Modelling 3D Mm-wave Scattering From Human Body Under Gaussian Beam Illumination With A 2.5D VIE Solver

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Abstract: In this paper, a two-and-a-half dimensional exact forward solver, based on a volume integral equation, is used to simulate three-dimensional millimeter wave scattering of a dielectric object hidden under clothing. Since a three-dimensional Gaussian beam only illuminates a spatially limited region of the human body, we can assume invariance of the electromagnetic properties of the abdomen in the longitudinal direction (vertical for a standing person). This way, the human body can be modelled as an infinitely long inhomogeneous (lossy) dielectric cylinder with arbitrary cross-sectional shape. A complex source formulation is used to implement this three-dimensional Gaussian beam, which may be oblique, and the human body is further reduced to a simple model, containing four different layers: clothing, air, human skin and body fat.

Keywords: 2.5D scattering, millimeter waves, contrast source integral equation, 3D Gaussian beam, simple human body model.

1. Introduction

For security applications, the detection of hidden objects under clothing is an important research area [1]-[3]. Millimeter waves (mm-waves) have ideal characteristics for this purpose since they are non-ionizing and penetrate clothing, while being absorbed and reflected by the human skin [4]. Moreover, the relatively small wavelength yields good resolution possibilities. For the development of such systems it is important to study the mm-wave scattering behavior of the human body. This could be done by full three dimensional (3D) electromagnetic simulation tools [5], but since the dimensions of the hidden object and the human body are several to many wavelengths and a fine discretization is needed due to the relatively high permittivity of the skin, this would yield a huge amount of unknowns. However, when mm-waves are used in active imaging systems, the incident field is usually a 3D Gaussian beam which only illuminates a spatially limited region. Since the size of the illuminated body region is only a few centimeter in the longitudinal direction (vertical for a standing person), it follows that we can assume invariance of the electromagnetic properties of the human abdomen along this direction. Therefore it can be modelled as an infinitely long inhomogeneous (lossy) dielectric cylinder with arbitrary cross-sectional shape.

For such configurations, we use a 2.5D full-wave forward solver [6], based on a Volume Integral Equation (VIE), to calculate the 3D electromagnetic scattered field. This way, objects with cross-sectional dimensions of several to many wavelengths can be handled with a reasonable computational effort, while maintaining

the full 3D character of the incident field. A similar technique is proposed in [7] for modeling geophysical low-frequency (diffusive) electromagnetic scattering in cross-well logging.

In this paper, we use a simple model for the cross-section of the human body to compare the mm-wave scattering behavior of the human body with and without hidden dielectric object. In section 2, the 2.5D forward solver is presented, as well as the implementation of the 3D Gaussian beam. Section 3 deals with the obtained simulation results.

2. 2.5D Forward Solver

A. Contrast Source Integral Equation

Consider an inhomogeneous, possibly lossy, dielectric cylinder with arbitrary cross-sectional shape and with axis along the z-direction in a 3D cartesian coordinate system $\boldsymbol{\rho} = \mathbf{r} + z\mathbf{u}_z$, with $\mathbf{r} = x\mathbf{u}_x + y\mathbf{u}_y$ the 2D position vector. This object is surrounded with free space and has a complex permittivity $\epsilon(\mathbf{r}) = \epsilon_r(\mathbf{r})\epsilon_0$. We formulate the problem in the frequency domain and omit the time dependence $\exp(-i\omega t)$. The scattering object is illuminated with a 3D incident field $\mathbf{E}^i(\mathbf{r}, z)$ and the resulting scattered field is defined as $\mathbf{E}^s(\mathbf{r}, z) = \mathbf{E}(\mathbf{r}, z) - \mathbf{E}^i(\mathbf{r}, z)$, with $\mathbf{E}(\mathbf{r}, z)$ the total field.

A contrast source integral equation (CSIE) in the 2D space-spatial frequency domain $(\mathbf{r}; k_z)$ is obtained from performing a spatial Fourier transform with respect to the z-coordinate, defined as $\hat{g}(\mathbf{r}, k_z) = \int_{-\infty}^{\infty} g(\mathbf{r}, z)e^{-ik_z z}\mathrm{d}z$, on the Maxwell equations:

$$\widehat{\mathbf{E}}^i(\mathbf{r}, k_z) = \frac{\widehat{\mathbf{D}}(\mathbf{r}, k_z)}{\epsilon(\mathbf{r})} - \left(k_0^2\mathbf{I} + \widehat{\nabla\nabla}\right) \cdot \widehat{\mathbf{A}}^s(\mathbf{r}, k_z). \tag{1}$$

The electric flux density $\mathbf{D}(\mathbf{r}, z)$ is chosen as the unknown of the scattering problem [5] and the vector potential $\widehat{\mathbf{A}}^s(\mathbf{r}, k_z)$ is defined as

$$\widehat{\mathbf{A}}^s(\mathbf{r}, k_z) = \frac{1}{\epsilon_0} \int_S \widehat{G}(\mathbf{r}, \mathbf{r}'; k_z)\chi(\mathbf{r}')\widehat{\mathbf{D}}(\mathbf{r}', k_z)\mathrm{d}\mathbf{r}', \tag{2}$$

where $\widehat{\nabla} = (\partial_x, \partial_y, ik_z)$ and

$$\chi(\mathbf{r}) = \frac{\epsilon(\mathbf{r}) - \epsilon_0}{\epsilon(\mathbf{r})} \tag{3}$$

is the normalized permittivity contrast. Because of this contrast, the integration in (2) can be limited to the object domain S, where the permittivity of the object $\epsilon(\mathbf{r})$ differs from ϵ_0. The Green's function is given by

$$\widehat{G}(\mathbf{r}, \mathbf{r}'; k_z) = \frac{i}{4}H_0^{(1)}\left(\sqrt{k_0^2 - k_z^2}\,|\mathbf{r} - \mathbf{r}'|\right). \tag{4}$$

We discretize the object domain S in square cells with cell size Δ and expand the 3D fields using rooftop basis functions. The complex permittivity takes a constant value within each cell. A Method of Moments with Galerkin weighting is applied to discretize the CSIE and the resulting linear set of equations is solved iteratively with a stabilized biconjugate gradient Fast Fourier Transform method.

B. 3D Gaussian Beam As Incident Field

The implementation of a Fourier transformed 3D Gaussian beam, under the paraxial approximation, is based on the complex-source beam formulation proposed in [8] for a beam-type wave object which corresponds with the classic formulation within the paraxial approximation. We consider a beam that is propagating along a $\mathbf{u}^i$-direction, with the beam center located at $\boldsymbol{\rho}_0 = (x_0, y_0, z_0)$ and beam waist w_0. A 3D complex source beam is obtained by evaluating the 3D Greens' function, $G(s) = \frac{1}{s}\exp(ik_0 s)$, with respect to a complex source-point $\boldsymbol{\rho}_c = \boldsymbol{\rho}_0 + ib\mathbf{u}^i$. This complex source point is a combination of the real source point $\boldsymbol{\rho}_0$ — the beam waist center — on the one hand, and beam parameters, as the beam collimation distance $b = w_0^2 k_0/2$ and the beam direction $\mathbf{u}^i$ on the other hand. A complex distance function $s(\mathbf{r})$ is defined as

$$s(\mathbf{r}) = ((x - x_c)^2 + (y - y_c)^2 + z_c^2)^{1/2}, \tag{5}$$

with $\Im m\,(s(\mathbf{r})) \le 0$. We obtain the Fourier transform of this beam by replacing the 3D Greens' function with the 2.5D Greens' function:

$$\widehat{\mathbf{E}}^i(\mathbf{r}, k_z) = \widehat{G}(s; k_z)\mathbf{u}_{pol} = \frac{i}{4}H_0^{(1)}\left(\sqrt{k_0^2 - (k_c - k_z)^2}\,s\right)\mathbf{u}_{pol}, \tag{6}$$

where $k_c = k_0\,\mathbf{u}^i \cdot \mathbf{u}_z$.

3. Scattering Of Objects Hidden On A Human Body

The 2.5D solver described above is used to study mm-wave scattering from a quasi-2D object that is hidden on an adult human body and which is illuminated by a 3D TM-polarized incident Gaussian beam — $\mathbf{u}_{pol} = \mathbf{u}_z$ — at 100 GHz. A simple model for the human body cross-section is shown is Fig. 1, where the limited penetration of mm-waves into the human body [4] as well as the finiteness of the illuminated region in the x-direction has allowed us to consider only a small part of the abdomen cross-section. The 3D Gaussian beam is propagating along the y-axis with a waist $w_0 = 8$ mm and its beam center $\mathbf{r}_0$ is chosen at the exterior surface of the skin in $x = y = 0$.

In this restricted model we distinguish 4 layers: clothing, air, dry skin and fat. The thickness d and relative permittivity ϵ_r for each layer are chosen as follows: $d = 2$ mm and $\epsilon_r = 4.0 + i\,0.1$ for clothing [4], $d = 3$ mm and $\epsilon_r = 1$ for air, $d = 2$ mm and $\epsilon_r = 5.60 + i\,7.09$ for dry skin [9] and $d = 10$ mm and $\epsilon_r = 2.89 + i\,0.64$ for fat [9]. A rectangular dielectric object with width 15 mm, thickness 2.5 mm and relative permittivity $\epsilon_{obj} = 2$, representing certain explosives, is placed between the clothing and skin. The computational domain has dimensions of 110 mm in the x-direction and 40 mm in the y-direction and is discretized into 1120×416 cells with cell size $\Delta = 0.1$ mm, yielding a total of 1.397760 million unknowns. The simulation without hidden object proves that the dimensions of the restricted model are large enough since no remarkable field values appeared on the upper and lower boundaries of Fig. 1, as well as inside the abdomen. The incident field is calculated using the complex-source beam formula for five different k_z values.

Simulations, with and without hidden object were computed in 2h. 43 min. and 2h. 35 min., respectively. Fig. 2 shows the amplitude and phase of the difference between the total field with and without object and clearly reveals the presence of the hidden object.
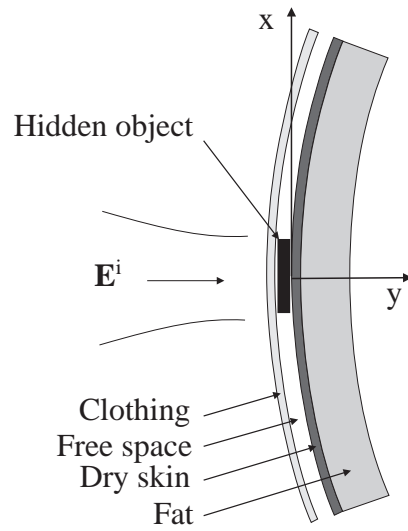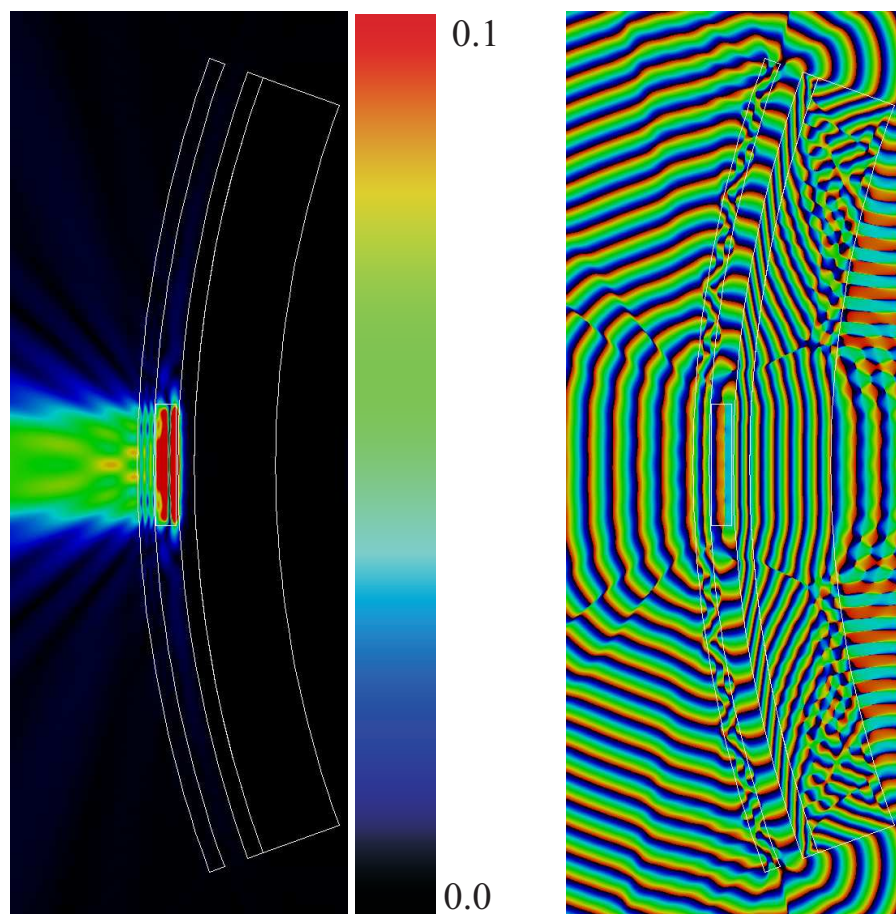
Figure 1: Configuration.

Figure 2: Amplitude (left) and phase (right) of the difference between the total field with hidden dielectric object and the total field without hidden object.

4. Conclusion

We have used a 2.5D exact forward solver to simulate three-dimensional millimeter wave scattering of a hidden dielectric object on a simplified human body model, which was illuminated by a 3D Gaussian beam. This beam has been implemented using a complex source formulation. Gaussian beam and millimeter wave properties have been used to reduce the abdomen cross-section to the presented simple model. The introduction of a hidden dielectric object has led to a noticeable change in the total field, as could be seen in a figure of the difference between the total field with and without object.

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