FDFD Verification and Analysis for Generation of Channel Spectral Responses

Richard G. Obermeier, Justin L. Fernandes, Jose A. Martinez, and Carey M. Rappaport
Work supported by ALERT, Gordon - CenSSIS, and Northeastern University, Boston, MA 02115 `(richard.obermeier@gmail.com)`

Abstract

As suicide bombings become more and more common in today's day and age,safe detection and neutralization methods are being actively researched. Millimeter-wave radar holds the potential to detect threat targets from standoff distances using a Synthetic Aperture Radar (SAR) imaging technique. In order to verify the fundamental sciences of this detection system, Finite Difference Frequency Domain (FDFD) Analysis is used to generate spectral responses for simulated targets. This project analyzes the FDFD to both verify and optimize the spectral responses for use in SAR imaging.

Background

- It has been proposed [1, 2] that millimeter wave radar has the potential to detect irregular contours along the human body
- An FMCW (Frequency Modulated Continous Wave) Radar system is used to transmit a signal in the passband (94Ghz - 100Ghz) range over a certain modulation period at a potential target

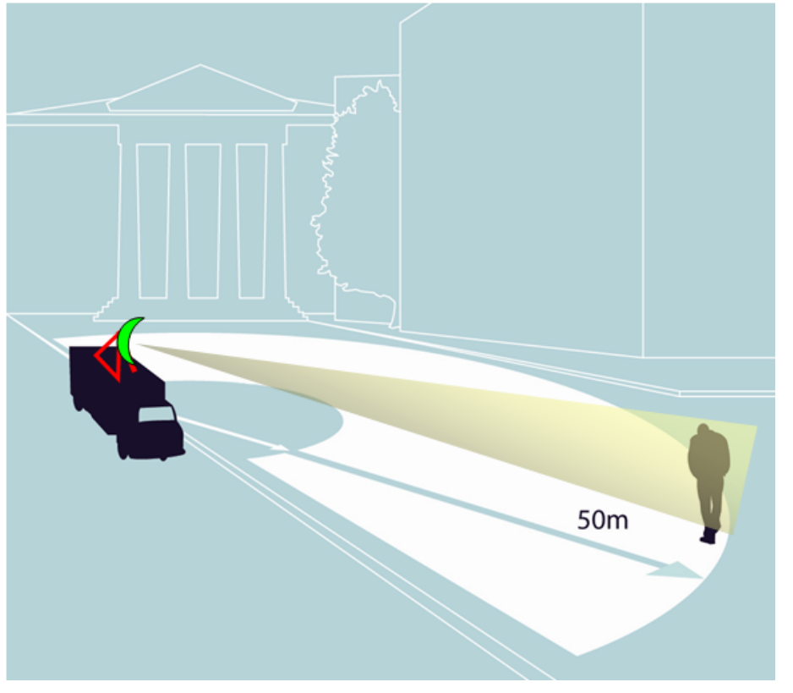


Figure 1: General sketch of our van-based, high resolution radar system for standoff detection of potential suicide bombers.

- Signal is transmitted at standoff distances (10m - 50m) from target
- The scattered signal is measured at the place of transmission and a SAR (Synthetic Aperture Radar) technique is used to create an image of target
- Ultimate goal is to conceal radar system on vehicle

ALERT Structure and State of the Art

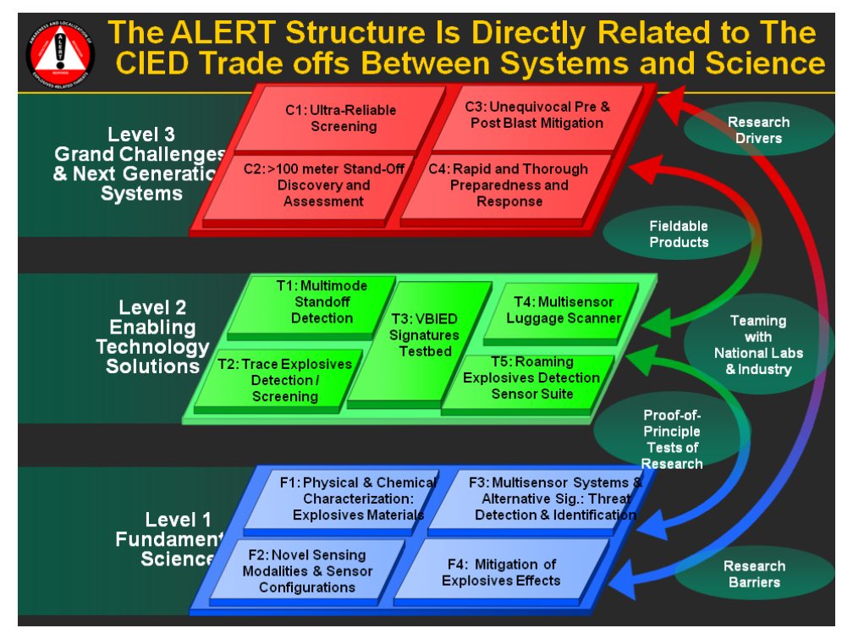


Figure 2: ALERT 3-Level Diagram

- Finite Difference Frequency Domain analysis seeks to uncover the fundamental science of the threat detection system (L1-F3)
- The main competitor to FDFD Analysis is the Finite Difference Time Domain method (FDTD)
- Errors in the FDTD compound as the simulation advances in time [3]; errors in the FDFD are isolated to the individual frequency simulations

- The time-step Δt of 2-D FDTD simulations are constrained by the stability condition: $\frac{c\Delta t}{h} < \frac{1}{\sqrt{2}}$, where h is the spatial grid size [3]
- The frequency step of the 2-D FDFD is only limited by the maximum ambiguous range: $R_{max} = \frac{c}{2\Delta f}$
- These conditions imply that FDFD can produce valid simulation data more efficiently with respect to simulation time and data storage than FDTD
- FDFD can be used to ***simulate any radar system***

Introduction to FDFD Analysis

- FDFD (Finite Difference Frequency Domain Analysis) is a numerical solution to Maxwell's Equations

- FMCW transmitted signal is transformed into the frequency domain by the Fourier Transform: $S_t(\omega) = \int_{-\infty}^{+\infty} s_t(t)e^{-i\omega t}dt$
- Simulates frequencies separately as uniform plane waves which satisfy the equation $Ax = b$, where A describes the impedence, x the field properties, and b the source.

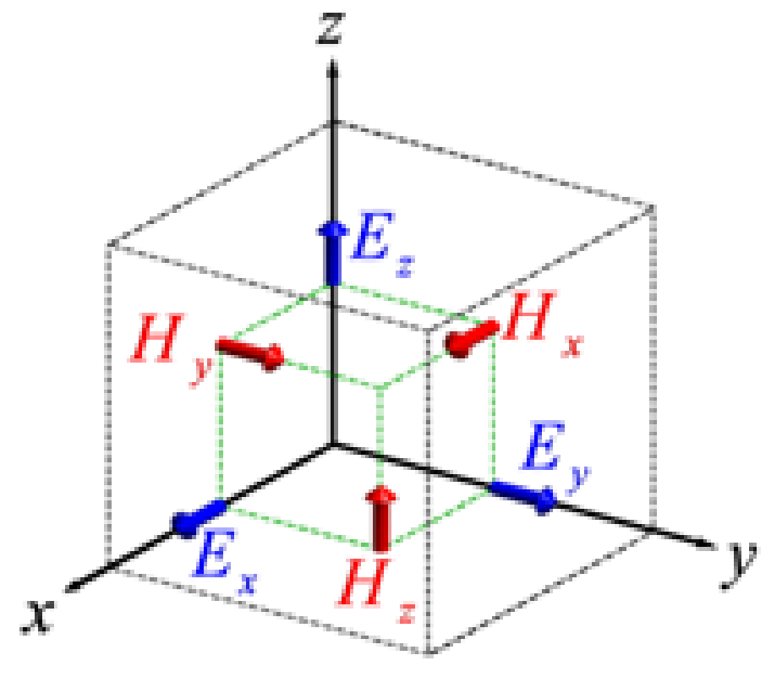


Figure 3: Finite Difference Yee Cube

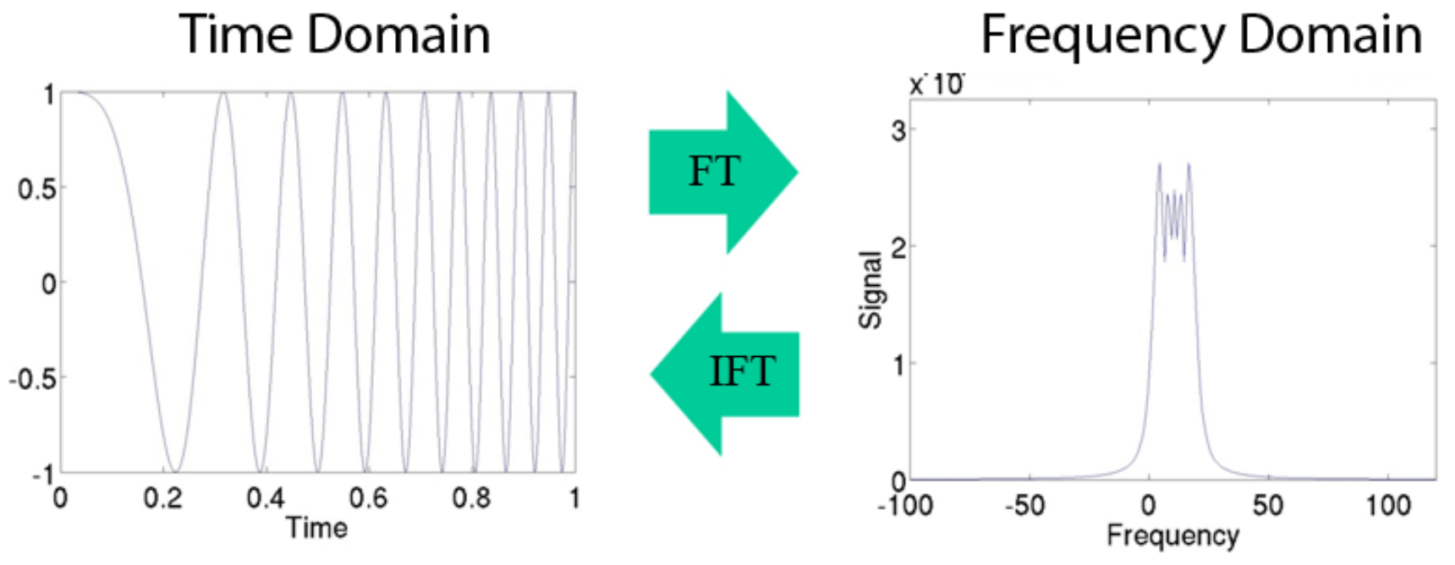


Figure 4: Fourier and Inverse Fourier Transform of sample FMCW signal

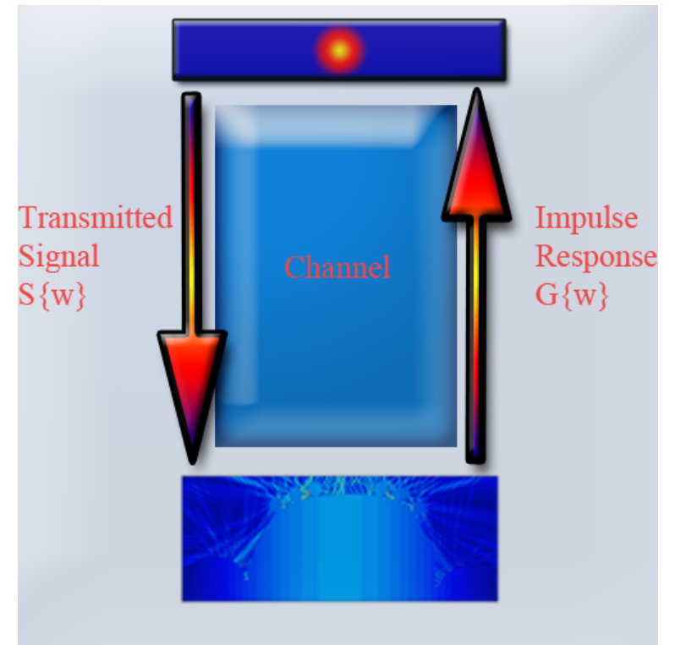


Figure 5: Diagram of Signal Transmission

- Inverse Fourier Transform of channel spectral response yields impulse response in time domain: $s_r(t) = \int_{-\infty}^{+\infty} S_r(\omega)e^{i\omega t}d\omega$
- The *goal* of this project is to *verify and optimize the FDFD simulation* of standoff explosives detection to *generate accurate spectral channel responses*

Verification of FDFD Analysis

- 2D TM infinite line sources/scatterers were used to verify the FDFD
- Compare FDFD to Analytic solution given by the Bessel Function
- Received fields for multiple arrays were compared

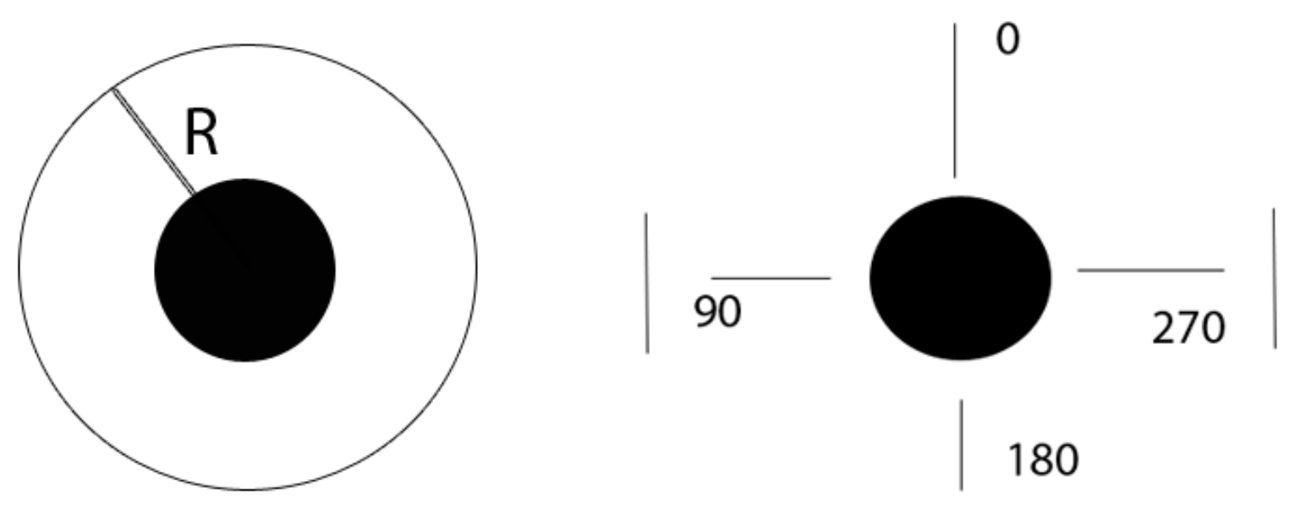


Figure 6: Conformal and planar arrays (left to right)

Conformal - line sources are isotropic

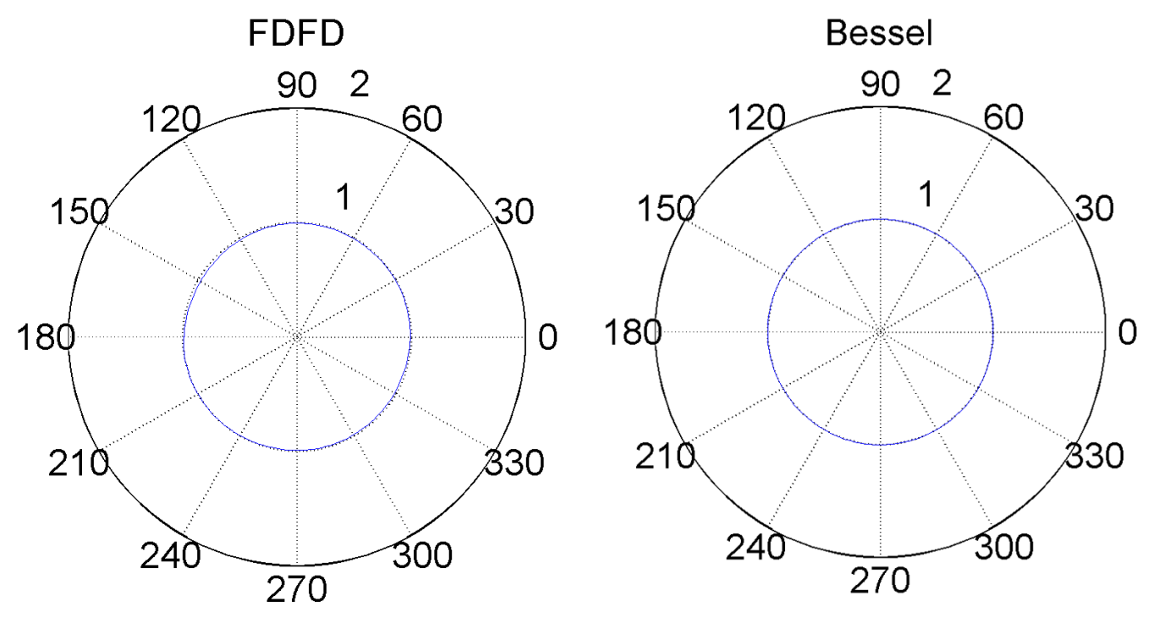


Figure 7: FDFD vs. Bessel - Received Field at arbitrary radius

- The received field for a conformal array does not vary at a constant radius: FDFD and Bessel agree

Planar - line scatterers are symmetric

- The received fields for a planar array do not vary with incident angle: line scatterer symmetry is preserved

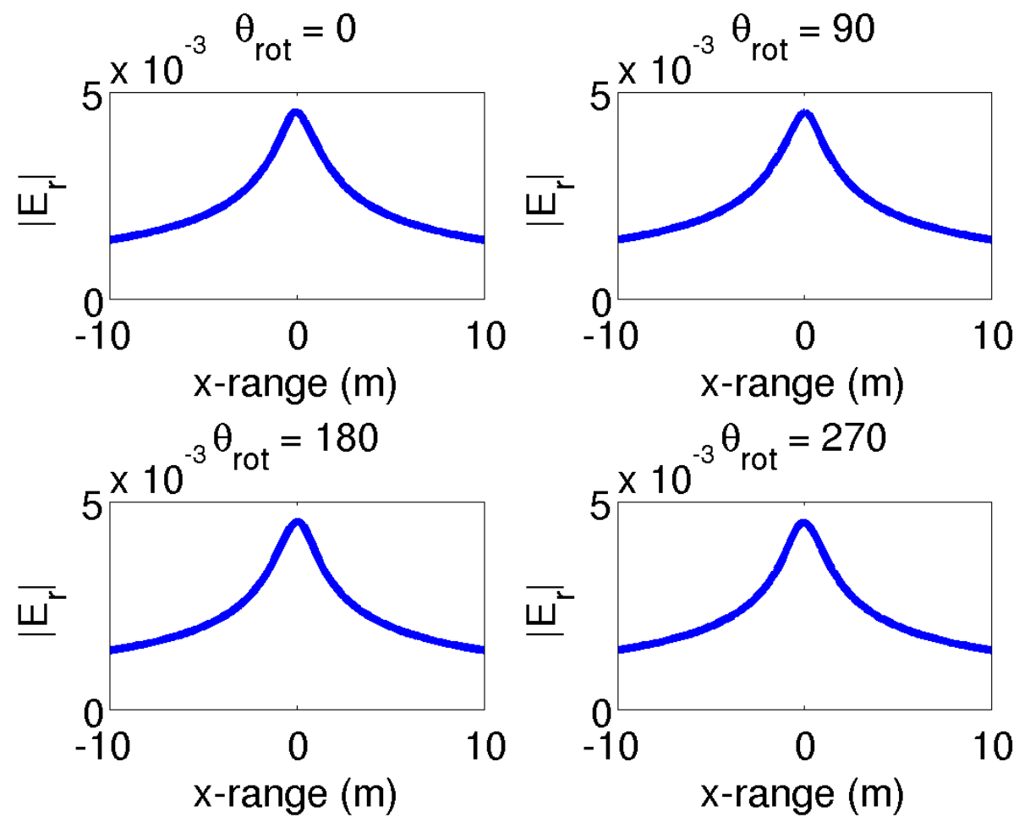


Figure 8: FDFD uniform plane wave transmission at different incident angles: 0 degrees (top-left), 90 degrees (top-right), 180 degrees(bottom-left), 270 degrees (bottom-right)

Optimization of FDFD Analysis

- Metal and dielectric materials: $\varepsilon_{metal} = \varepsilon_0, \varepsilon_{diel} = 2.9\varepsilon_0, \varepsilon_0 = 8.854^{-12}\frac{F}{m}$

Points per Wavelength - number of sample points along uniform plane wave

- L^2 norm gives a measure of error relative to the ideal solution

$$L^2(p) = \sqrt{\frac{\sum_{k=1}^{n}|E_k(P)-E_k(p)|^2}{\sum_{k=1}^{n}|E_k(P)|^2}}$$

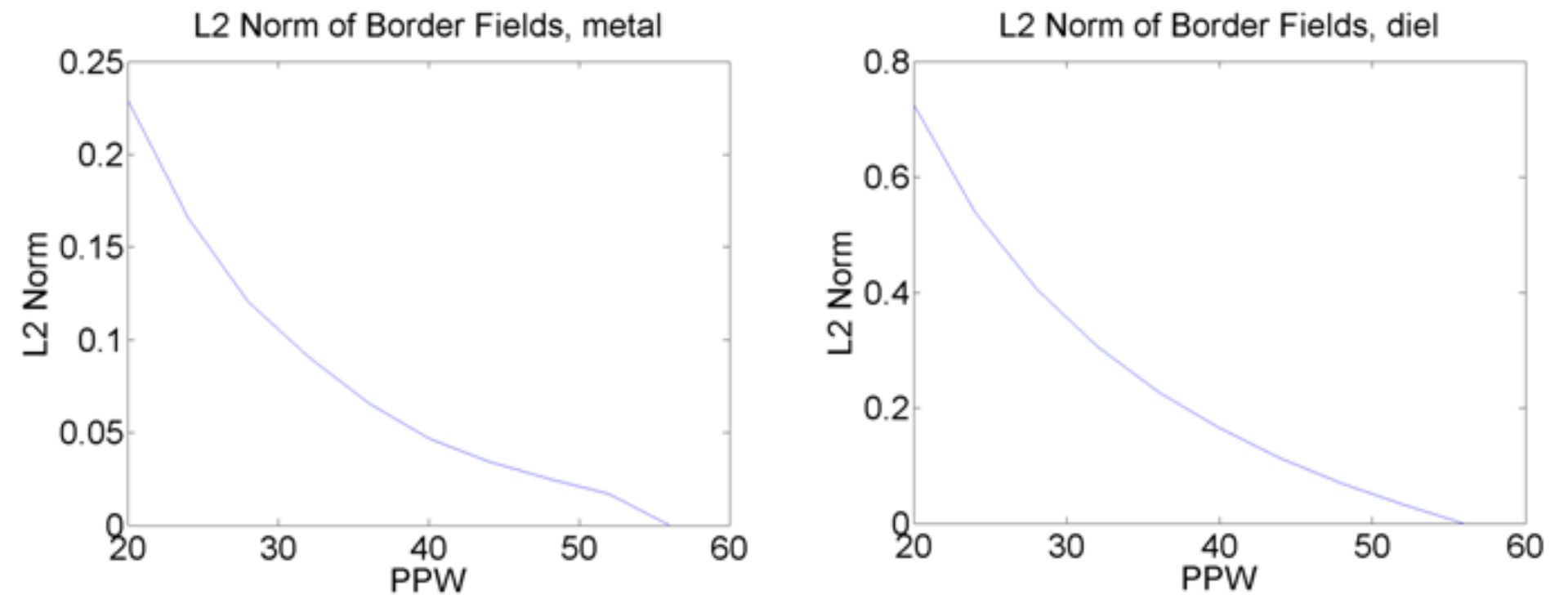


Figure 9: L^2 norm of received field from metal (left) and dielectric cylinders at 94 GHz as a function of ppw

- The dielectric geometry begins to converge at a higher ppw than the metal geometry

Frequency Step - frequency increment to model transmitted spectrum

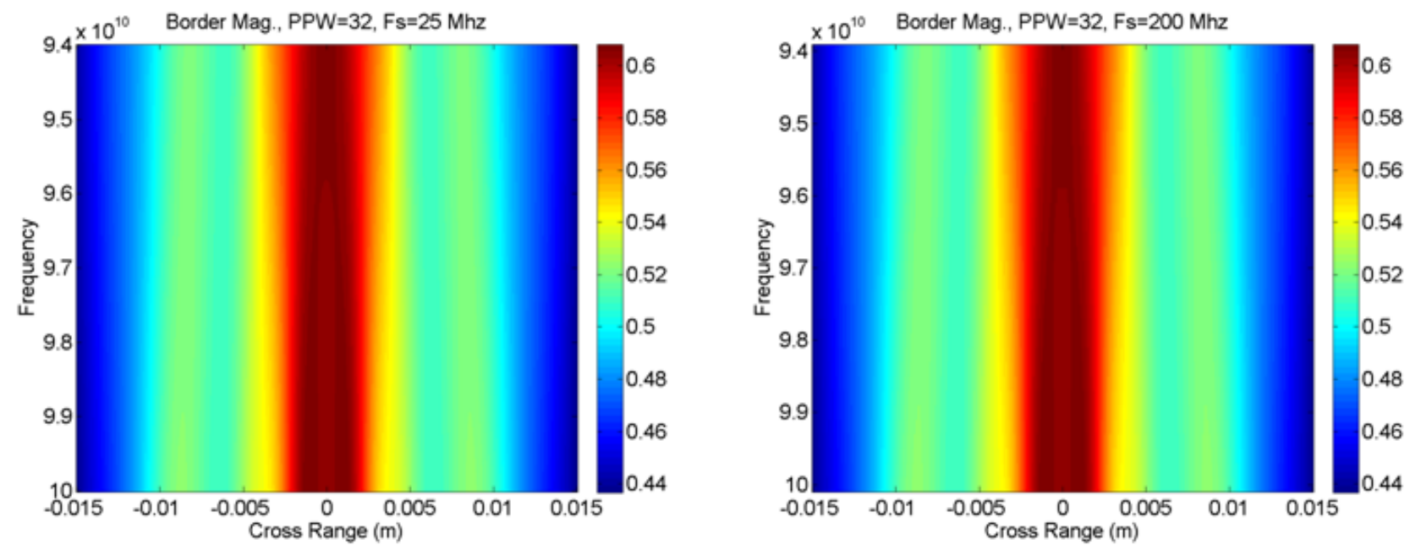


Figure 10: Spectral response of metal geometry vs. frequency and receiving cross range with frequency step of 25 and 200 MHz (left to right): metal can be simulated with a large (≈200 MHz) frequency step

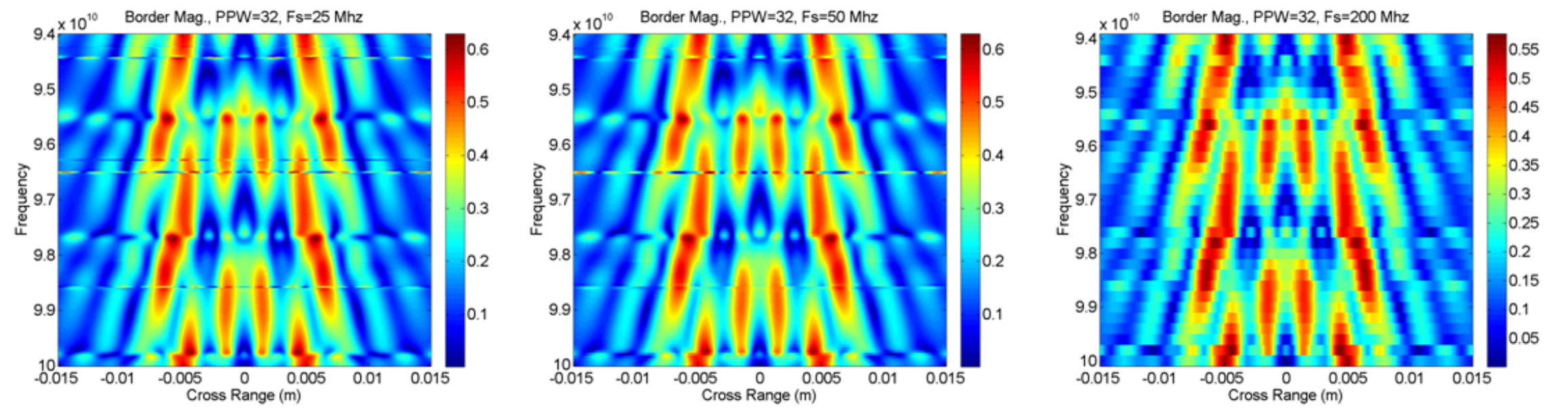
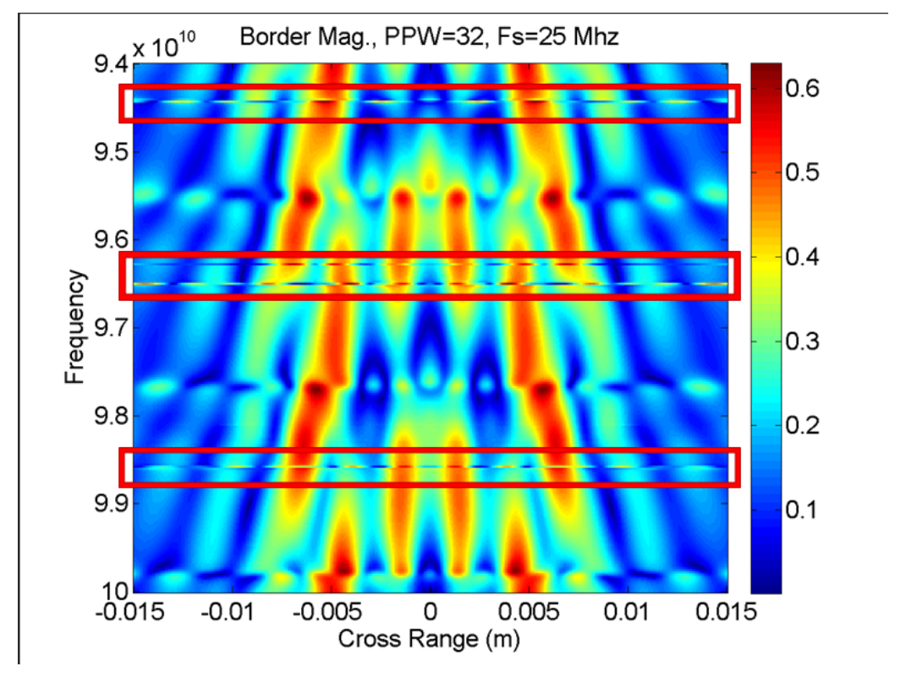


Figure 11: Spectral responses of dielectric geometry vs. frequency and receiving cross range with frequency steps of 25, 50, and 200 Mhz (left to right)



- Dielectric geometry is much more frequency dependent than the metal
- Discontinuities are found in the spectral response of the dielectric material

FDFD Discretization and Resonance

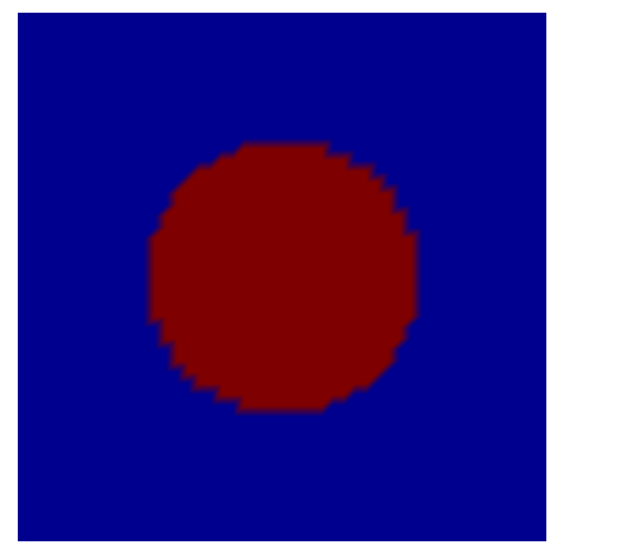


Figure 12: Sample cylindrical geometry created with a ppw of 12

- FDFD discretized grid approximates geometries: each point in the grid is a square
- Discretized cylinder suffers from edging effects, potentially inducing artificial resonance (Figure 13)

- Metal materials are perfect electric conductors (PEC's), expel all radiation: discretization has little effect
- Dielectric materials are not PEC's, radiation can propogate through
- Properties of dielectric cylinder ($\varepsilon_{diel} = 2.9\varepsilon_0$) combined with discretization may induce resonance at certain frequencies

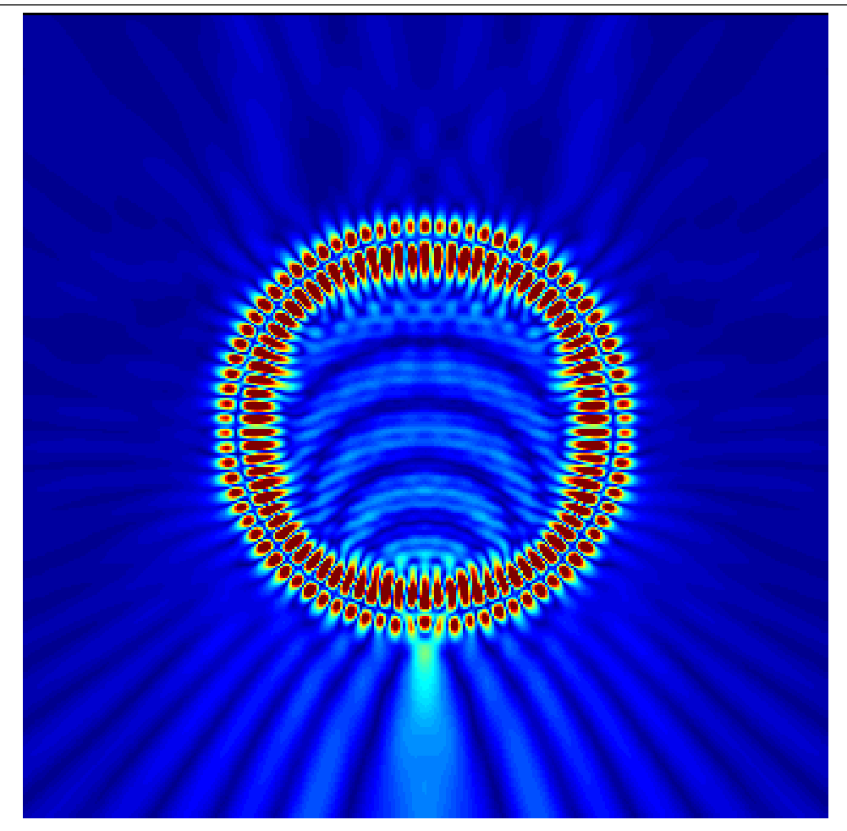


Figure 13: $|E_z|$ of dielectric cylinder at spectral response discontinuity

Channel Spectral Responses and SAR Images

Metal Cylinder

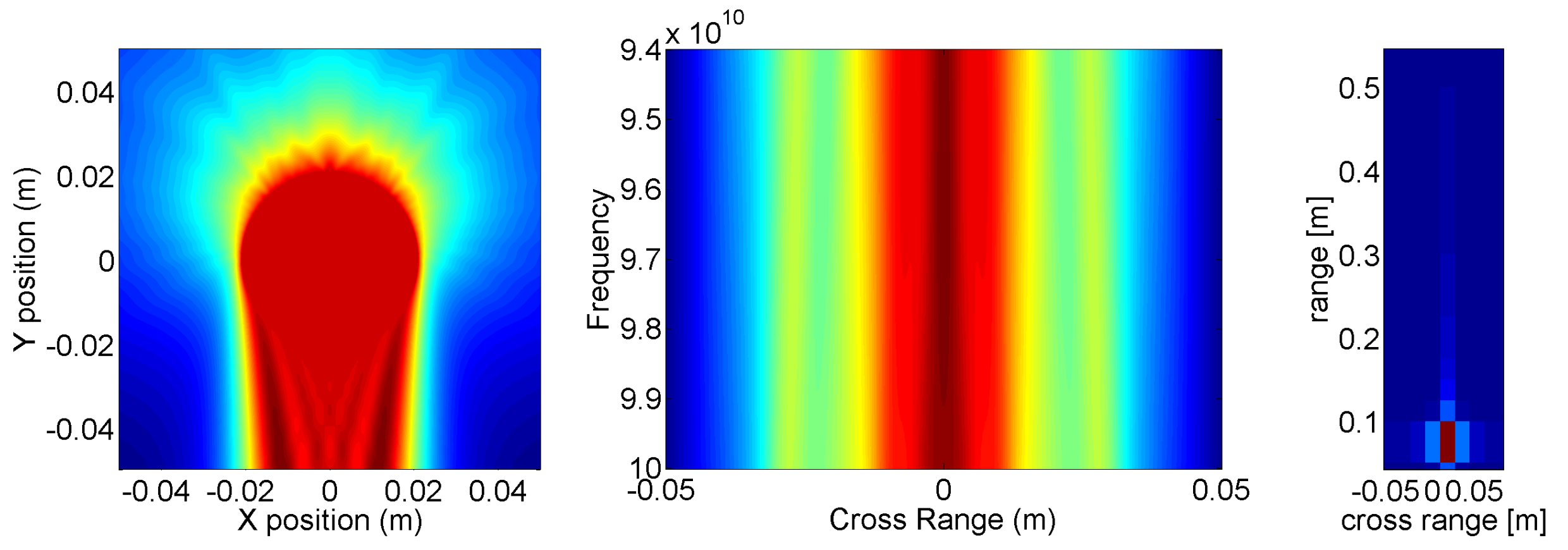


Figure 14: Near field, spectral response, and SAR image of metal cylinder (left to right)

Dielectric Cylinder

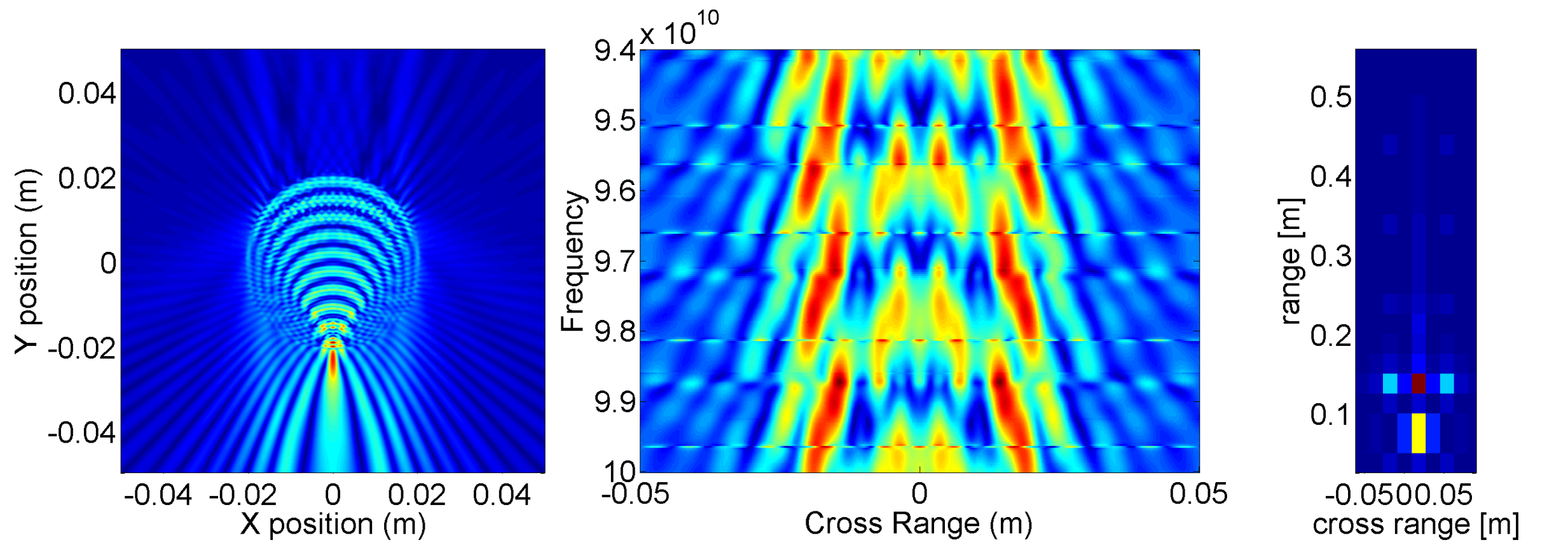


Figure 15: Near field, spectral response, and SAR image of thick dielectric cylinder (left to right)

Conclusion

- FDFD is verified for producing valid spectral responses for SAR imaging
- 50 MHz Frequency step is ideal for simulations in the the passband (94Ghz - 100Ghz)
- Freq. Dep. geoms must be sampled above 40 ppw to avoid discretization effects
- The absolute cause of the discontinuities in spectral respones of dielectric materials is currently under further investigation

References

[1] Martinez-Lorenzo, J. A., Rappaport, C. M., et al. , "Standoff Concealed Explosives Detection Using Millimeter-Wave Radar to Sense Surface Shape Anomalies". , AP-S 2008, IEEE AP-S International Symposium, San Diego, CA, USA, Jun. 2008.

[2] Martinez-Lorenzo, J. A., Rappaport, C. M., Sullivan, R. and Pino, A. G., "A Bi-static Gregorian Confocal Dual Reflector Antenna for a Bomb Detection Radar System". , AP-S 2007, IEEE AP-S International Symposium, Honolulu, Hawai'i, USA, Jun. 2007.

[3] Sadiku, M., "Numerical Techniques in Electromagnetics", 2nd ed., CRC Press LLC, 2001.

This material is based upon work supported by the U.S. Department of Homeland Security under Award Number 2008-ST-061-ED0001. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied of the U.S. Department of Homeland Security.