Modeling Focused CW Mm-Wave Scattering of a Penetrable Dielectric Slab Affixed to a Human Body

Ann W. Morgenthaler and Carey M. Rappaport
Department of Electrical and Computer Engineering
Northeastern University, Boston, MA USA
rappaport@ece.neu.edu

***Abstract*—Predictive 3D mm-wave nearfield radar modeling requires challenging tradeoffs between computational size and accuracy. For raster-scanned focused spot antenna systems, both the focusing array antenna and the target region must be finely and fully sampled, but the intervening space is large, making the computational space huge. For focusing along the axis in target geometries with only material variation in range, it is possible to scale the transmitter/receiver array and its range to target by a factor of two or four. But for even small amounts of off-axis focusing, the scaling must be done with care to avoid specular reflected rays that might miss the scaled transceiver array. Simulations based on ray analysis, analytic arrays of dipoles, and Quasi-Axisymmetric Finite Difference Frequency Domain (QAFDFD) compare well with each other. Only QAFDFD, however, can model target edge effects in the presence of large ground planes**.

Keywords—security imaging; mm-wave sensing; radar scattering; inverse methods; FDFD

I. INTRODUCTION

To model mm-wave radar focal spot security scanning systems, it is essential to consider both the focusing transmitter/receiver array and the scattering of objects under observation. Unlike phased array or synthetic aperture array-based radar, focal spot illumination systems, such as the Smiths Detection, Inc. eqo [1], electronically reconfigure a massive multi-element Fresnel reflect-array to generate a focal spot both on transmit and receive, which is quickly raster scanned through three-space. Both hardware cost and processing time are minimized as there are no moving parts, the focusing is done with hardware, and only a single frequency is used. In addition, the since the focal spot is fully formed for each voxel in succession (rather than as an SAR inversion), the human subject can move while being scanned with almost no blurring.

One important application of mm-wave person scanning is the determination of the dielectric constant of concealed slabs attached to the skin. While mm-wave radar can detect non-human anomalies, it is valuable to rule out the many innocent objects that might worn against the body, but alarm only on slabs that might be high explosive. Most high explosives such as TNT are weak dielectrics with dielectric constant of about 2.9 and low conductivity. By carefully modeling the amplitude and phase of the focused wave interaction with penetrable slabs in contact with a strongly conductive backing plane, it is possible to determine the dielectric characteristics and thickness of the slabs.

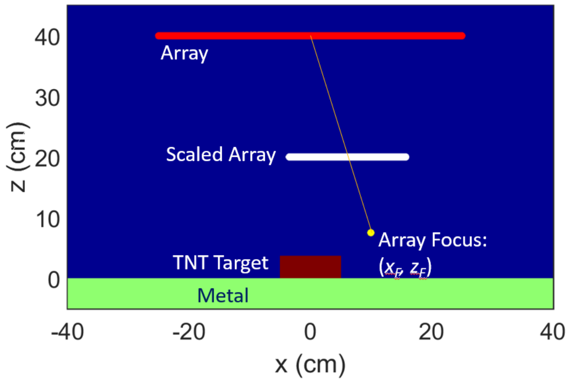

Fig. 1: A TNT target [50 mm radius, 37 mm thickness with dielectric constant ε = 2.9 (1+0.001*i*)] is located at the center of an axisymmetric coordinate system. A large horizontally-polarized source array of radius 50 cm located $z_0 = 80$ cm above the metal "skin" focuses at (x_F, z_F). It turns out that a quarter-size offset array centered at $x_F\left(1-(z_d-z_F)/(z_0-z_F)\right)$ does an excellent job of simulating the scattering from this geometry while requiring only a 1/16 to 1/4 sized computational grid (depending on its degree of offset). In the general case of off-axis focusing, the dipole sources are not axisymmetrically located, nor are they *z*-polarized so Quasi Axisymmetric (rather than strict 2D Axisymmetric) FDFD is necessary.

Using a ray-based Virtual Source (VS) approach for focusing both on transmission and reception is simple and effective [2] but is limited to one-dimensional object variation (no slab corners) and tends to miss nulls and weaker sidelobes. Analytic source and receiver models using arrays of ideal small dipoles are useful for uncovered ground plane sensing, but cannot be used for predicting the scattering by a covering dielectric slab. Similarly, the Method of Moments is hard to apply because of the penetrable nature of the dielectric and the infinite size of the conductive ground plane in the model. Physical Optics has been used [3], but its accuracy at slab edges is uncertain. To appreciate (i) the non-ideal effects path length focusing for vector fields (ii) the scattering at the slab edges, and (iii) the multiple reflections from the ground plane and the front dielectric face, it is best to use the Finite Difference Frequency Domain method. In particular, the Quasi-Axisymmetric version, QAFDFD [4] efficiently calculates

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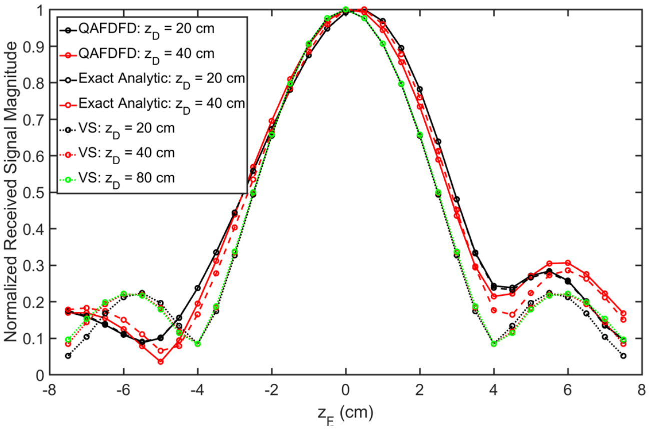

Fig. 2: Comparison of QAFDFD, analytic (exact), and VS simulations of the received signal from an array as a function of focusing depth z_F for the simplest case of on-axis focusing ($x_F = 0$) over bare metal with no TNT target. In all cases, the array radii scale linearly with array distance (e.g., the small, medium, and large arrays have 12.5, 25, and 50 cm radii, respectively, with corresponding 20, 40 and 80 cm distances from the metal "skin" surface).

propagation and scattering from non-symmetric excitation of bodies of revolution. However, because of the significant standoff of focused systems, it may be necessary to scale the array and its location.

II. NUMERICAL RESULTS

Fig. 1 shows the geometry of the antenna/target configuration, where the large array antenna (z_0 = 80 cm, R_0 = 50 cm) may be modeled by a smaller scaled version closer to the metal "skin" layer if the center of the scaled array is translated so the two antennas and the focus spot lie along a line. We model this smaller, closer array with a significantly smaller computational grid for Finite Difference Frequency Domain (FDFD) type methods but without sacrificing too much accuracy. Fig. 2 compares the QAFDFD, analytic and VS methods for the simplest case of a (no target) bare metal half-space probed with a dipole array where the dipole elements are phased to focus at (x_F, z_F). Because this configuration may be solved exactly using image sources, it serves as a check on the QAFDFD and VS methods, seen by comparing the QAFDFD and analytic solutions for $z_d = 20$ and 40 cm. The $z_d = 20$ cm array has a focusing peak at $z_F = 0.4$ cm and a half intensity peak width of 5.7 cm while the $z_d = 40$ cm array has a peak at $z_F = 0.2$ cm and slightly narrower peak width of 5.5 cm. The computationally faster Virtual Source (VS) method gives the general shape of the curve but with no peak shift – the VS curves are symmetric in z_F because the focal spot is assumed to have zero width – and a narrower peak width of 5 cm. The VS solution is also quite insensitive to the scale of the array.

Excellent agreement is seen between the QAFDFD and analytic results and these results are comparable for the small and medium arrays as well. The simplistic VS method gives quite reasonable agreement, though it is unable to predict the asymmetries which exist between focusing above and below the metal surface. Fig. 3 depicts the shift in response as a function of focusing depth z_F for on-axis ($x_F = 0$) relative to off-axis ($x_F = 40$ cm) focusing. Adding the TNT scatterer shifts the peak about 2.3 cm to the right, which is reasonably close to the lowest order shift of $\left(\sqrt{\varepsilon'}-1\right)d_{TNT}$ ~ 2.6 cm for a 3.7 cm thick slab of TNT with ε' =2.9. Edge effects of the TNT target create a significantly more asymmetric response and the half intensity peak widths narrow slightly to 4.5-5.1 cm from 5.7-5.8 cm for metal. There is no simple way to analyze this geometry through VS or analytic methods.

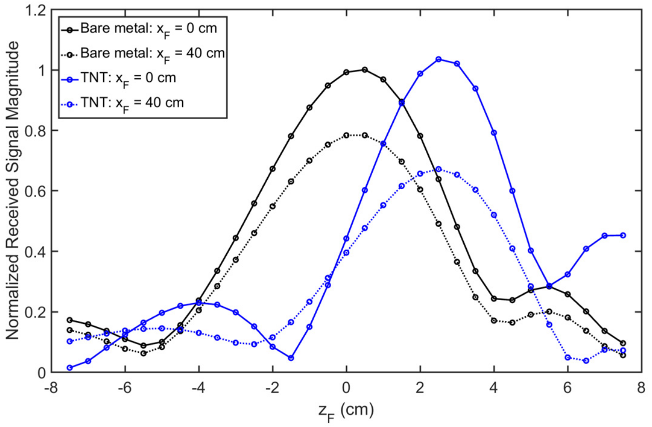

Fig. 3: Comparison of QAFDFD simulations of bare metal and TNT geometries for the small $z_d = 20$ cm array with focusing on axis ($x_F = 0$ cm) and off axis near the edge of the TNT target ($x_F = 4$ cm) where the all simulations have been normalized to the peak maximum of the bare metal on-axis simulation in Figure 2. For on-axis focusing and horizontally-polarized RCP sources ($\hat{x}+i\hat{y}$ in Cartesian or $(\hat{\rho}+i\hat{\phi})e^{i\phi}$ in cylindrical coordinates), only a single $m = 1$ mode is needed; all fields have $e^{i\phi}$ dependence using cylindrical coordinates in an axisymmetric geometry. For off-axis focusing, the dipole array is created from a Fourier decomposition of RCP sources, each one varying as $\exp(im\phi)$. The QAFDFD algorithm is run independently for each source component and the resulting scattered fields are superposed; only modes such that $|m| \le M$ are kept, where M is the mode truncation index. In these simulations, M is typically about 15 so scattered fields will converge to an accuracy of about 3×10^{-5}.

III. CONCLUSIONS

We have demonstrated that the QAFDFD computational forward model can efficiently simulate the interaction of raster scanned focused of radar waves with axisymmetric layered media. Using appropriate antenna array geometric scaling, the problem size can be reduced to manageable levels without compromising accuracy. The results have been confirmed by comparing with analytic and virtual source reference cases.

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