Fast Forward and Inverse Scattering Algorithms

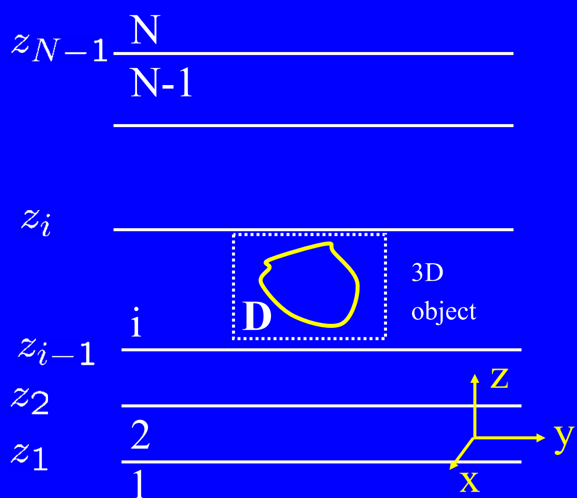
Qing H. Liu
Department of Electrical and Computer Engineering
Duke University

June 28, 2006

Outline

- Summary of Accomplishments
- Recent work on fast forward simulation
- Recent work on fast inverse modeling
- Phenomenological modeling of IEDs
- NUFFT imaging of IEDs
- Summary and Future Work

EM and Seismic Sensing of Buried Objects



Modalities

- **Radar**
- **Seismic**

Challenges

- **Complex interactions**
- **Large computation domain**

Objectives of Research

- To develop the state-of-the-art phenomenological EM/seismic models for buried/concealed objects.
- To develop the state-of-the-art inverse scattering algorithm to image buried/concealed objects.
- To apply these forward and inverse methods for system design and data processing

Summary of Accomplishments

- Forward solvers developed in this program
  - PSTD (pseudospectral time-domain) method
  - Discontinuous Galerkin method
  - BCGS-FFT method for heterogeneous objects in layered media
  - Spectral integral method
  - Diagonal tensor approximation (DTA) for rapid modeling

Summary of Accomplishments (continued)

- Inverse solvers developed in this program
  - Diagonal tensor approximation (DTA) for rapid inversion
  - Distorted Born iterative method (DBIM) inversion for objects in layered media
  - Contrast source inversion (CSI) for objects in layered media
  - Nonuniform fast Fourier transform (NUFFT) imaging
  - Joint inversion method for seismic/radar data

Summary of Accomplishments (continued)

- Systems designed and analyzed
  - An ultra wideband GPR antenna (transitioned to Niitek)
  - Design and optimization of an induction-radar sensor for landmine detection (transitioned to Niitek)
  - Phenomenological modeling of landmines
  - Phenomenological modeling of tunnels

Summary of Accomplishments (continued)

- Datasets processed
  - Georgia Tech radar data sets have been processed to achieve high-resolution 3D imaging
  - Niitek datasets for landmines have been processed to obtain both 2D and 3D images
  - IED datasets from Niitek have been processed to obtain high-resolution 3D images
  - 2D and 3D imaging results have been obtained for tunnel detection with synthetic datasets

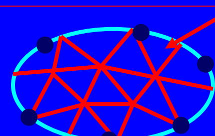
Outline

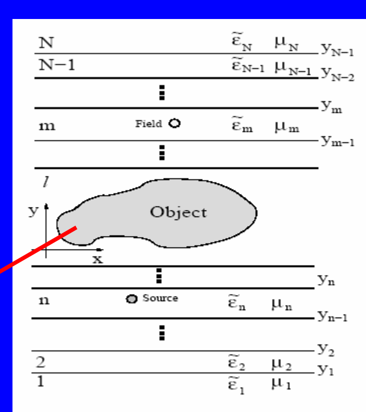
- Summary of Accomplishments
- Recent work on fast forward simulation
- Recent work on fast inverse modeling
- Phenomenological modeling of IEDs
- NUFFT imaging of IEDs
- Summary and Future Work

Recent work on fast forward simulation: Spectral Integral Method Hybrid With FEM

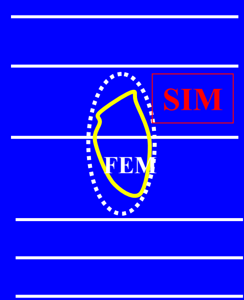
- Can treat metal and inhomogeneous dielectrics
- No stair-casing errors
- Highly efficient radiation boundary condition for FEM

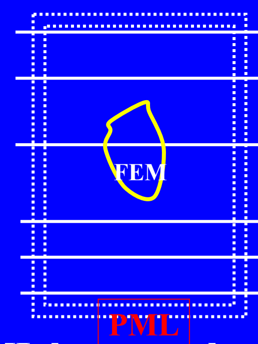
Interior is treated by FEM





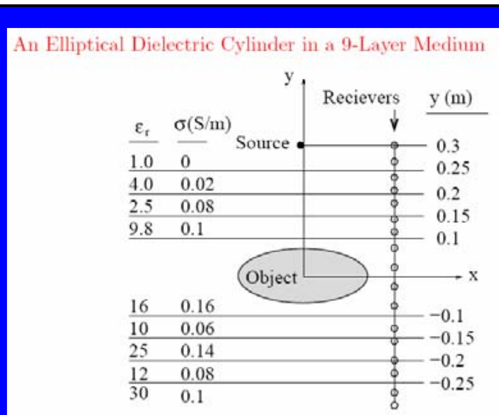
SIM/FEM for Complex Objects: Comparison against FEM with PML absorbing boundary condition





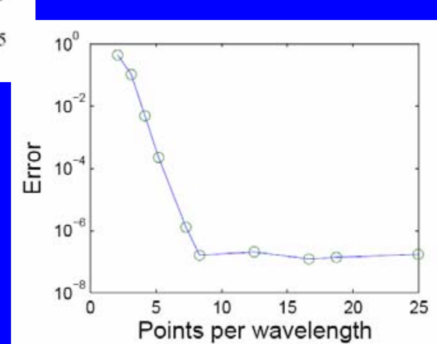
- SIM radiation boundary can be placed close to object
- Much fewer unknowns than PML/FEM

- PML has to enclose the whole domain
- Much more unknowns SIM/FEM

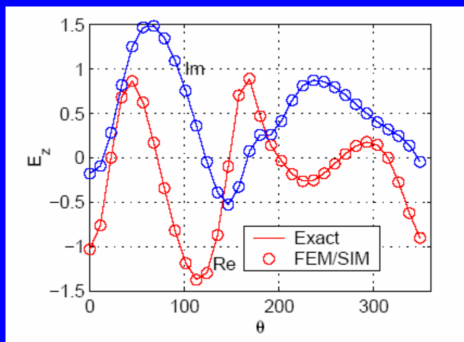


- Sampling of 3 points per wavelength is adequate for 1% accuracy

- **SIM error decreases exponentially as sampling density increases**

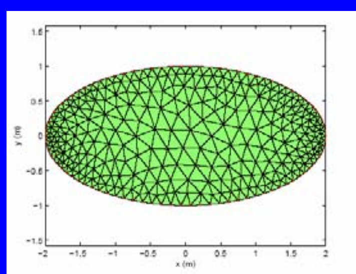


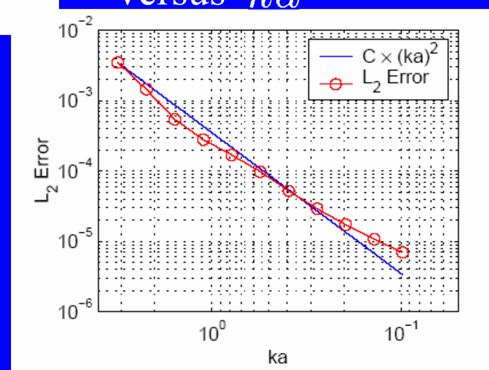
Hybrid SIM/FEM



Field on the boundary for $ka = \pi$

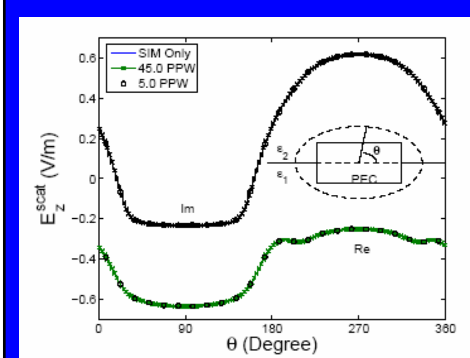
Convergence curve versus ka

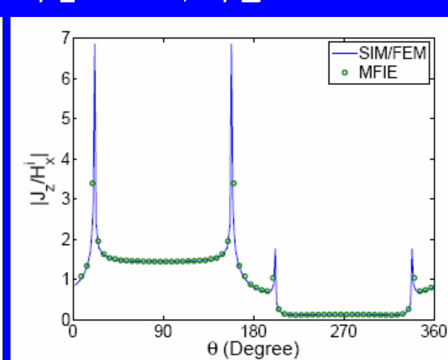




A PEC Object in Two Layers

PEC: $12.5 \times 5\ \text{cm}^2$ $\epsilon_{r1} = 1, \epsilon_{r2} = 4$



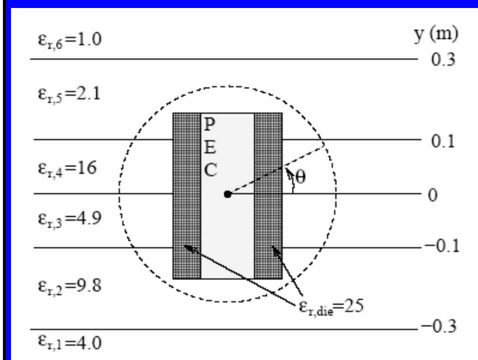


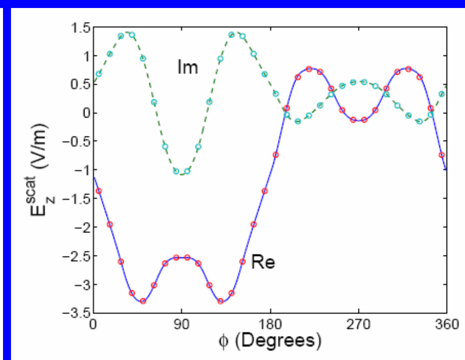
f=300 MHz

Error <1% at 5 PPW

Comparison with MOM

A Six-Layer Example





PEC: $20 \times 30\ \mathrm{cm}^2$

Coating: $5\ \mathrm{cm}$

5.7 PPW already gives highly accurate result

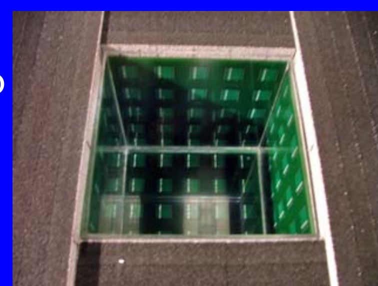
Outline

- Summary of Accomplishments
- Recent work on fast forward simulation
- Recent work on fast inverse modeling
- Phenomenological modeling of IEDs
- NUFFT imaging of IEDs
- Summary and Future Work

Recent work on fast inverse modeling: A Microwave Imaging System

- Arrays with 100 and 60 antenna elements have been constructed
- Operating frequency: 2.72 GHz

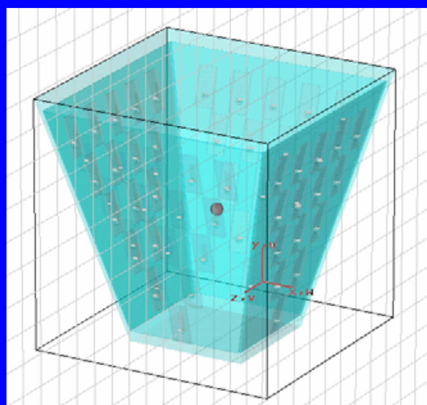
3-D

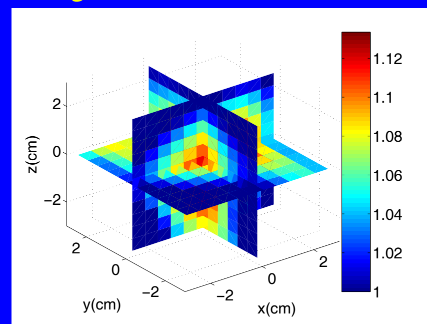


Duke's Proof-of-Concept Systems

- The imaging chamber has a dimension of approximately 15 cm x 15 cm x 15 cm
- The system is built to test the capability to perform super-resolution at microwave frequencies
- A small (1.9 cm) clay ball is placed at the center of the imaging chamber
- The BCGS-FFT method is used as a fast forward solver
- The DTA method is used as a rapid inversion method

3-D Experimental Result for a 1.9 cm Object

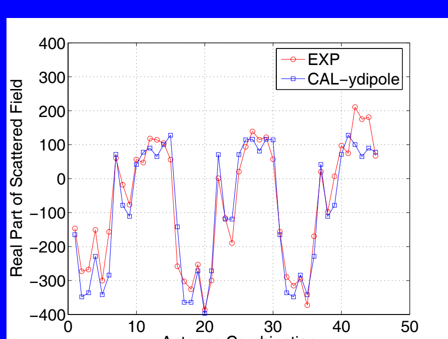


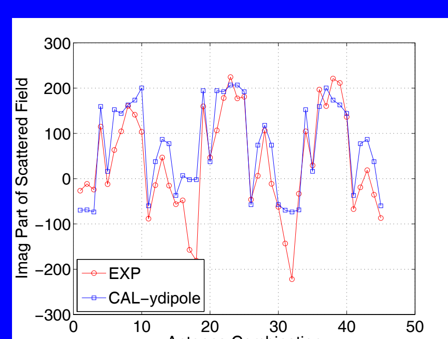


Reconstructed permittivity using DTA-BIM at 2.72 GHz

This demonstrates that the system can detect and image an object smaller than 1/5 of a wavelength in size.

Comparison measured data with simulation





(T5-R45 Combination)

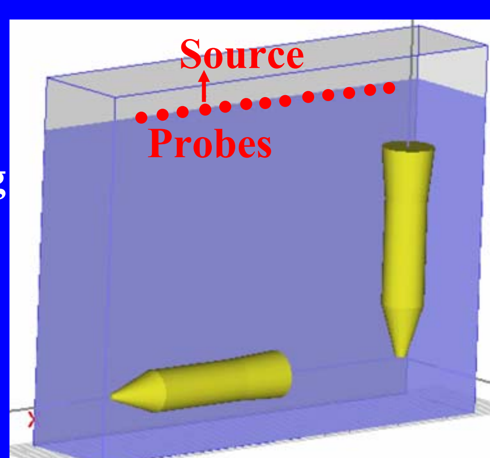
Outline

- Summary of Accomplishments
- Recent work on fast forward simulation
- Recent work on fast inverse modeling
- Phenomenological modeling of IEDs
- NUFFT imaging of IEDs
- Summary and Future Work

Phenomenological modeling of IEDs: Two IEDs Buried in Soil

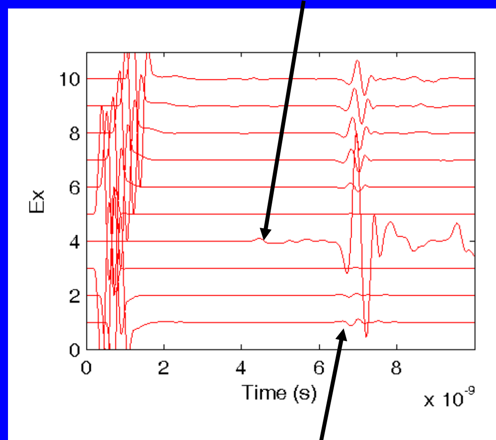
2 IEDs

40 cm long



Waveforms at the probes

From vertical IED

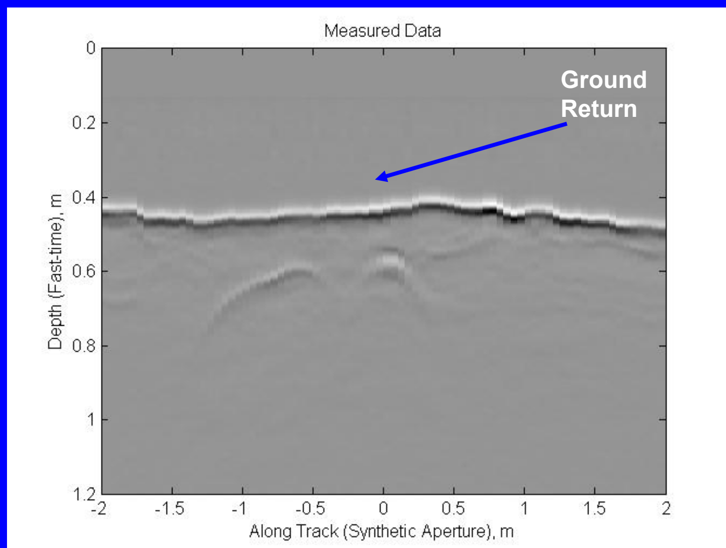


From horizontal IED

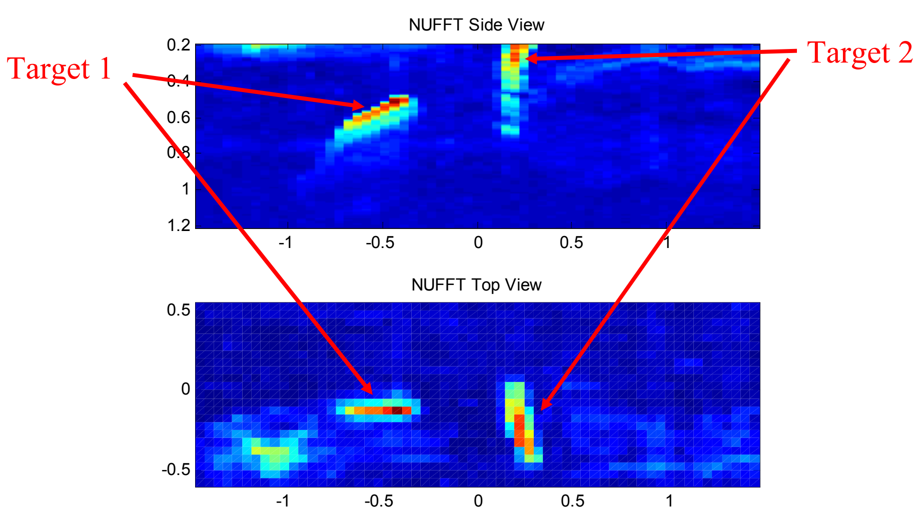
Outline

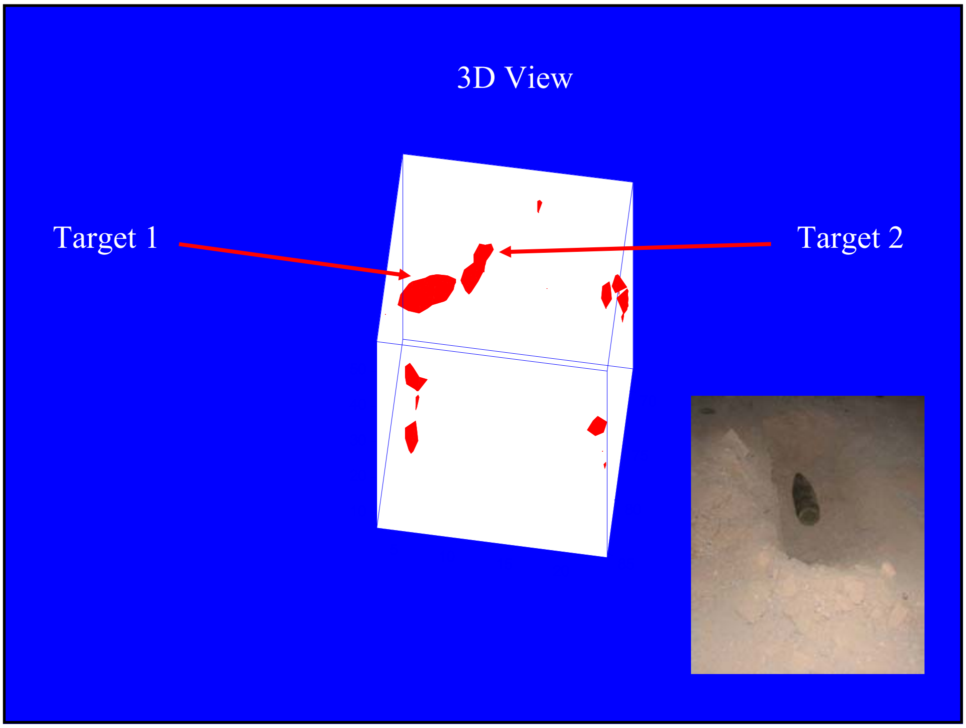
- Summary of Accomplishments
- Recent work on fast forward simulation
- Recent work on fast inverse modeling
- Phenomenological modeling of IEDs
- NUFFT imaging of IEDs
- Summary and Future Work

NUFFT imaging of IEDs: A Niitek Field Example of IED Imaging



NUFFT Imaging





Summary

- Several fast forward and inverse solvers have been developed for both radar and seismic detection and imaging.
- A spectral integral method is developed as the radiation condition for FEM. Highly effective for objects in layered media.
- Experimental data inversion confirms high fidelity and super-resolution of the DTA inversion method.
- Both forward and inverse solvers have been applied to the IED problem.