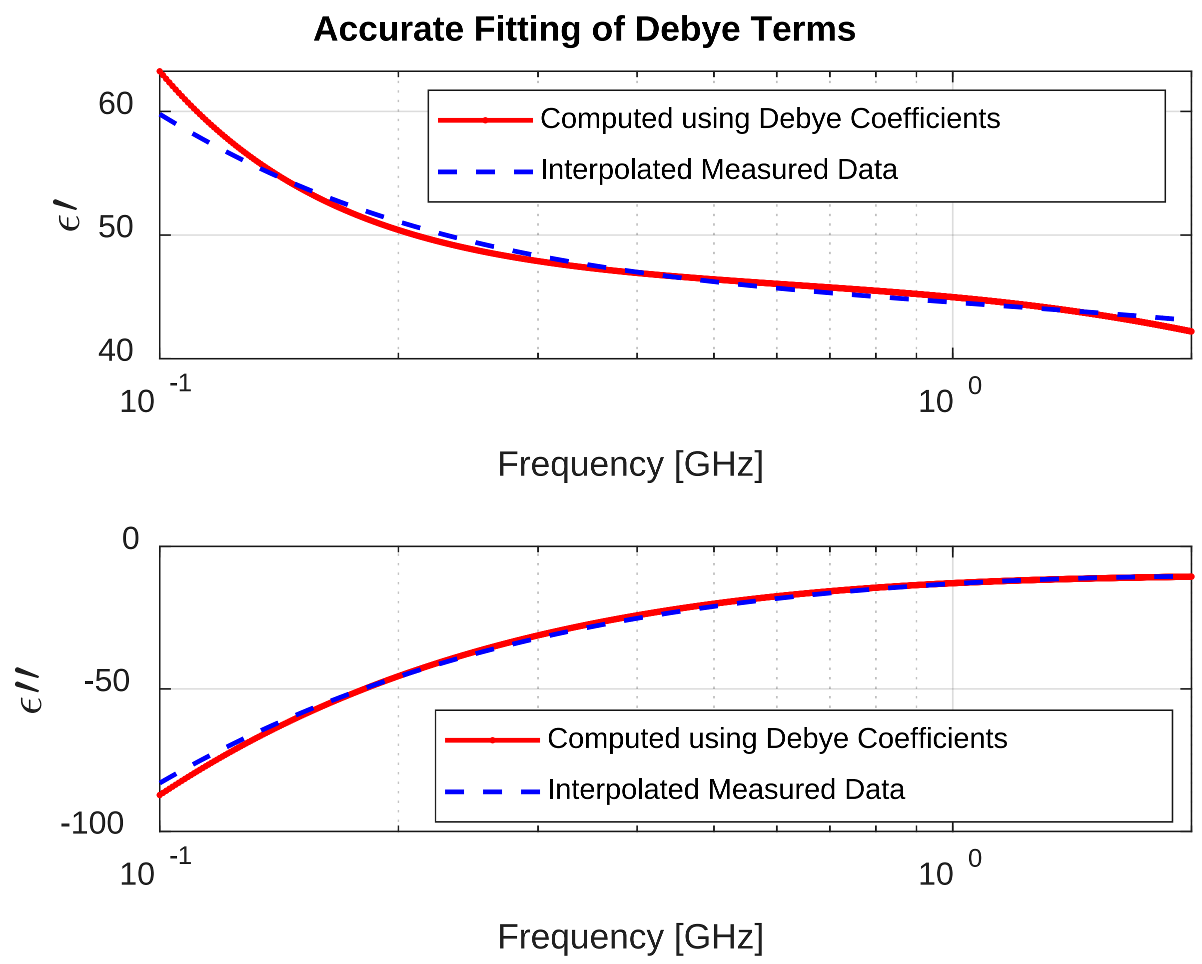
ARC

Comparison of Debye Model to Measured Data

Aorta Tissue

$$\epsilon_r^*(\omega) = \epsilon_\infty + \sum_{k=1}^{N} \frac{\Delta\epsilon_k}{1 + j\omega\tau_k}$$

- Frequency step size = 0.95 MHz
- Obtained coefficients:
  - ε_∞ = 24.470
  - $\Delta\varepsilon$'s = [19.900 10.265 960.303]
  - τ's = [0.025 0.799 19.115]
- # poles used: N = 3 **(3 terms Debye)**
- Max error between model and data
  - ε′ : 0.513 %
  - ε″ : 1.252 %



SAR Definition and Computational Sections

- 3-D Multiphysics head model consists of 21 biological tissues

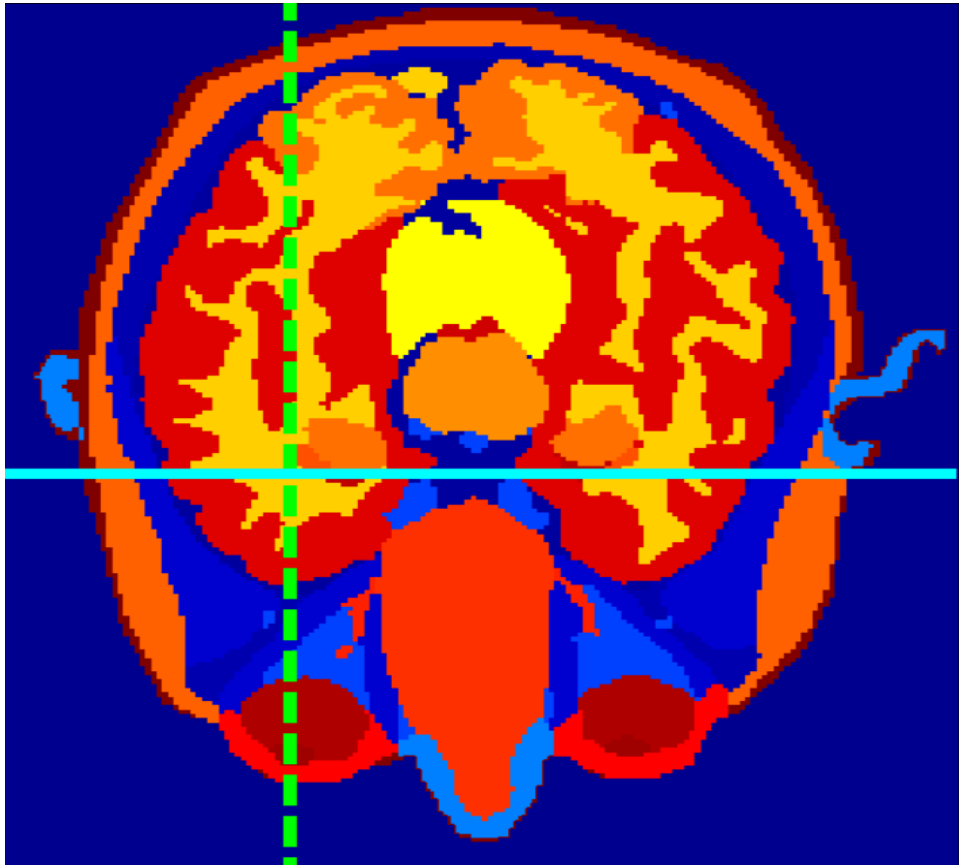
- Two version of model
  - Layer A Model – No eye tissue
  - Layer B Model – Eye tissue

- SAR equation for 1-D multi-layer model

$$SAR(i) = \frac{\sigma(i)}{2\rho(i)}(|E(i)|^2)$$

- σ and ρ are conductivity [S/m] and mass density [kg/m^3] of tissue, respectively, and i denotes indexed cell

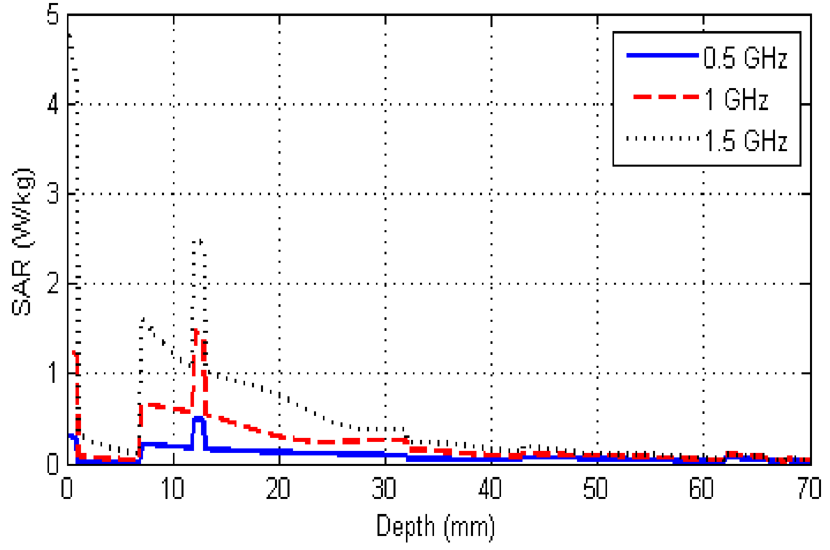
- Maximum SAR values increase at frequencies close to 100 GHz while penetration depths decrease substantially

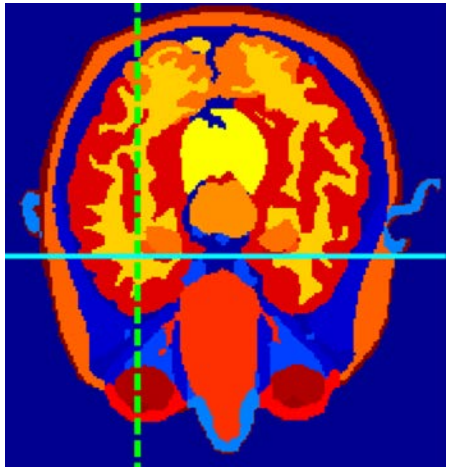


Horizontal cross-section of the 3D human head model

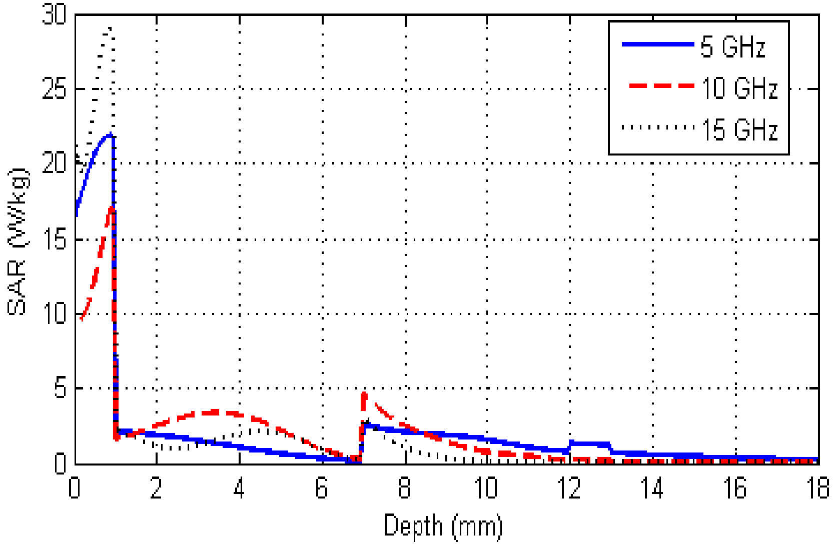
Local SAR Distribution for Layer A Model

0.5 – 1.5 GHz

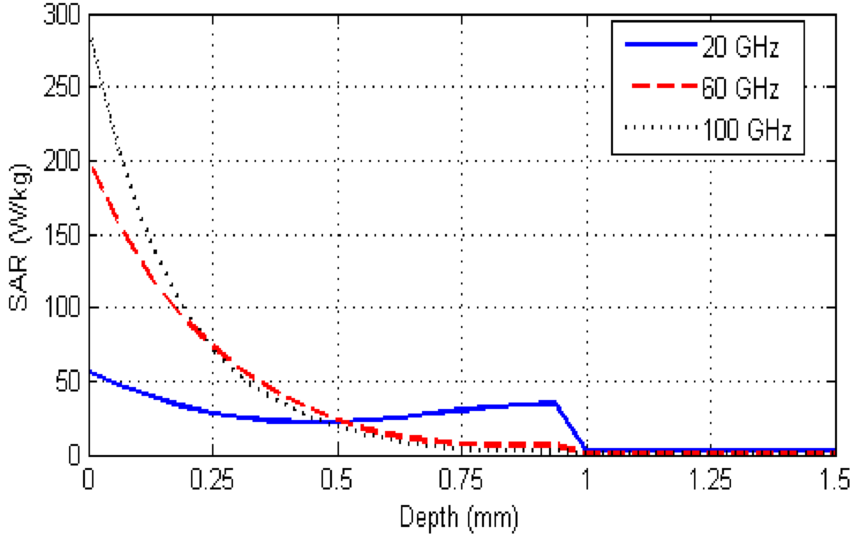




5- 15 GHz



20 – 100 GHz

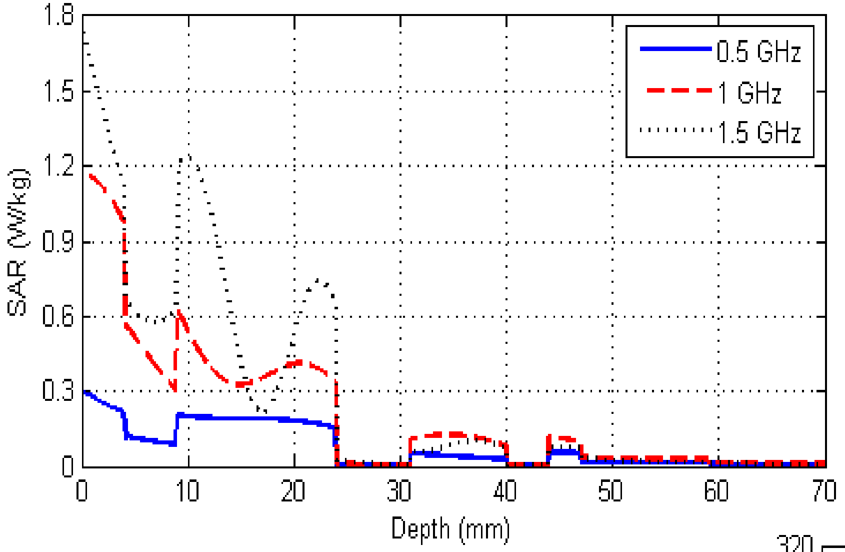


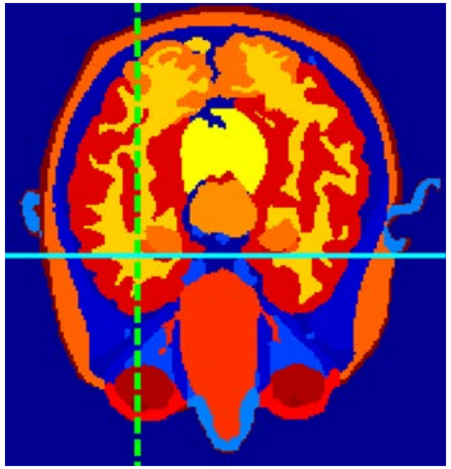
ELECTRICAL ENGINEERING
COLORADO SCHOOL OF MINES

ARC

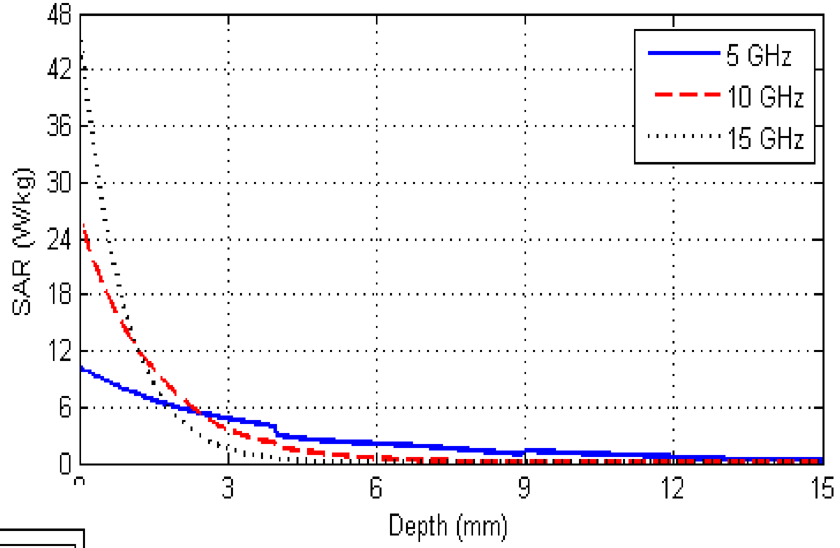
Local SAR Distribution for Layer B Model

0.5 – 1.5 GHz

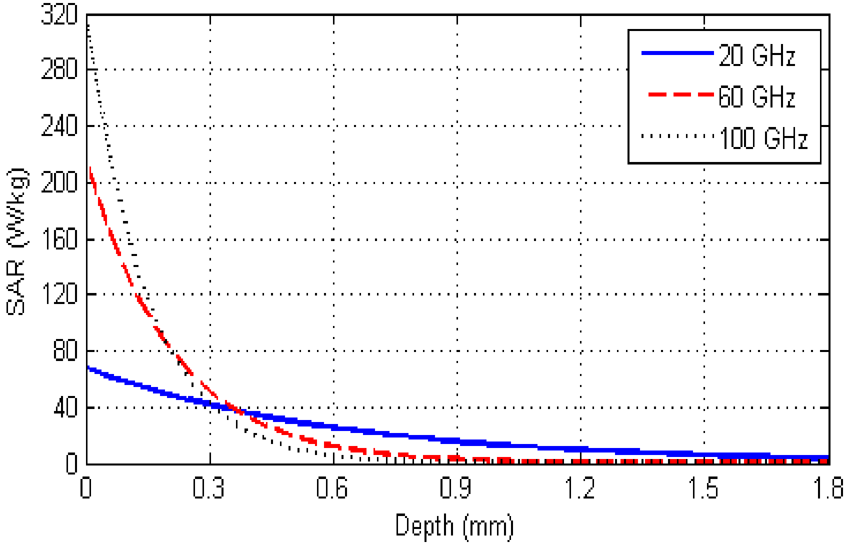




5- 15 GHz



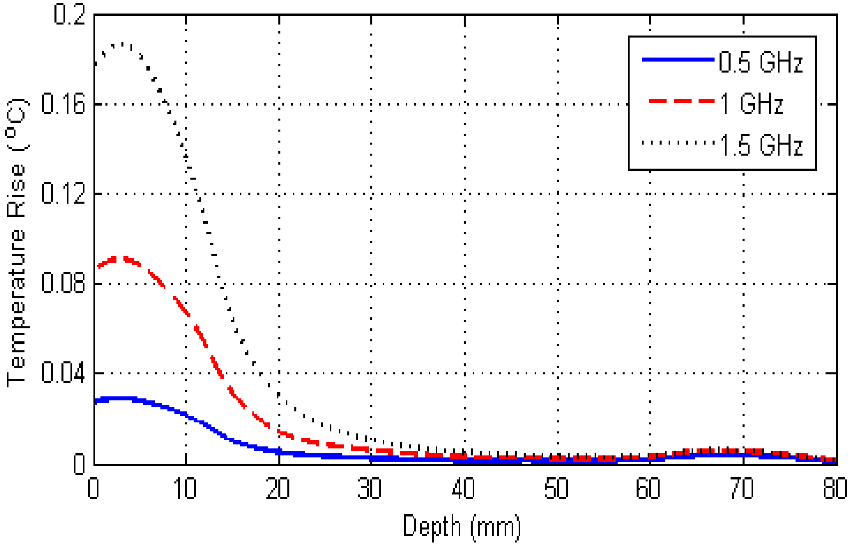
20 – 100 GHz

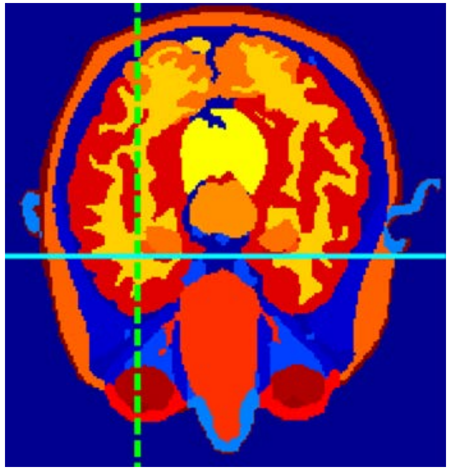


ELECTRICAL ENGINEERING
COLORADO SCHOOL OF MINES

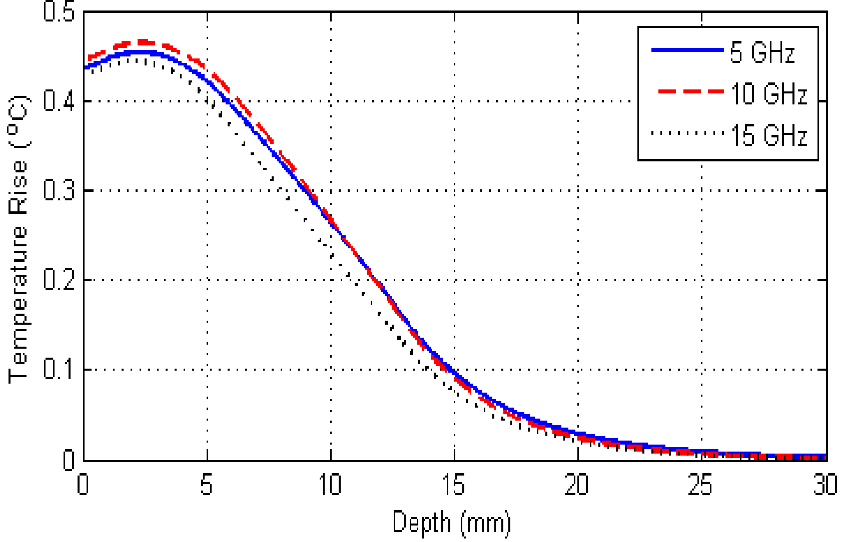
Temperature Rise Distribution for Layer A Model

0.5 – 1.5 GHz

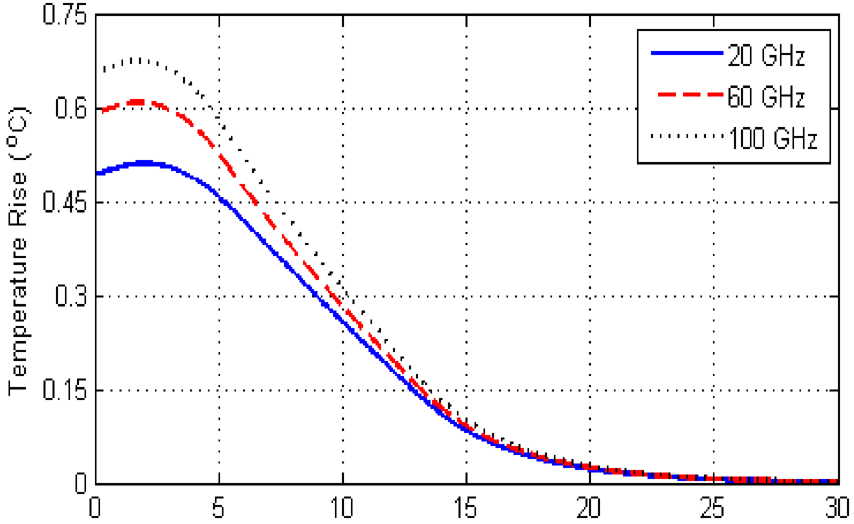




5- 15 GHz

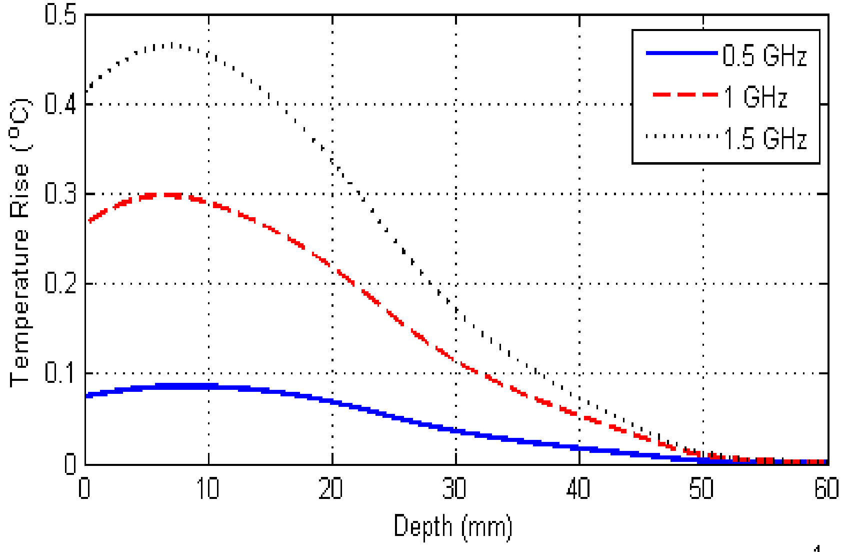


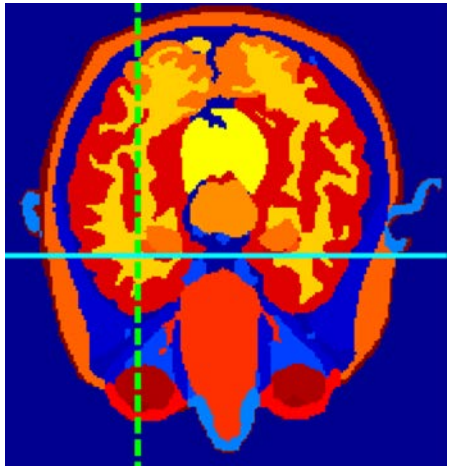
20 – 100 GHz



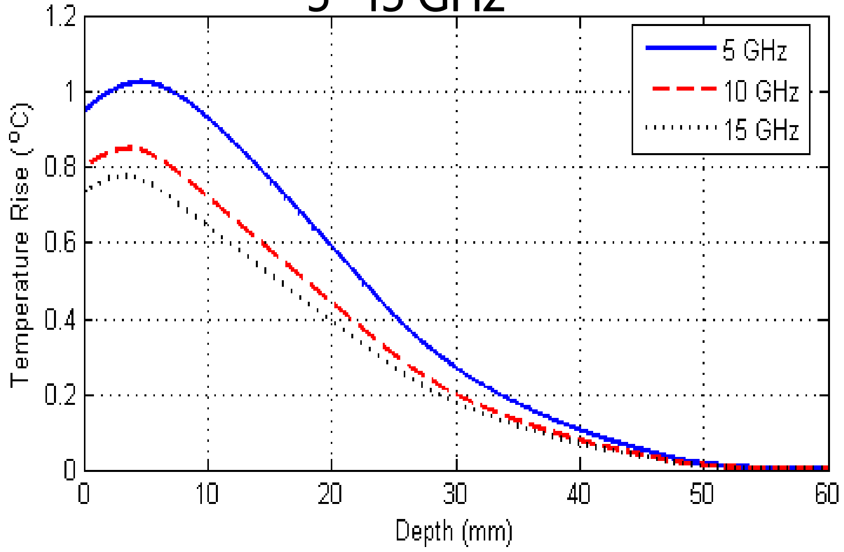
Temperature Rise Distribution for Layer B Model

0.5 – 1.5 GHz

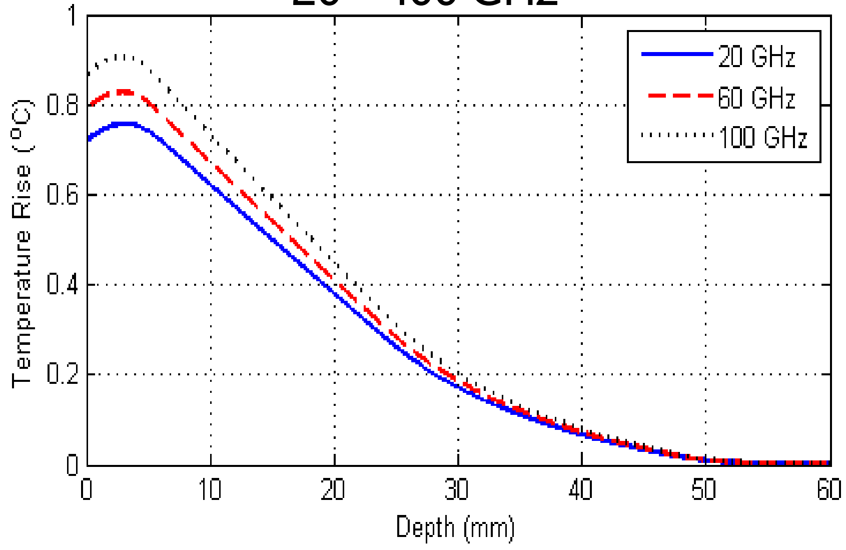




5- 15 GHz



20 – 100 GHz



ELECTRICAL ENGINEERING
COLORADO SCHOOL OF MINES

ARC

Conclusions

- Dielectric properties for over 45 biological tissues are analyzed using Debye Model with maximum errors for coefficients of 3.047 and 3.958 percent, respectively.
- One dimensional FDTD formulation with auxiliary differential equation is implemented.
- FDTD method is capable of accurately simulating the wave propagation for SAR and temperature rise characteristics.
- Maximum SAR values of 0.616 W/kg has been shown for two cuts to be less than the ICNRP exposure limits.
- Maximum temperature rises are less than 0.73 ^{o}C and 1.03 ^{o}C for layers A and B, respectively.
- Other areas of the body will be analyzed using the Debye coefficients and FDTD method.