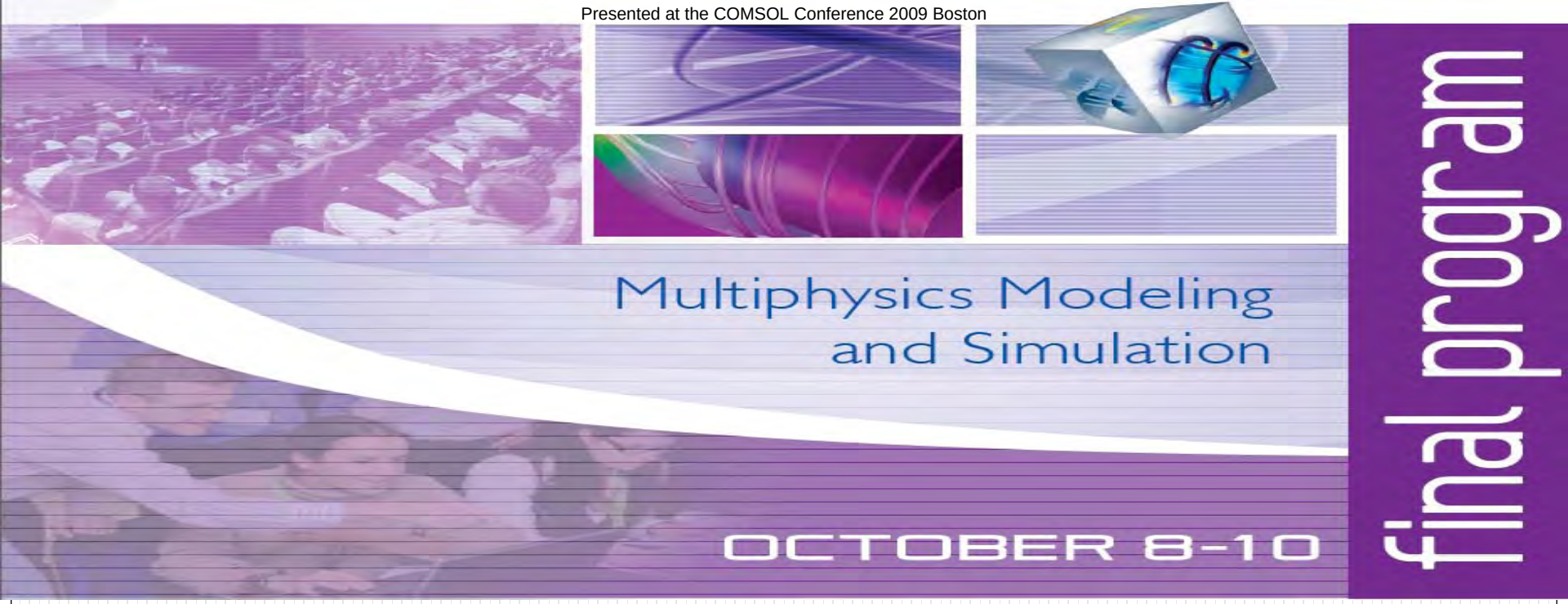
Presented at the COMSOL Conference 2009 Boston




# Effect of Antennae Polarization Relative to Tunnel Orientation on Electromagnetic Wave Scattering due to Underground Tunnels

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# Outline:

- Problem Identification
- 2D-FDFD and Experimental Simulation
- Previous Work & Challenges
- COMSOL 3D Simulation
- Conclusion

# Problem Identification

Underground tunnels present both military and homeland security threats: Frequently used to avoid border security and checkpoints; excavated by prisoners to flee from prisons; used by smugglers as transit routes for trafficking weapons, people, drugs, etc.; assailants entrance to high security facilities to plant and detonate high-grade explosives; help high-level prisoners to escape detention centers; nowadays, International terrorism , the most important

Need for a forward model for tunnel detection and real-time monitoring of activities

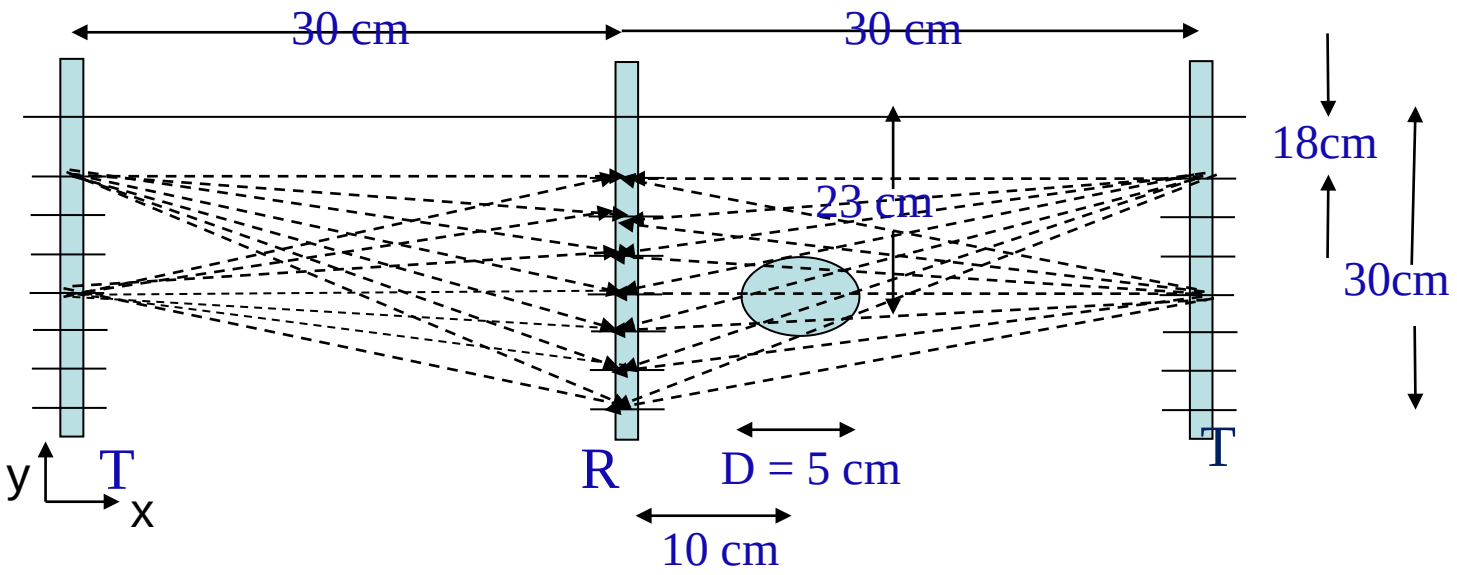
A tunnel near Otay Mesa, California (Sandy H, Getty Images, 2006); and another starting in an abandoned house in Tijuana, Mexico (David Maung, AP, 2004)

# Experimental Validation

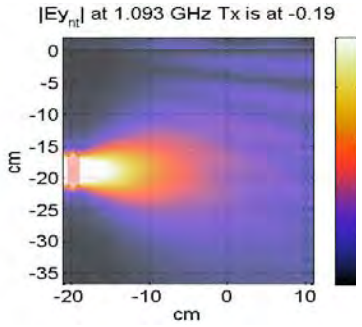
- Experimental validation of forward model:
  - Cross-well radar measurements across PVC-cased borehole antennas used to monitor localized changes in soil integrity, and dielectric properties.
  - PVC-cased monopole antennas installed in fully water-saturated sandy soil across a 137.16 cm (4.5') horizontal PVC-cased air-filled tunnel with a diameter of 5.08 cm (2") buried between the antennas
  - Multiple-depth transmission and reflection wide-band frequency-response measurements collected to evaluate the response of the saturated sandy soil with/without the air-filled pilot-scale tunnel.
  - Real-time monitoring of a pocket of water moving through the PVC tunnel to simulate a human body.

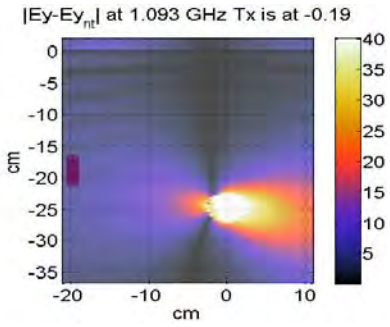
- Theoretically simulation of all of the above, using a 2D Finite Difference Frequency Domain (FDFD) method.

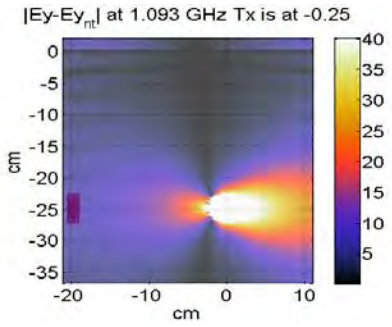
# Experimental Setup for Multiple-Depth Data Collection

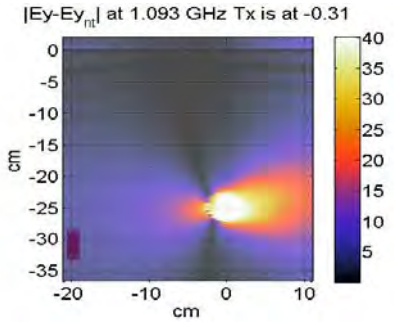


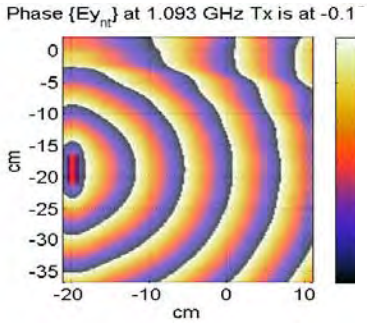

# 2D-FDFD Simulations

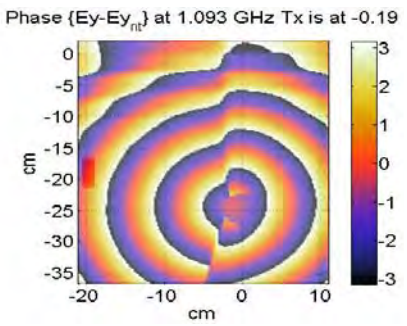


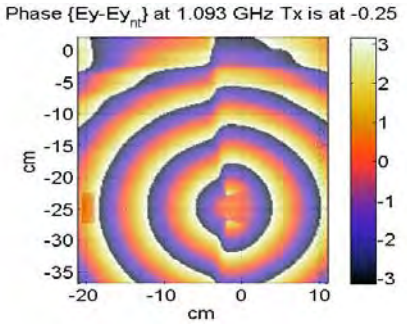



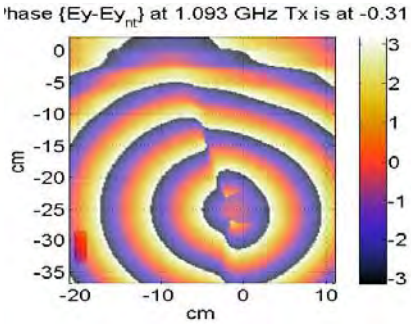



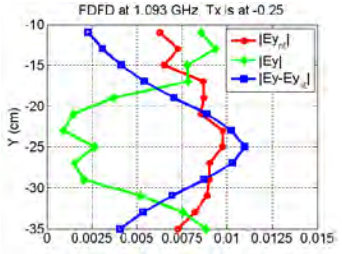




(a) (b.1) (b.2) (b.3)

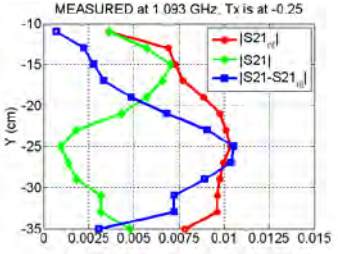
Y-component (top) and phase (bottom) of: a) incident, and b) scattered electric field by tunnel located at (x= 0 cm, y = -23 cm), source of incident field (transmitting antenna) at: x = -20 cm, and y (depth) of: a) -19 cm, b.1) -19 cm, b.2) -25 cm, and b.3) -31 cm

# Comparison between Experiment & Theory

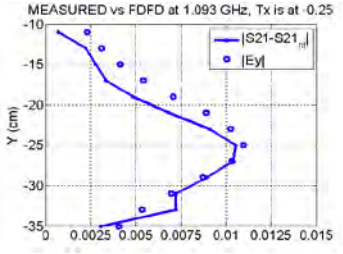
The 2D FDFD simulation was compared with the experimental data, to ensure agreement to achieve a reliable and realistic forward model for future inversion and image reconstruction.



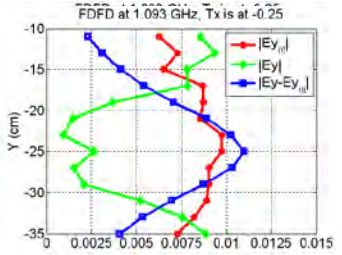

(a.i)



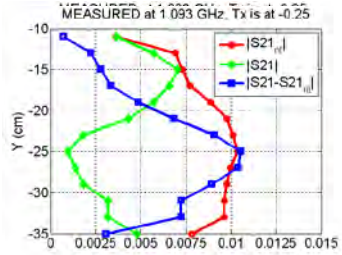

(b.i)



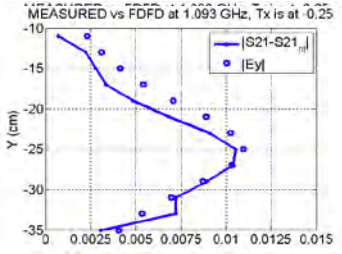

(c.i)



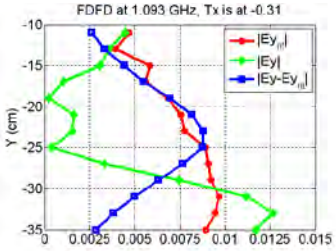

(a.ii)



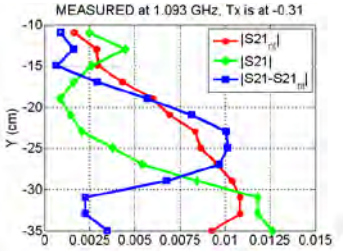

(b.ii)



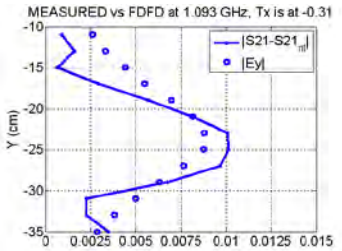

(c.ii)




(a.iii)




(b.iii)

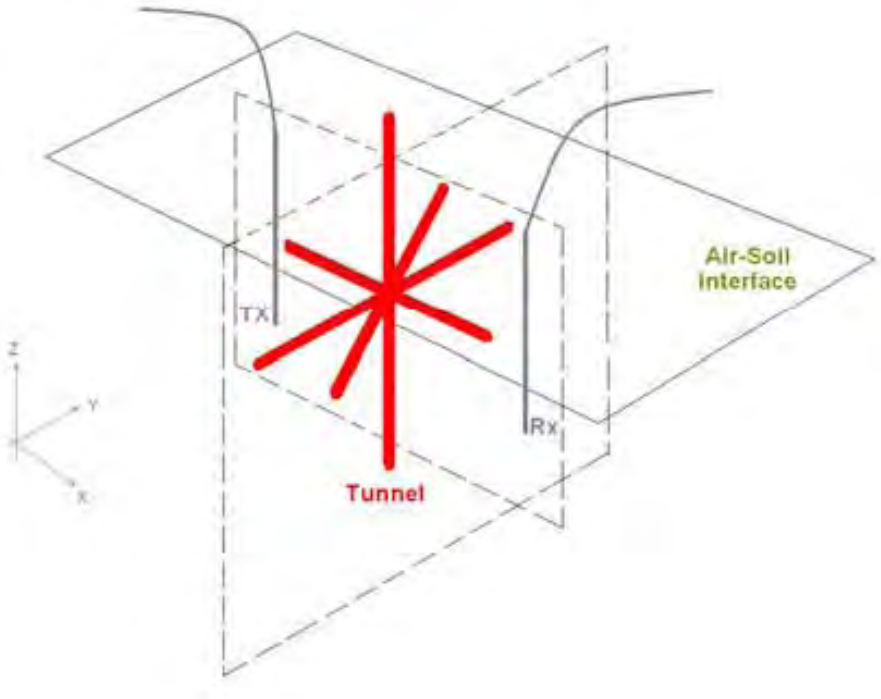



(c.iii)

a) Theoretical simulation, $E_y$, b) experimentally measured, $S_{21}$ data, and c) comparison between the two; for incident (subscript “Int”), total (no subscript), and scattered field due to the tunnel (the difference), for transmitter depths: (i) 19 cm, (ii) 25 cm, and (iii) 31 cm

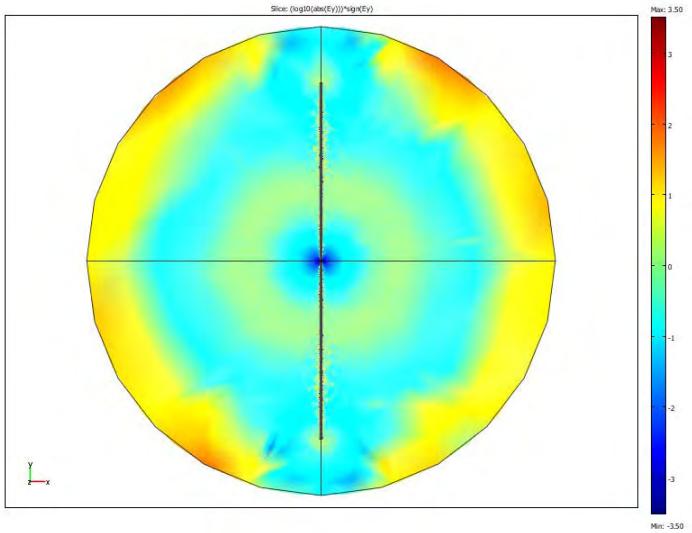
# Need for 3D simulation (COMSOL)

- Magnitude of scattered field peaks at the depth of the tunnel, regardless of the depth of the incident field source (i.e. transmitting antenna):
  - Strong representative of the tunnel depth
- Phase of scattered field can be used for travel time tomography;
- Remarkable agreement between experimental and simulated scattered fields;
  - Reinforces choice of the 2D-FDFD model as an accurate forward model for inversion and image reconstruction for detection and localization of tunnel objects
- Problem: small, deep tunnels: “Physical challenge of balancing trade-off between image resolution and skin depth”;
- Tunnels have extremely large aspect ratios: “discriminating tunnel length at lower frequency and tunnel cross-section at higher frequency;
- Study the effect of frequency and antennae polarization with respect to antennae need to be studied;
- A 3D-FD forward model is required;
- COMSOL  is a user-friendly option.

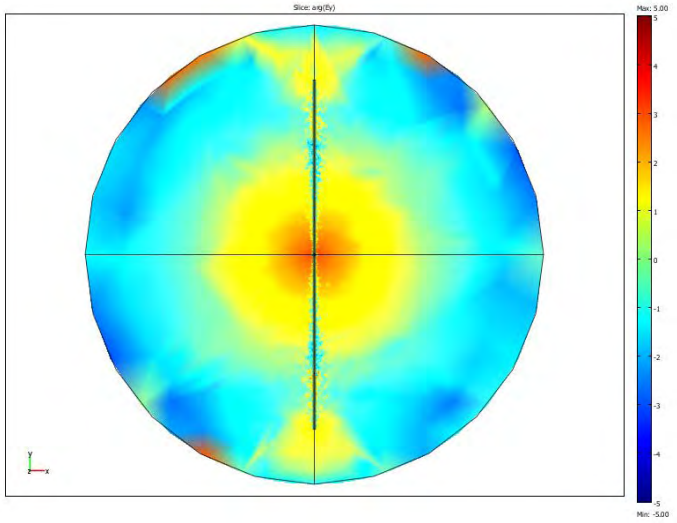



New Experimental and theoretical Model Setup

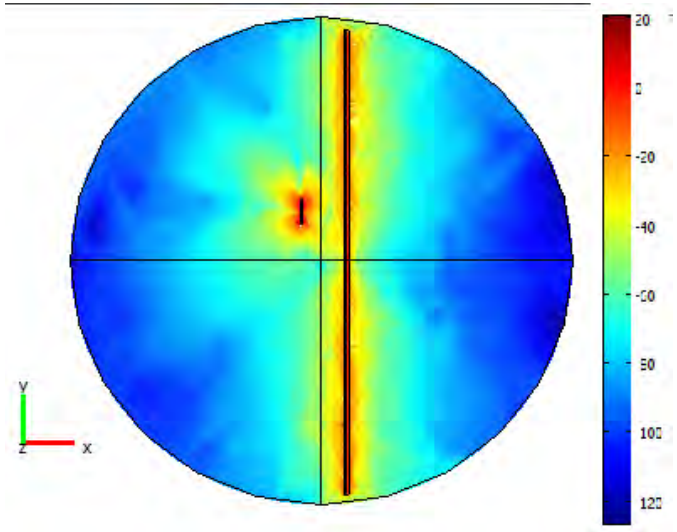
(a)



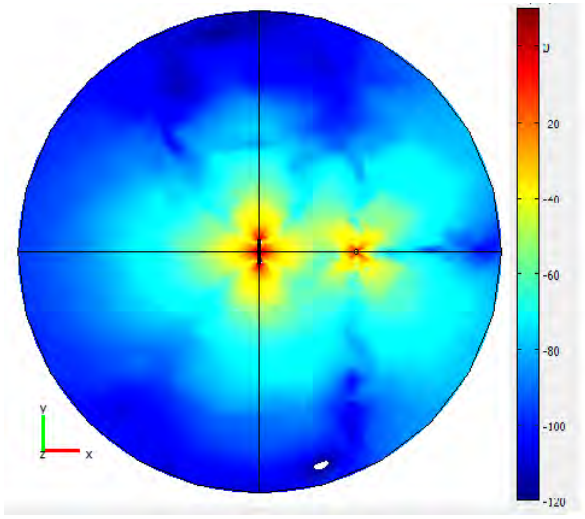
(b)



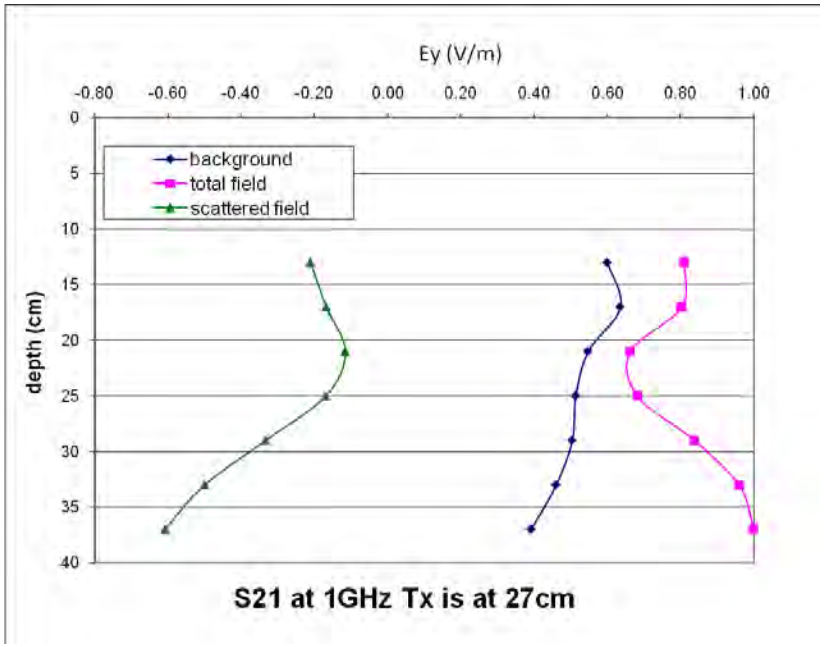
(c)



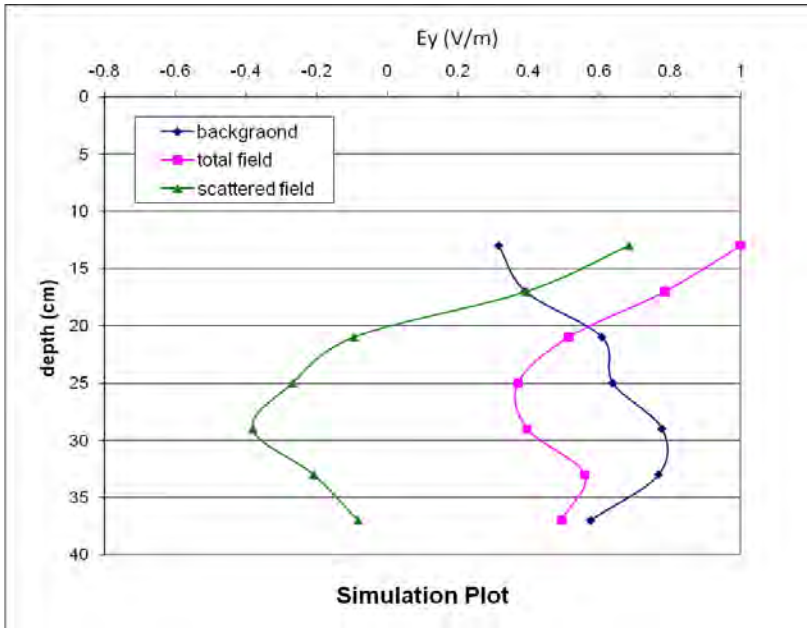
(d)



Incident field in background soil on a depth slice (XY-plane) with a vertically polarized dipole source (1 GHz) : (a) amplitude of incident $E_y$ in dB scale; (b) phase of incident $E_y$; (c) amplitude of scattered $E_y$ in dB scale due to perpendicular tunnel; and (d) amplitude of scattered $E_y$ in dB scale due to perpendicular tunnel.




(a)




(b)

Incident, total and scattered Y-component of electric field and frequency of *f* = 1.093 GHz: a) Simulated in COMSOL, 27 cm deep transmitter; and b) Experimentation, 30 cm deep transmitter

# Challenges:

- Modeling the monopole or dipole antennas
- Spherical PML, easy to model, but not the best mesh generation
- Cubical PML, more complicated to generated, but more effective mesh generation
- Yet to successfully experimentally validate the 3D model (could be due to short-come in the experimental setup)

# Theory versus Experiment

The 2D FDFD simulation was compared with the experimental data, to ensure agreement to achieve a reliable and realistic forward model for future inversion and image reconstruction.

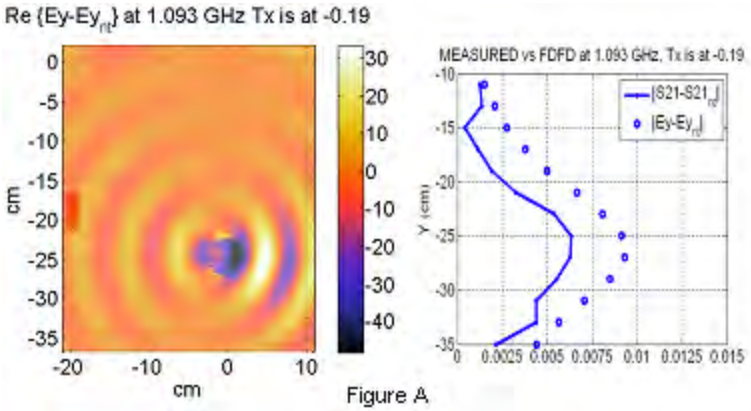



Figure A

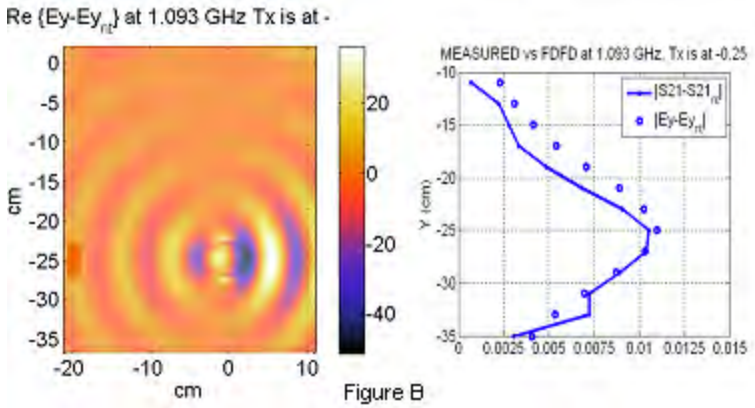



Figure B

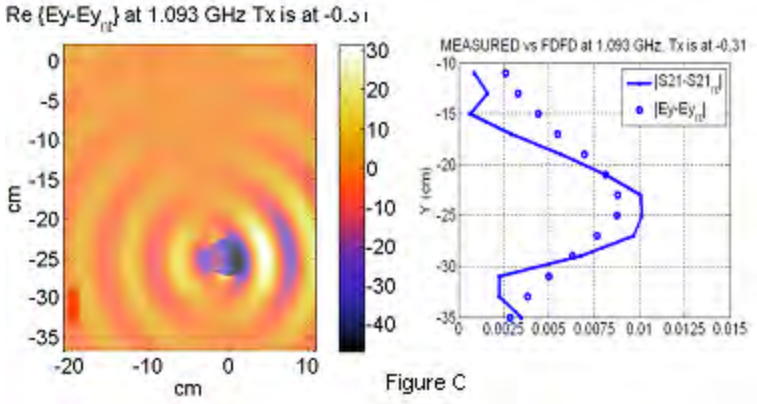



Figure C

Right: scattered field on depth slice views, Left: comparison between simulated (solid) and experimental results (dotted), for transmitter depths: (a) 19 cm, (b) 25 cm, and (c) 31 cm