

Single Frequency Fast Dielectric Characterization of Concealed Body-Worn Explosive Threats

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Abstract—The efficiency and effectiveness of airport security can be improved through fast and high-fidelity detection of concealed threat objects. If detected objects can be accurately characterized, the number of false alarms will be reduced, while terrorist threats could be more quickly noticed and apprehended. This study aims to accurately characterize the physical properties of weak dielectric objects (like explosive threats) covering a conductive plane (like the human body), using a single frequency mm-wave radar system with a Fresnel aperture. While the conventional synthetic aperture radar (SAR) method requires data over a broad bandwidth, our proposed method works even at a single frequency and is particularly suitable for focused-beam CW mm-wave sensing systems. This method is validated with experimental data.

Index Terms—Airport security, electromagnetic propagation in absorbing media, explosive detection, inverse scattering, millimeter-wave radar, focusing in layered media.

I. INTRODUCTION

RECENT studies on aviation security indicate a need for faster and safer checkpoints, to improve the safety of air travel and decrease the waiting time in security lines [1]–[3]. New approaches include use of cameras and game theory [4], [5]. Accurate characterization of concealed body worn weak dielectric objects will reduce the necessity of manual controls [1], the emotional tax on passengers [6], [7], and false alarms [8].

High-accuracy millimeter-wave scanning is a promising solution to effectively determine whether a person is concealing potential threats or contraband under clothes, and is the primary full-body scanner technology used in airports by the Transportation Security Administration (TSA), an agency of the Department of Homeland Security (DHS) [9]–[12]. The feasibility of synthetic aperture radar (SAR) imaging to predict the geometry and constitutive parameter information for loss-less weak dielectric objects was discussed in [13]–[15]. However, SAR imaging basically requires reflection data over a broad bandwidth to provide images with accurate resolution [16]. X-ray imaging and terahertz-wave scanning systems provide human body torso images with accurate resolution [17]–[20]. Nevertheless, the former makes use of ionizing emission while the latter is expensive and moreover relies on mechanical scanning. Nuclear method and fast neutron approach can detect some dielectric properties of the target [21]–[23], but are not

able generally to determine the geometrical features of the concealed object.

Among the mm-wave systems, the Continuous-Wave (CW) design is cheaper to build than wide band systems, e.g. the eqo system [24], [25]. The eqo system employs a 2D reflector array as an active Fresnel aperture to focus a 24.16 GHz wave on 10^7 raster-scanned set of pixels in 3D space, and measures the scattered signal's amplitude and phase. Each element of the array is a small adjustable reflector antenna that reflects the wave in or 180 deg. out of phase to build a constructive wave form at the desired focal point. The constructed focal point acts as a source point illuminating the array Point Spread Function (PSF) [26], [27]. The imaging resolution is dependent on the properties of the PSF at the focal point. The resolution of the actual 1m by 1m Smiths Detection, Inc. eqo system aperture is 1cm in range, and 3mm in cross range. A better resolution for this system can be achieved by increasing the size of the aperture, number of reflector elements, and frequency. Millimeter-waves are safe [28] and pass transparently through clothing [29], while the human skin provides a highly conductive background in the mm-wave spectrum (up to 300 GHz) due to its high water content [30], [31]. This makes millimeter-wave systems ideal for scanning the body for foreign objects concealed under clothing.

This work aims to complete a series of previous works on determining material characteristics of concealed objects on the body using millimeter-wave scanners [32]–[36]. Scattering formulations were presented in [32], and used to build the Virtual Source (VS) model to efficiently simulate and compute the reflection responses for a dielectric slab on a conductive plane [33], and a dielectric slab on a conductive plane with a finite air gap [36]. A thin air or cloth gap produces a noticeable, but relatively small effect in the imaging and inversion results. The idea of the inverse algorithm was presented for lossless dielectric objects in [34], [35].

In this paper, a 3D version of the VS model is used to create a library of expected response signals from objects with different thicknesses (d), relative permittivities (ϵ) and dielectric loss tangents ($\tan \delta$). The objects are modeled covering a Perfect Electric Conductor (PEC) to simulate an object attached to a human body. A real-time physics-based recursive algorithm is created to compare the measured response from the test object with the precomputed data, giving a close estimate of the size and electric properties of the object. Our developed method explicitly requires the assumption that the target is planar and backed by a PEC ground (which simulates the approximately planar parts of the body such as chest or belly). At 24 GHz,

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wet skin has a complex relative permittivity of $20-j18.7$ [37], which corresponds to a relatively large reflection coefficient magnitude of 0.7. While this is 30% less than that of PEC, it is large enough so that the latter provides a good, generally accepted modeling approximation for human tissue.

This paper is organized as follows. Section II presents the 3D formalism of VS model to efficiently compute the received responses from penetrable dielectric slabs on a highly conductive ground plane. Section III develops the physics-based inversion algorithm to predict the thickness, relative permittivity, and dielectric loss of the test object. This technique is shown in Section IV to be an efficient framework for fast and low-cost characterization of concealed body-worn threat objects to increase the safety of airline passengers while minimizing inconvenience at security checkpoints. The paper concludes in Section V.

II. VIRTUAL SOURCE MODEL

Consider a 2D transmitter/receiver array of adjustable reflectors, behaving like a Fresnel aperture, parallel to a ground plane (PEC). The transmitted signal is a continuous wave that is focused to a desired point. The phases of the transmitted rays are adjusted so that the rays from each element interfere constructively at the apparent focal point at a height $z = f$ above the ground plane, as in Fig. 1. The Fresnel reflector can be considered a transmitting phased array with appropriate phases at each position to create a nearfield focused beam. The ground plane acts as a mirror, and the scattering from the focal point (VS point) illuminates the same array which now acts as a receiving phased array, with the same phases that are used for transmission. If the focal point coincides with the ground plane, the reflected rays are exactly focused by the array with transmission phases. This can be visualized by using the method of images for the ground plane, with incident rays appearing to originate at an image transmitting array at an equal distance below the ground plane. These rays then follow their way back to the original array, now considered to be a receiving array. As the path lengths are the same in this case for transmitted and received rays, the transmit phase focusing constructively combines them. For focal points off the PEC ground plane, the VS model calculates the coherent sum of the dominant rays in 3D space from the VS focal point to the array. This coherent combined return signal R of the scattered wave at a height f above the ground plane is thus:

$$R(f) = \sum_i -e^{-j\kappa(\sqrt{\rho_i^2 + (H+f)^2} - \sqrt{\rho_i^2 + (H-f)^2})} \quad (1)$$

where κ is the wave-number, H is the distance between the array and the ground plane with ρ_i , $H+f$ and $\sqrt{\rho_i^2 + (H+f)^2}$ being the horizontal, vertical and absolute distances from the i^{th} array element to the VS point in the image space below the ground plane, in cylindrical coordinate. Note that the adjusted transmitter phase of the i^{th} element of the array is $\kappa\sqrt{\rho_i^2 + (H-f)^2}$. Clearly, when $f = 0$, all rays contribute constructively, and R is maximized. Using the method of images avoids having to calculate scattered field from currents on the ground plane.

The total reflected signal from a dielectric slab with thickness d and refractive index n covering the ground plane comes from a combination of multiple reflections from the air/dielectric and dielectric/metal interfaces. The planar wave method for reflection and refraction [38] is not sufficient for a complex sum of multiple reflections because the wave fronts here are not planar; therefore, we derive the complex sum of the dominant reflections to reproduce the reflected signal, Eq. (2). With loss factor $L_m = e^{-2dm\kappa \tan(\delta)}$, reflection coefficient Γ^m , phase offset O^m , and the vertical distance l_m between the VS point to the array are represented in Table I. We approximate the reflection Γ , transmission T , and L loss coefficients of all the rays to be the normally incident plane wave values.

$$R(f) = \sum_m \sum_i L_m \Gamma^m e^{-j\kappa(O^m + \sqrt{\rho_i^2 + l_m^2} - \sqrt{\rho_i^2 + (H-f)^2})} \quad (2)$$

Therefore, the total reflected signal from the dielectric-covered ground plane at distance H from the array is a combination of ($m = 0$) the scattered signal from the front surface of the dielectric, and ($m = 1, 2, \dots$) the infinite number of waves scattered into the dielectric media, and multiply reflecting from the PEC surface and front surface of the dielectric slab before transmitting back out. The model of the reflection from the dielectric front surface is similar to Eq. (1) with $L_0 = 1$, $O^m = 0$, $l_m = H - 2d + f$, and reflection coefficient of $\Gamma^0 = \Gamma$ from the air/dielectric interface instead of the -1 reflection coefficient of the air/metal interface. The derivation of the reflected waves that traveled through dielectric media requires further analysis.

The combined effect of refraction from the dielectric/air interface and the longer electric path length of rays in dielectric media shifts the apparent focal point from the array focal point location. Calculation of the path lengths from the array to the apparent focal point would require solving a fourth order polynomial equation [35]; However, it can be accurately approximated by straight paths from the array to the point $H - \Delta$ plus an additional constant phase offset S , to represent the difference between the electrical and physical path lengths of the normal incident ray. The path length p_i from element i of the array to the focal point can be approximated by

$$p_i = \sqrt{\rho_i^2 + (H - \Delta)^2} + S \quad (3)$$

where Δ can linearly be approximated as a function of the dielectric depth d (Fig. 2), and the depth of the adjusted focal point inside the dielectric, by $d(1 - q/n)$, based on a constant ratio q . From the visual illustration of error on Fig. 3, $q = 0.96$ balances the error across the width of the rays incident on the ground plane.

For the wave that is scattered once off the ground plane and then returned to the array, ($m = 1$), the coherent combined return signal R can be approximated by using the Eq. (2). When the system is focused inside dielectric at f above the ground, the apparent focal point would be at $\frac{n}{q}(d - f)$ depth inside dielectric; and the VS point would be at $2d - \frac{n}{q}(d - f)$ depth inside dielectric image. The distance from the approximated path length center point (Eq. (3)) to the array l_1 , can be derived

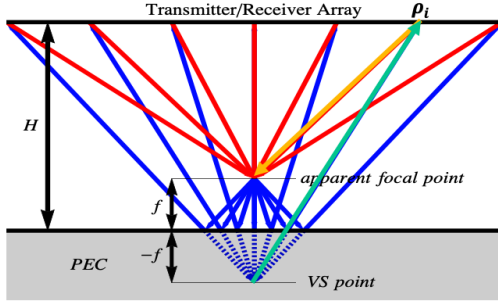


Fig. 1. 2D representation of the dominant rays scattering from the ground in cylindrical coordinate.

TABLE I
VS MODEL GENERAL FORMULA COEFFICIENTS.

m	Γ^m	O^m	l_m
0	Γ	0	$H - 2d + f$
1	$-(1 - \Gamma^2)$	$2d(n - q/n)$	$H - 2d(1 - q/n) + f$
2	$-\Gamma(1 - \Gamma^2)$	$4d(n - q/n)$	$H - 2d(1 - 2q/n) + f$
3	$-\Gamma^2(1 - \Gamma^2)$	$6d(n - q/n)$	$H - 2d(1 - 3q/n) + f$
4	$-\Gamma^3(1 - \Gamma^2)$	$8d(n - q/n)$	$H - 2d(1 - 4q/n) + f$
5	$-\Gamma^4(1 - \Gamma^2)$	$10d(n - q/n)$	$H - 2d(1 - 5q/n) + f$

as $l_1 = H - d + \frac{q}{n}(2d - \frac{n}{q}(d - f))$, thus $H - 2d(1 - q/n) + f$. Sum of the phase changes O^1 due to the additional path lengths of the normally incident rays (S in Eq. (3)) is the difference between the path length of the traveling rays inside the dielectric and the approximated rays traveling in air from the array to the approximated path length center point [35].

More complicated paths arise from multiple reflections off of the internal dielectric surface. The method of images stretches the thickness of dielectric to $2dm$, where m is the number of reflections from the ground plane. Equation (2) is used to replicate the total response from the dielectric slab with metal background, using the five dominant reflections in Table I.

The VS model accurately fits the eqo system's measurements [33], [35], and takes milliseconds to compute rather than a day on a personal computer, as full-wave models would. [39]–[41]. More complicated geometries, such as the dielectric slab separated from the metal surface by a finite air gap, can be modeled with the VS model [36] and validated with measurements on the dielectric slab attached to the metal surface with Velcro tape.

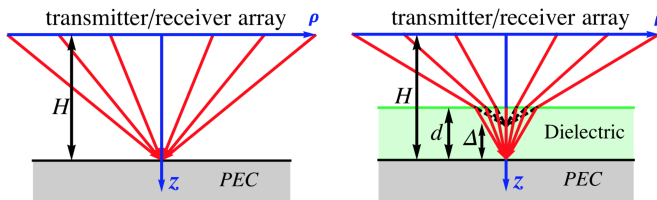


Fig. 2. 2D representation of measurement setup for (left) bare metal and (right) dielectric covering metal, when incident rays are in red.

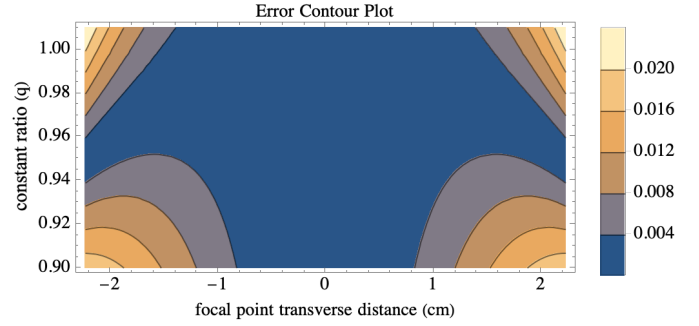


Fig. 3. Path length approximation error for $n = 1.7$, and $d = 3.7\text{cm}$.

III. INVERSION ALGORITHM

The model that was precomputed using the VS model can be used to predict properties of the dielectric, including thickness, relative permittivity, and dielectric loss. A physics-based, real-time inversion algorithm is used to compare the VS model with results from a real focused mm-wave scanning system. In Fig. 4, the response of the bare ground plane is compared to a dielectric covered ground plane with $H = 80\text{cm}$, dielectric thickness $d = 3.7\text{cm}$, permittivity $\epsilon_r = 2.9$, and loss $\tan \delta = 0.01$ at 24.16 GHz.

Three clear observables emerge from Fig. 4: the ratio of peak magnitude in the response of the dielectric slab to the bare metal case; the difference in range of the peak, referred to as peak displacement; and the mean phase difference between dielectric-covered and bare metal peaks. The inversion algorithm compares the values of these three observations to the precomputed model to predict the characteristics of the dielectric object. The result of the algorithm will be the closest one-to-one match between precomputed model and observed data. The peak ratio, displacement, and phase difference, as observed in the received reflection from the test object, are compared to the same parameters precomputed for dielectric slabs with various thickness, relative permittivity, and dielectric loss. For the example shown in Fig. 4, the peak ratio is 0.73, the Δ displacement is 1.9cm , and the mean phase difference is -2.98 radians.

A subset of the computed library at $\tan \delta = 0.01$ is shown in Fig. 5 for $1 \leq \epsilon_r \leq 5$ and $0 \leq d \leq 7\text{cm}$. The ripples in

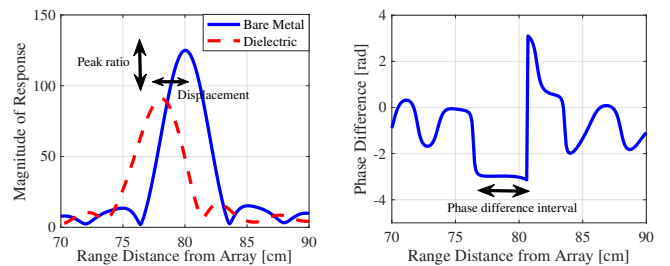


Fig. 4. Magnitude (left) and phase difference (right) between dielectric-covered and bare metal cases to introduce the three parameters used for inversion algorithm, namely, peak ratio, displacement, and the mean phase difference.

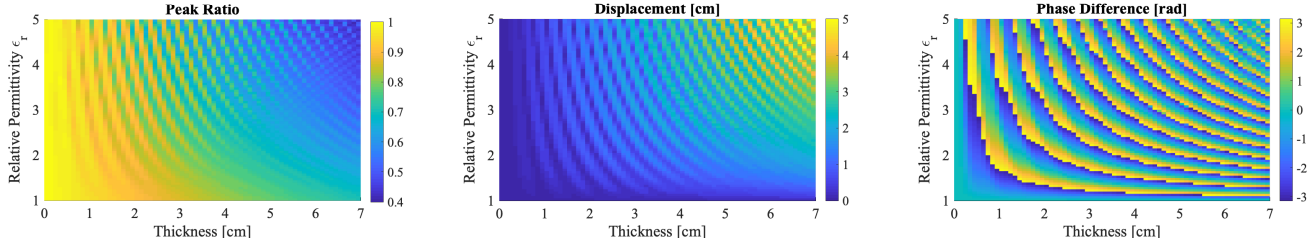


Fig. 5. Precomputed library for peak ratio (left), displacement (middle), and phase difference (right) shown for $\tan \delta = 0.01$, $1 \leq \epsilon_r \leq 5$ and $0 \leq d \leq 7\text{cm}$.

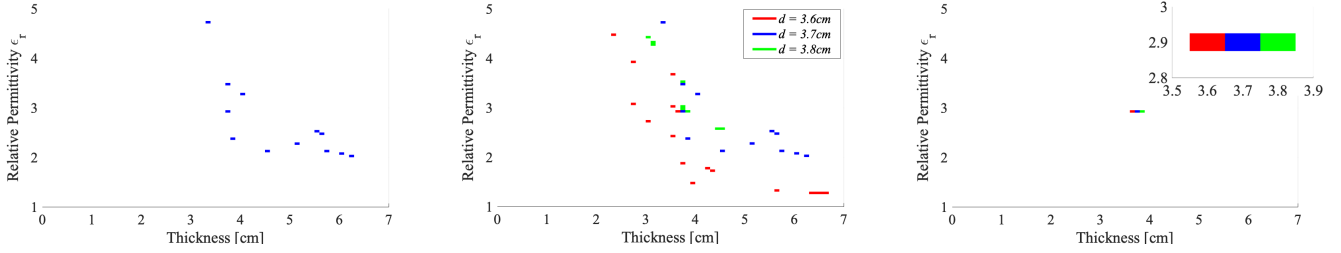


Fig. 6. Inversion algorithm solution for observables corresponding to $\epsilon_r = 2.9$, $\tan \delta = 0.01$, and the thickness $d = 3.7\text{cm}$ (left), observables corresponding to the same material but for the thicknesses $d = 3.6, 3.7$, and 3.8cm in red, blue, and green, respectively (middle), and the overlap of the three (right).

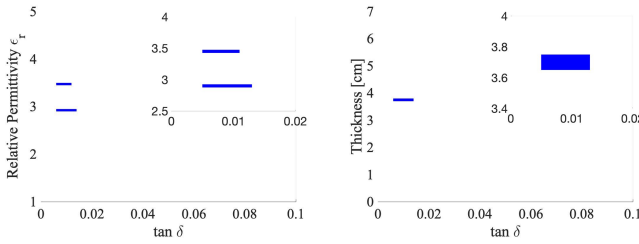


Fig. 7. Final solution for observables corresponding to the test object: relative permittivity ϵ_r vs. loss-tangent $\tan \delta$ at nominal thickness (left) and thickness d vs. loss-tangent $\tan \delta$ at nominal relative permittivity (right).

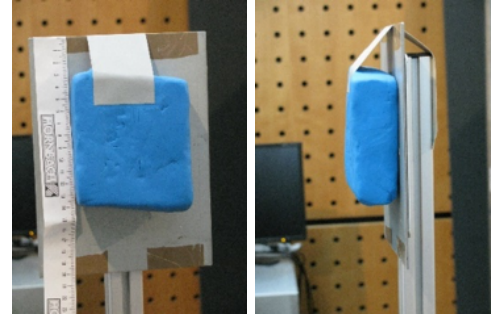


Fig. 8. Plasticine with 3.7cm thickness taped to the metal plate: front view (left) and side view (right).

the displacement of the peaks 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.

The inversion algorithm characterizes the test object by incorporating the measured reflection from the test object at the receiver array to the precomputed library, and masking the overlap between the observed peak ratio, displacement, and phase difference. For the simulated example shown in Fig. 4, three binary masks are created for: peak ratio, 0.73 ± 0.10 ; displacement, $1.9 \pm 0.1\text{cm}$; and phase difference, $-2.98 \pm 0.50[\text{rad}]$. The masks are multiplied to determine their overlap, as demonstrated in Fig. 6 (left). The overlap mask will have multiple solutions, due to the multi-valued nature of the phase plot and the oscillations of the displacement, which could translate to multiple false alarms for a security sensing system.

To overcome this problem, we assume that the thickness of the dielectric is unlikely to be perfectly uniform over its surface. Therefore, we can use a small variety of thicknesses with the same electric properties to generate multiple sets of predicted observables for these slightly different solution

regions. Using the fact that the solutions for these similar thicknesses should result in the same relative permittivity and dielectric loss, the non-realistic solutions can be disregarded. For the simulated example of Fig. 4, the inversion algorithm is repeated for thicknesses $\pm 1\text{mm}$ from the nominal surface.

For each set of three observables, the corresponding masks are multiplied to determine the overlap, in the manner of Fig. 4(a). The total overlap masks for the each of three thicknesses are shown in the middle plot in Fig. 6 to demonstrate all the possible solutions which come from $d = 3.6, 3.7$, and 3.8cm thicknesses. The overlap of these three masks is acquired and shown in Fig. 6 (right), where they meet at a unique solution with the same relative permittivity and dielectric loss for three thicknesses situated next to each other. The final answer agrees perfectly with the nominal dielectric thickness of 3.7cm and relative permittivity of 2.9 .

The same inversion algorithm is performed to find the dielectric loss of the test object. Fig. 7 (left) shows the final result of relative permittivity ϵ_r vs. loss $\tan \delta$ when the thickness is 3.7cm . This leads to two solutions: one is $\epsilon_r = 2.9$ and $\tan \delta = 0.009$ which agrees very well to the

nominal values, and the other is $\varepsilon_r = 3.45$ and $\tan \delta = 0.008$ which is considered as a false alarm. Note that for a lossy dielectric, the total relative permittivity is a complex number in the form of $\varepsilon_r(1 - j \tan \delta)$. Therefore, solving the inversion algorithm for ε_r vs. $\tan \delta$ might not result in one unique answer. Solving the inversion algorithm for thickness d vs. loss $\tan \delta$ at nominal relative permittivity leads, however, to a unique solution $d = 3.7\text{cm}$ and $\tan \delta = 0.009$ which agrees closely with the nominal values, and is shown in Fig. 7 (right). For the inversion algorithm of the simulated case explained above, the total masks were derived using observables for the nominal thickness and thicknesses $\pm 1\text{mm}$ from the nominal surface, and the overlap of these three masks determined the final solution. For the measured case, however, we cannot use this technique since the nominal thickness of the test object is not known a priori. Instead, we consider the measured observables corresponding to different points on the surface of the test object or the average over the area of the test object, as described in the next section.

IV. RESULTS

The numerical results of the inversion algorithm are presented for a plasticine slab taped to a metal plate in front of a focused CW eqo system made by Smiths Detection, Inc., to experimentally validate our developed algorithm. Fig. 8 shows a $10\text{cm} \times 9\text{cm}$ slab of plasticine with a nominal thickness of 3.7cm taped to the metal plate. Plasticine is a type of modeling clay with estimated relative permittivity $\varepsilon_r = 3.2$ and $\tan \delta = 0.056$ at 24.16 GHz [25] (close to TNT's relative permittivity $\varepsilon_r = 3 \sim 3.2$ [42]). The metal ground plane that models the highly conductive human body is placed at a range

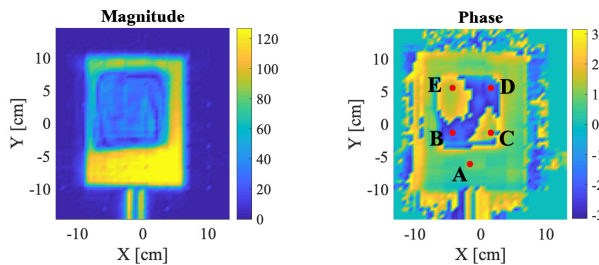


Fig. 9. Magnitude (left) and phase in rad. (right) of measured reflection at $z = 79\text{cm}$ for 3.7cm thick plasticine on a metal plate.

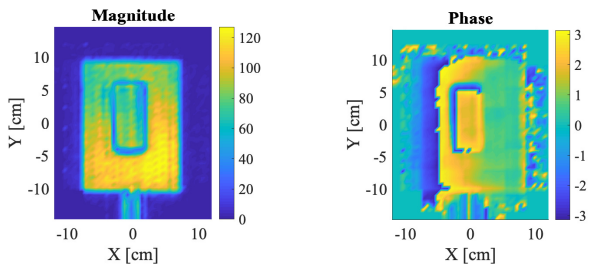


Fig. 10. Magnitude (left) and phase in rad. (right) of measured reflection at $z = 80\text{cm}$ for 1.2cm thick beeswax affixed on metal plate.

of 79cm from the eqo transmit/receive array. The magnitude and phase of the reflection being received at 79cm from the panel are plotted in Fig. 9. The magnitude and phase of the response at five points across the object (A, B, C, D, E), shown in Fig. 9 (right), are used in the algorithm to find the expected properties of the object. The measurement data for the eqo detection system is in the form of 3D matrix with 1cm resolution in the range (z -direction). However, the rapid change of phase in the range direction enables inversion to 1mm accuracy. The displacement of the peak location for each of the five points on the surface of the dielectric is almost the same.

To apply the inversion algorithm, we consider the reflection received at a distance of 77cm from the eqo panel, thus 2cm before the metal plate inside the dielectric volume. The peak ratio and range displacement curves are estimated through 1mm Gaussian interpolation of the magnitude of the received signal (measured with 1cm resolution) along the z -axis at every point on the surface of the dielectric. Phase difference is computed simply by taking the mean of the difference of phases for the dielectric vs. bare metal from $z = 77\text{cm}$ to $z = 79\text{cm}$. The values of the three inversion parameters — peak ratio, displacement, and phase difference — are considered for the inversion algorithm.

Figure 11 (left) depicts the inversion algorithm solutions in terms of relative permittivity and thickness for three points on the surface of the test object. Fig. 11 (middle) shows the overlap of these solutions when they meet at a unique solution; $d = 3.7 \sim 3.9\text{cm}$ and $\varepsilon_r = 3.30$. The inversion algorithm results are in excellent agreement with the nominal real-world values. Fig. 11 (right) also shows the inversion algorithm solution for relative permittivity vs. loss-tangent: a true solution $\varepsilon_r = 3.30 \sim 3.45$ and $\tan \delta = 0.020 \sim 0.028$, and a false alarm $\varepsilon_r = 3.90 \sim 4.05$ and $\tan \delta = 0.016 \sim 0.024$.

As a second example, the inversion algorithm is applied to find the thickness and electric properties of a beeswax brick affixed to a metal plate before the Smiths eqo detection system to further validate our developed algorithm. Fig. 10 shows the magnitude and phase of the reflection from a 1.2cm thick beeswax covering a metal plate. The relative permittivity and dielectric loss of the beeswax is well-known for different frequencies; for our range of frequency it is estimated to be $\varepsilon_r = 2.35$ and $\tan \delta = 0.0055$ [43].

The metal plate is placed at $H = 80\text{cm}$ from the eqo panel in range (z -axis). The reflection received at a range of 79cm from the eqo panel, inside the beeswax volume, is considered. Gaussian curves are fitted to the magnitude of the received signal, and the three observables are estimated at each point on the surface of the test object. The values of the three inversion parameters — peak ratio, displacement, and phase difference — are considered for the inversion algorithm.

Fig. 12 (left) shows the inversion algorithm solutions for three points on the object surface. Figure 12 (middle) shows the overlap of the solutions: a true solution at $d = 1.3 \sim 1.5\text{cm}$ and $\varepsilon_r = 2.05$, and two false alarms at $d = 2.8 \sim 3.0\text{cm}$ and $\varepsilon_r = 1.45$, and at $d = 3.1 \sim 3.3\text{cm}$ and $\varepsilon_r = 1.40$.

Fig. 12 (right) also shows the inversion algorithm solution for thickness vs. loss-tangent with a unique solution $d =$

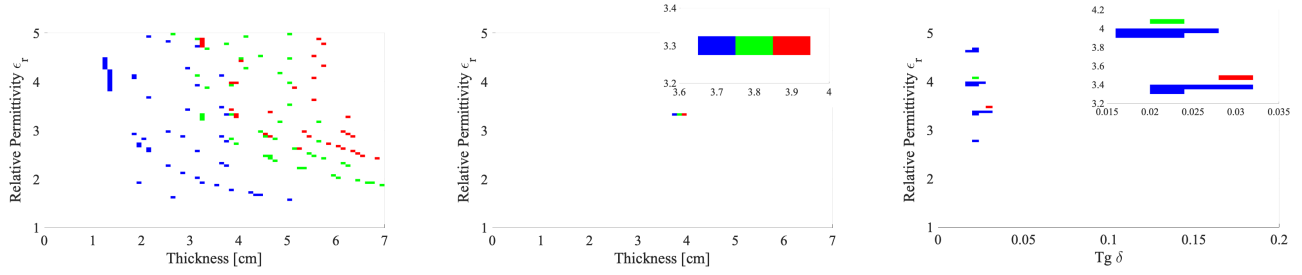


Fig. 11. Inversion algorithm solution for observables corresponding to three points on the surface of the plasticine test object (left), overlap of the solutions for three points when they meet at a unique solution (middle), and final result for electric permittivity vs. loss-tangent (right).

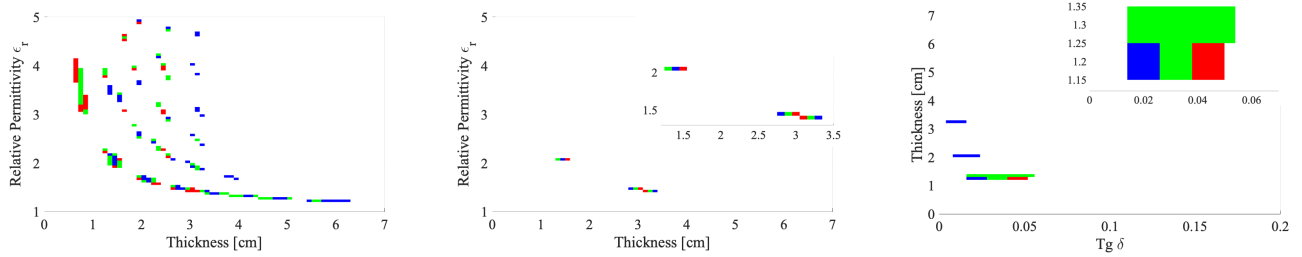


Fig. 12. Inversion algorithm solution for observables corresponding to three points on the surface of the beeswax test object (left), overlap of the solutions for three points (middle), and final result for thickness vs. loss-tangent (right).

1.2cm and $\tan \delta = 0.016 \sim 0.048$. The results are in agreement with the nominal values, while the inversion algorithm to incorporate the measured data with the precomputed library of observables is carried out in real-time.

V. DISCUSSION AND CONCLUSIONS

We have completed an investigation on single frequency detection of penetrable dielectric threats, concealed on the body with millimeter-waves [32]–[36]. We developed a non-iterative ray-tracing forward model of the radar system to create a library of predicted measurements on low-loss dispersive dielectric slabs, and built a library of precomputed data. Then, a recursive cross section algorithm was established to incorporate the measured data to the precomputed library and estimate permittivity and thickness of an unknown object, to distinguish between explosive threats and non-explosives.

The method identifies the thickness, loss, and the permittivity of the unknown object. It is built for focused systems and validated with the measurements done by the eqo system (a full body scanner) with multiple objects like plasticine and beeswax bricks attached to a calibration metal ground plane stand.

A 3D version of the VS model was developed for the first time to create a library of expected response signals from weak dielectric TNT slab models. The slabs are modeled covering a PEC to simulate objects attached to a human body. A real-time physics-based recursive algorithm was created to compare the measured response from the test object with the precomputed data, giving a close estimate of the size and electric properties

of the object. To the best of our knowledge, this method is the first attempt in using single frequency mm-wave for characterization of loss and permittivity of dielectric objects.

Contrary to the conventional method of synthetic aperture radar (SAR), which requires reflection data over a broad bandwidth for accurate resolution, the characterization of test object's thickness and electrical properties can be performed accurately and within *mm* error with this method at even one single frequency. The method has been designed and experimentally validated primarily for characterization of weak dielectrics (similar to TNT). Another application of the method can be to detect the concealed contraband.

The active Fresnel aperture is a 2D reflector array without any mechanical part. Its fast scanning speed enables capturing objects on the move, and design of walk through screening system which screen the passenger while passing the hallway. Moreover, the design of single frequency security scanners like the eqo system is cheaper and require less transmitter/receiver elements than a wideband system [44], [45].

Accurate identification of concealed dielectric objects characteristics is a necessary process to rule out innocent objects from explosive threats. This method enables the single frequency security systems to identify such characteristics in addition to their capability of detecting the geometries of the concealed objects. The thickness of the concealed object is usually within 1 to 5cm. Thus, even if the object is layered or in general non-homogeneous, our developed VS model can be used to estimate an effective dielectric constant for the concealed dielectric object. The inhomogeneity in the 2D

cross-section does not pose a major problem, as the eqo system focuses point by point on the object. Large amounts of inhomogeneity in range must be analyzed with more sophisticated algorithms.

Our developed method explicitly requires the assumption that the target is planar and backed by a PEC ground (which simulates the approximately planar parts of the body such as chest or belly). This work can be generalized by characterization of dielectric objects covering non-planar conductive backgrounds, and characterization of concealed dielectric objects covering finite conductivity backgrounds. More explicitly, we are currently working in our research group on both the mm-wave characterization of weak dielectrics with circular substrate attached to human body using the same eqo system, and also the characterization of bags filled with liquid using the wideband synthetic aperture radar system developed recently by the US Department of Homeland Security [46]–[48]. The simple uniform planar slab model shows excellent promise for the general non-ideal geometries. The details of these approaches are left for future works.

SUPPLEMENTARY MATERIALS

The MATLAB code for VS model is on git repository (<https://github.com/MahdiarSadeghi/VirtualSourceModel.git>).

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