

Determining the Dielectric Permittivity and Thickness of a Penetrable Slab Affixed to the Human Body Using Focused CW Mm-Wave Sensing

Mahdiar Sadeghi*, Elizabeth Wig and Carey Rappaport
Northeastern University
Boston, MA

*sadeghi.ma@husky.neu.edu

Abstract— We propose a fast and accurate method of finding the thickness and dielectric permittivity of weak dielectric objects using a focused continuous-wave radar security scanning system, to characterize objects that may be explosive threats. Building on the previously developed ray-based Virtual Source model for sensing scattering from slabs, this work presents an inversion algorithm using two observable CW millimeter wave probe parameters by considering expected small variations of dielectric slab thickness over its surface. The determination works reasonably well with a simulated dielectric covered conductive ground plane as a representation of body worn explosives.

Keywords—inverse scattering; mm-wave sensing; security imaging;

I. INTRODUCTION

Faster and more efficient security checkpoints are required to effectively prevent airplane terrorist attacks while minimizing the inconvenience of long security lines. This paper develops an algorithm for the characterization of weak dielectric slabs that might be explosive threats, using a focused continuous wave (CW) radar system, like the Smiths Detection Inc. eqo [1]. The eqo focuses mm-waves on a raster-scanned set of pixels in 3D space and measures scattered signal at each point by adjusting the phase (0 or π) of each array element. We consider the responses received from focal points along the axis perpendicular to the array as a function of distance from the array. It is assumed that dielectric slab is smooth with small variation in thickness and perfectly attached to the body, with no gaps, and that the highly conducting skin surface is reasonably approximated as being a planar metal ground plane.

The Virtual Source model was previously developed by Sadeghi [2] to predict the expected return signal from weak dielectric slabs on the surface of the human body. This paper presents an inverse model. By comparing the measured return signal for focal points along the range axis for bare metal plane (or skin) versus for a dielectric slab on a metal background, two observable parameters related to the signals' shapes are identified and used to determine the basic characteristics of the dielectric slab: its thickness and permittivity.

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.

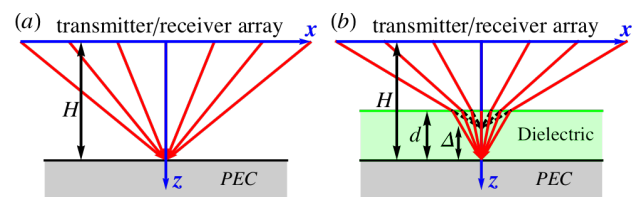


Figure 1: The setup of the simulation. The ray paths (red arrows) of focusing on (a) bare metal, and (b) dielectric layer on metal.

II. INVERSION PARAMETERS

Fig. 1 is the schematic of the simulation geometry, with Fig. 1(a) showing rays focused on a bare metal ground plane parallel to the transmitter/receiver array, and Fig. 1(b) showing rays focused inside a dielectric slab with thickness of d , lying on the metal ground plane at a distance H from the array. The transmitted continuous wave is iteratively focused on a set of focal points along the range axis (z axis), and the receiver coherently combines the returning rays from each focal point to give the magnitude and phase of the reflected response. The response will have a distinct peak at the range corresponding to the focal point of maximum reflection.

Based on the VS model [2], the magnitude and the phase of the reflected continuous wave responses over the z axis can be modeled as a function of H , d and dielectric permittivity. Two defined observables are: (i) the range displacement of the dielectric covered response peak from the bare metal peak, and (ii) the mean of the differential phase between the covered peak and the bare peak.

Ideally, for lossless dielectric objects, we expect the magnitude peak height ratio between the bare metal and metal covered with dielectric to be close to one (energy conservation). Any decrease in peak height with the dielectric response is most likely due to be the dissipated power inside dielectric.

For this simulation setup, the 1.0m by 1.0m array is located at a nominal distance of $H = 80\text{cm}$ from the ground plane. Fig. 2 is the illustration of the two observables (Fig. 2(a) the displacement and Fig. 2(b) the phase difference) as a function of dielectric slab thicknesses and permittivity derived from 3 dimensional version of the VS model. The ripples in the displacement are due to the constructive and destructive interference of reflections from dielectric front and back interfaces, and the rapidly changing phase difference is due to the natural wrapping behavior of the phase.

III. INVERSION ALGORITHM

The inversion algorithm works based on the Fig. 2, using observable pairs: peak displacement and phase difference, to solve for the dielectric slab thickness and permittivity.

The first step is to find the overlap of the observed displacement with the observed phase difference. This pair of observables will have multiple solutions, due to the multi-valued nature of the phase plot and the oscillations of the displacement values.

To avoid the multiple solutions, we considered that the thickness of the dielectric is likely to be changing slightly over its surface. Therefore, there are multiple thicknesses with the same dielectric permittivity that result in multiple observable pairs and different solution regions. Using the fact that each of the solutions for different pairs should result in the same dielectric permittivity but similar thickness, the non-realistic solutions can be discarded.

This method is implemented for example, when the correspondence test with three pairs of observables for the dielectric with $\epsilon_r = 2.9$ and thicknesses say of $d = 3.6, 3.7$ and 3.8cm . The displacements and wrapped phase differences for these three thicknesses are: $(0.9, -2.1)$, $(1.8, -3)$ and $(2.2, 2.9)$. Fig. 3(a) shows all the possible combinations of thickness and relative permittivity that generate the same pair of response observables in blue, red and green respectively.

To find the unique solution of each observable pair e.g. $(1.8, -3)$, corresponding to $d = 3.7\text{cm}$ and $\epsilon_r = 2.9$, two more binary masks based on other two observables are formed (without knowing *a priori* the true values of the different d). Each mask is built by extending the solution dots for the two different d values in Fig. 3(a) $\pm 2\text{mm}$ in thickness. If the original observable lies within both binary masks, all three solutions are declared to be physical. Fig. 3(b) shows the results of inversion algorithm by multiplying each individual observable pair solutions to the masks derived from other two observable pairs.

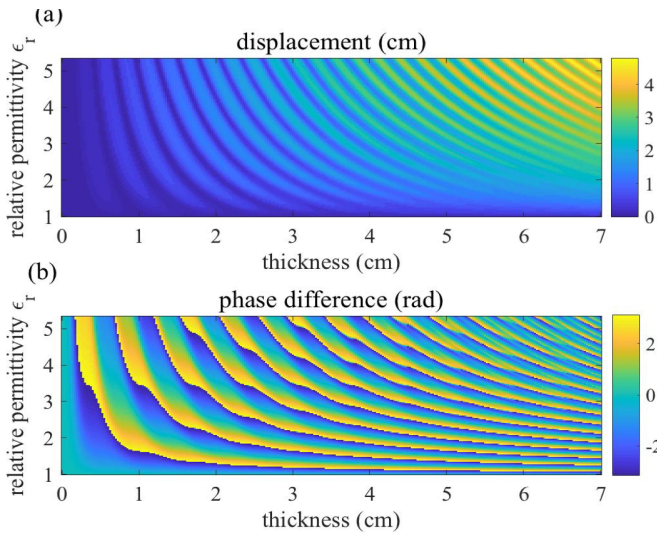


Figure 2: Observables from simulation of bare metal and metal covered with dielectric for different dielectric thicknesses and permittivities: (a) displacement of the magnitude of the response peaks and (b) mean phase difference of responses between the peaks of the magnitude responses.

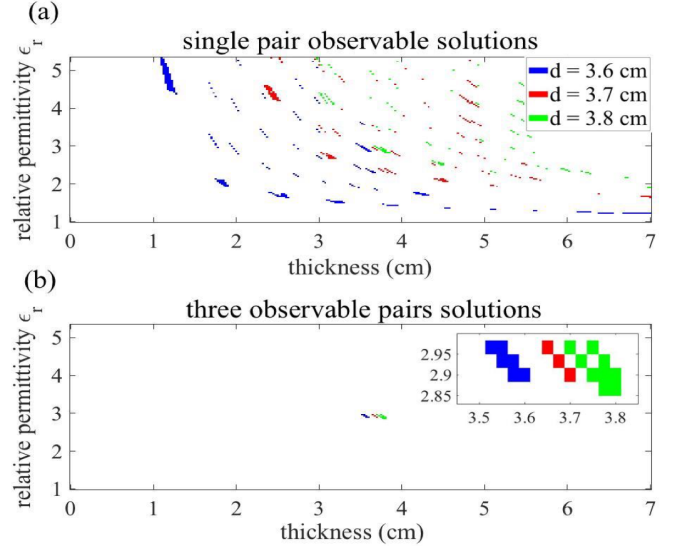


Figure 3: Inversion algorithm solutions for (a) single pairs of observables for $d = 3.6, 3.7$, and 3.8cm , thicknesses and $\epsilon_r = 2.9$ separately in blue, red, and green respectively, and (b) three corresponding pairs of observables for different thicknesses $d = 3.6, 3.7$, and 3.8cm , with the same $\epsilon_r = 2.9$.

IV. RESULTS

The improvement due to using multiple pairs of observables over a single pair for a dielectric slab with thickness $d = 3.7\text{cm}$ and relative permittivity $\epsilon_r = 2.9$ for our proposed inversion algorithm is illustrated in Fig. 3(b). Note that all the non-physical solutions have vanished, with reconstruction accuracy of about 3%.

V. CONCLUSION

Using observable values for a high explosive as a nominal case for a low loss dielectric slab, we were able to isolate its exact and unique relevant parameters: thickness and relative permittivity through exhaustive search. The same procedure can be used for various objects like silicone sealant, different kinds of Plasticine, Bees Wax, Powder Soap, Candle Wax, and explosives like Semtex with different thicknesses. The variation of the inversion parameters over different thicknesses of the same object plays a key role.

This research has direct relevance to the Smiths Detection eqo system, and could be applied to many other scanning systems, to characterize detected anomalies and rule out innocent objects that currently generate false alarms. This can lead to more informed decisions about potential threat objects, which means shorter lines and heightened security for all parties involved.

ACKNOWLEDGMENTS

The authors are grateful to Christoph Weiskopf and Claudius Volz of Smith Detection, Inc. for useful discussions.

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 and C. Rappaport, "Virtual Source Model for Wave-based Sensing of Dielectric Slabs on Ground Planes," unpublished.