

Virtual Source Model for Ray-Based Analysis of Focused Wave Scattering of a Penetrable Slab on PEC Ground Plane

Mahdiar Sadeghi and Carey Rappaport
Northeastern University
Boston, MA

sadeghi.ma@husky.neu.edu,
rappaport@coe.neu.edu

Abstract—We develop a Virtual Source Model which is an intuitive, non-iterative, forward model to analyze the differential scattering of a dielectric covered conductive ground plane. This simple model is well suited for focused beam, nearfield mm-wave sensing of body-worn explosives for person scanning security systems. Ray analysis using the method of images for multiple interfaces yields good, experimentally-validated results.

Keywords—virtual source; mm-wave sensing; security imaging;

I. INTRODUCTION

Long security lines are a frustration for airline passengers who must undergo pat downs when current mm-wave imaging system falsely alarm innocent objects. To speed Advanced Imaging Technology (AIT) scanning, we propose an algorithmic approach to determine the dielectric constant of concealed objects, and rule out non-explosive dielectric objects. We present the Virtual Source (VS) model which is an intuitive forward model for characterization of weak dielectric objects (like threat objects) on the surface of a highly conducting ground plane (modeling the body skin), for focused continuous-wave (CW) sensing applications.

We consider a vertical transmitter/receiver array parallel to the ground plane which can focus a monostatic CW signal to a raster-scanned spot by adjusting the phase (0 or π) of each array element. This configuration is employed by the Smiths Detection, Inc. eqo system [1]. Assuming an infinitely wide dielectric slab on an infinite ground plane reduces the response of the VS model to just a function of distance from the array.

The basic idea of the VS model is that waves are scattered by the front surface of the dielectric slab and the ground plane at the back surface, and that this scattering can be reasonably well predicted by using the method of images. Initially, a 1D focused array is analyzed, then a more realistic 2D array is considered.

The VS model improves previous results [2] which used a similar ray approximation, but fundamentally different approach for selecting dominant rays. The VS model separates the wave propagation into two parts: the transmitted wave from the array to the focal point, and the receiving wave from the VS point to the array.

This work is supported by the U.S. Dept. of Homeland Security, Science and Technology Dir., Office of University Programs, under Grant Award 2013-ST-061-ED0001. The views and conclusions contained herein are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Dept. of Homeland Security.

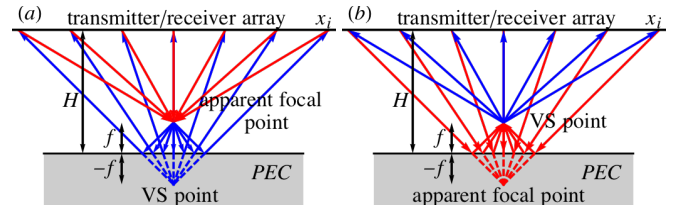


Fig. 1. Virtual source model for bare metal ground plane case when the array is focused at point f (a) above and (b) below the ground plane. Transmitting rays are shown in red, while the received rays from the VS are shown in blue.

II. VIRTUAL SOURCE MODEL

Fig. 1 shows the VS model for the most fundamental case, an infinite bare metal ground plane. The array focuses at either point f , Fig. 1(a) above, or $-f$, Fig. 1(b) below the ground plane. The transmitted wave (indicated by red arrows) extend from the focal array source to the specified apparent focal point, and the receiving wave (blue arrows) extend from the VS point back to the focal array, now acting as a receiver. If the apparent focal point were to lie on the ground plane, the VS would also be at the focal point, and both transmitted and received rays would yield maximum scattering and give the strongest response. Otherwise, the VS is found as the image of the apparent focal point. Since the phase focusing at the array for transmitted rays is the same for received rays, while the path lengths for the two sets of rays is different, the response is weaker.

The coherent summation of the ray signals over all array elements gives the return signal R , which is function of focal point distance from the ground f :

$$R(f) = \sum_i -e^{-jk(\sqrt{x_i^2 + (H+f)^2} - \sqrt{x_i^2 + (H-f)^2})} \quad (1)$$

Where k is the wavenumber, x_i is the cross range position of each antenna element from the middle of the array, H is the actual range of the array from the ground plane, $\sqrt{x_i^2 + (H+f)^2}$ is the blue arrow path length corresponding to the focal distribution of the array in Fig. 1(a), $+k\sqrt{x_i^2 + (H-f)^2}$ is the phase of rays received from the VS, and the initial negative sign is due to the reflection coefficient from the ground plane. Note that when $f=0$, the exponent for every element position is zero, giving the maximal response.

The return signal when a dielectric slab with refractive index n and thickness d lies on the ground plane is a combination

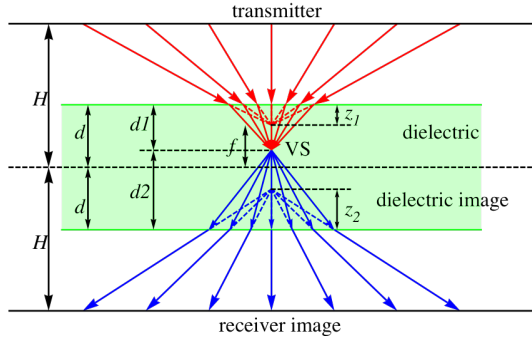


Fig. 2. Virtual source model for the first reflection from the ground plane when the array is focused inside dielectric at a point f above the ground plane. Unlike the simple surface reflection of Fig. 1, the method of images is used for the array, when it is considered as the receiver.

of multiple reflections from the dielectric and metal interfaces. In addition to reflection from front dielectric surface, there is a first reflection from the ground plane after the ray refracts while transmitting through the air/dielectric interface, and then more complicated multiple reflection paths inside the dielectric.

Reflection from dielectric front surface is similar to the bare metal case, but with a reflection coefficient of air/dielectric interface, which is approximated to be the normally incident plane wave value $\Gamma = (1 - n)/(1 + n)$

Fig. 2 is the illustration of the ray paths for the first reflection from the ground plane when the array is focused inside the dielectric at a point f above the ground plane. It was previously showed that the refracted red arrows are approximately focused at the true focal point deeper inside dielectric at distance of d_1 below the surface of dielectric, and that this point would be the virtual source point. The method of images is used again, but this time for both the slab and the array, acting as the receiver, on the other side of the ground plane [2]:

$$P_r = -jk \left(S_r + \sqrt{x_i^2 + (H - d + z_r)^2} \right), \quad r = 1, 2 \quad (2)$$

where P_1 is the phase change due to the ray paths from the array to the VS point (red transmit arrows), which can be approximated by straight paths from the array to the apparent focal point z_1 plus an additional constant phase offset S_1 . The phase change P_2 due to the ray paths from the VS point to the image of the array (considered as the receiver blue arrows) are approximately equal to the straight path lengths from point z_2 in the dielectric image region to the array plus a constant additional phase, offset S_2 .

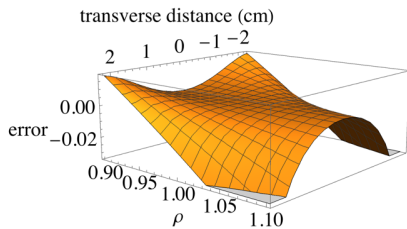


Fig. 3. The path length difference between true refracted rays and approximate ray paths emanating from a best fit focal point at $z_1 = \rho d_1/n$, for dielectric with 3.7cm thickness and refractive index of 1.7.

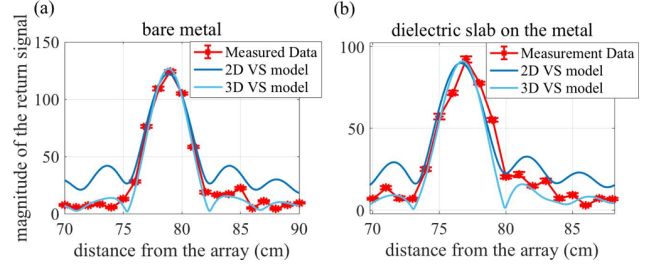


Fig. 4. Comparison of 2D and 3D version of VS model with the real measurement taken by the Smiths eqo system for (a) bare metal, and (b) dielectric slab with 3.7cm thickness and refractive index of 1.7 on the metal.

The real refracted focal point location is chosen to best fit the center of the circular expanding wavefronts. This point is simply and accurately approximated to be $z_1 = \rho d_1/n$, for some choice of fitting parameter ρ . Fig. 3 represents the error of as a function of ρ and transverse position for a slab with $d = 3.7$ cm thickness and refractive index $n = 1.7$ on a metal ground. The nominal range from the 1m wide array to the ground plane $H = 80$ cm. Fig. 3 clearly shows that $\rho = 0.96$ balances the error across the width of the rays incident on the ground plane.

With this approximate focal point, the sum of the phase offsets is constant $S_1 + S_2 = 2d(n - \frac{\rho}{n})$, and the return signal is:

$$R(f) = \sum_i e^{-ik \left(S_1 + S_2 + \sqrt{x_i^2 + (H - 2d(1 - \rho/n) + f)^2} - \sqrt{x_i^2 + (H - f)^2} \right)} \quad (3)$$

More complicated paths can be driven by considering multiple reflections inside the dielectric slab. In this work we consider the five dominant reflections. 3D modeling follows straightforwardly, with array focusing in both x and y .

III. RESULTS

Fig. 4 is a comparison of the 2D and 3D version of VS model with the real measurements taken using the Smiths eqo raster scanned focused CW system. The sensing observables: peak displacement and pulse width are in good agreement for both 2D and 3D models.

IV. CONCLUSIONS

We developed Virtual Source model as a non-iterative way to predict the received response from a lossless dielectric slab on a highly conductive background based on ray focusing and the method of images. The results are verified experimentally.

ACKNOWLEDGMENTS

The authors are grateful to Christoph Weiskopf and Claudius Volz of Smith Detection, Inc. for providing measurement data from the eqo system.

REFERENCES

- [1] K. Roe and C. Gregory, "Wave-based Sensing & Imaging for Security Applications," *European Conf. Ant. Prop. (EUCAP)*, Lisbon, 2015, pp. 1-5.
- [2] M. Sadeghi, E. Wig, A. Morgenthaler and C. Rappaport, "Modeling the response of dielectric slabs on ground planes using CW focused mm- waves," *European Conf. Ant. Prop. (EUCAP)*, Paris, 2017, pp. 759-763.