# Accurate Permittivity Estimation Method for Double-layered Dielectric Object for UWB Radars

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***Abstract*—A microwave ultra-wideband (UWB) radar system is one of the most promising technologies for the internal imaging of dielectric objects in applications such as non-invasive inspection and non-destructive measurement. For such applications, we have already proposed an efficient method of estimating permittivity employing a geometrical optics (GO) approximation and exploiting dielectric outer boundary points and their normal vector accurately obtained with the range points migration (RPM) method. However, this method assumes that there is a highly lossy object buried in a single-layered homogeneous dielectric medium. This paper proposes an accurate permittivity estimation method for a double layered dielectric medium that employs the RPM or Envelope method extended to boundary extraction for each dielectric layer, and an estimation of time delay based on a geometrical optics approximation. The results from finite-difference time-domain (FDTD) based simulations demonstrate that our method accurately estimates permittivity and the boundary of the two layers simultaneously.**

***Key words*—UWB sensor, Range points migration (RPM), Envelope method, Inverse scattering problem.**

## I. INTRODUCTION

There are emerging demands for an innovative technique of imaging objects embedded in dielectric media. Such a technique would be used in non-invasive screening of the human body for medical purposes and the monitoring of artificial structures to reduce damage in the event of a natural catastrophe. One of the most promising technologies is UWB radar system that has sufficient range resolution and the ability to penetrate dielectric objects, especially at lower microwave frequencies. For such application, there are various inverse scattering methods for reconstructing the dielectric constant, such as that based on domain integral equations [1]. However, the size of space discretization must be severely constrained to avoid sluggish convergence in multi-dimensional optimizations. While methods such as those in [2] require less computational resources owing to their GO approximation, another approach assumes a simple and known structure of the dielectric medium, such as a cuboid.

We have already developed a promising method of simultaneously obtaining an accurate internal image and estimating permittivity [3]. This method employs the original method of range points migration (RPM) [4] to correctly reconstruct dielectric boundary points and their normal vectors. The actual time delay of the microwave propagating through the dielectric medium can then be accurately estimated from the recorded transmissive data. However, this method is specific to a simple target model in which highly lossy material is buried in a single-layered homogeneous medium.

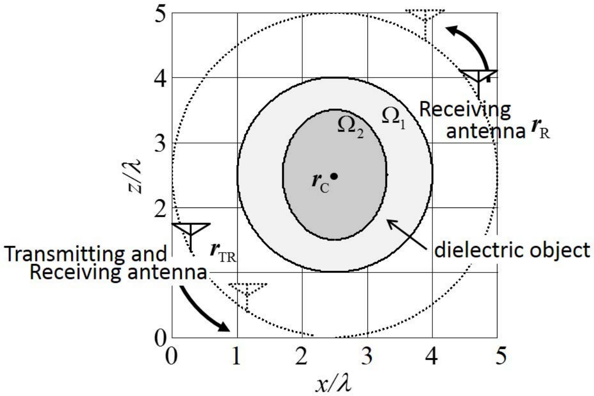

Fig. 1. System model.

To remove this limitation, this paper proposes a novel method of accurately estimation permittivity and extracting the boundary within a double-layered medium. In this method, the extended Envelope method is introduced to reconstruct the inner boundary points and their normal vectors, and GO based permittivity estimation is adopted to reduce the required computational resources. The results of numerical simulation show that our proposed method simultaneously estimates permittivity accurately and extracts the boundary within the inner medium with accuracy on the order of 1/20 of the wavelength of the transmitting signal.

## II. SYSTEM MODEL

Figure 1 shows the system model. It is assumed that a dielectric object has a double layered structure. The regions of the outer and inner media are denoted $\Omega_1$ and $\Omega_2$, respectively. Two omni-directional antennas scan along a circle with center $\boldsymbol{r}_{\mathrm{c}}$ and radius $R_{\mathrm{c}}$ that completely surrounds the dielectric object. One transmitting and receiving antenna is located at $\boldsymbol{r}_{\mathrm{TR}} = (X, Z)$, and an antenna playing only a receiving role is located at $\boldsymbol{r}_{\mathrm{R}} = (X, Z)$, where $\boldsymbol{r}_{\mathrm{c}} = (\boldsymbol{r}_{\mathrm{TR}} + \boldsymbol{r}_{\mathrm{R}})/2$ holds. A mono-cycle pulse with center wavelength $\lambda$ is used as the transmitting current. $S_{\mathrm{TR}}(X, Z, R)$ and $S_{\mathrm{R}}(X, Z, R)$ denote the output of the matched filter at antenna positions $\boldsymbol{r}_{\mathrm{TR}}$ and $\boldsymbol{r}_{\mathrm{R}}$, respectively, where $R = \mathrm{c}t/2$ is expressed by time $t$ and the propagation speed of the radio wave c. The range points extracted from the local maxima of $S_{\mathrm{TR}}$ and $S_{\mathrm{R}}$ are debited $\boldsymbol{q}_{\mathrm{TR}} = (X_{\mathrm{TR}}, Z_{\mathrm{TR}}, R_{\mathrm{TR}})$ and $\boldsymbol{q}_{\mathrm{R}} = (X_{\mathrm{R}}, Z_{\mathrm{R}}, R_{\mathrm{R}})$, respectively, and the detailed process of the extraction has been described previously [4]. The sets of these range points $\boldsymbol{q}_{\mathrm{TR}}$ and $\boldsymbol{q}_{\mathrm{R}}$ are respectively denoted $\mathcal{Q}_{\mathrm{TR}}$ and $\mathcal{Q}_{\mathrm{R}}$.

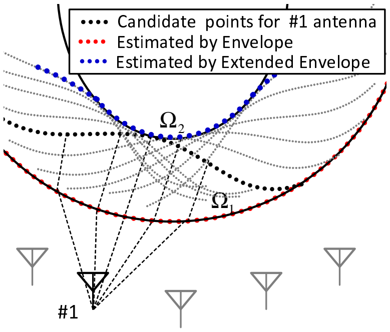

Fig. 2. Principle of Extended Envelope method.

## III. PROPOSED METHOD

We proposed a method of accurately estimating permittivity in a previous paper [3]. As a notable feature of this method, the dielectric constant of the medium surrounding the inner target can be accurately estimated with a computational cost lower than that required by conventional approaches that solve the domain integral equation [1]. In addition, our method has an advantage over the methods described in [2], which are typically used in through-the-wall applications, in that it does not require a *priori* information about the shape of the dielectric object. However, our method can only be applied to a limited object model, such as a single-layered homogeneous medium, in principle. To relax this limitation, this paper extends the former method [3] to double-layered dielectric media.

First, the set of range points $\boldsymbol{q}_{\mathrm{TR},1}$ is extracted from $\mathcal{Q}_{\mathrm{TR},1}$. $\mathcal{Q}_{\mathrm{TR},1}$ is derived from the maximum value of $S_{\mathrm{TR}}(X, Z, R)$ for each antenna location $(X, Z)$, regarded as the measured range from the antenna to the outer dielectric boundary. The outer dielectric boundary point $\partial\hat{\Omega}_1$ is estimated by applying the Envelope method to the range points $\boldsymbol{q}_{\mathrm{TR},1}$. These boundary points are denoted $\boldsymbol{r}_{1,i} = (x_{1,i}, z_{1,i})\ \ (i = 1, ...N_1)$. Second, $\mathcal{Q}_{\mathrm{TR},2} = \mathcal{Q}_{\mathrm{TR}} \cap \overline{\mathcal{Q}_{\mathrm{TR},1}}$ are extracted, and the included range points are denoted $\boldsymbol{q}_{\mathrm{TR},2}$. Here, to reconstruct an inner dielectric boundary $\partial\Omega_2$, the existing envelope method [5] is extended as follows. Figure 2 shows the reconstruction principle of the extended Envelope method. In this method, the candidate curve for the inner boundary point of each range point $\boldsymbol{q}_{\mathrm{TR},2}$ is calculated using Snell's law and the estimated outer dielectric boundary $\partial\hat{\Omega}_1$ and its normal vector. The outer envelope of these candidates curve is then extracted as the inner dielectric boundary $\partial\hat{\Omega}_2$. These inner boundary points are denoted $\boldsymbol{r}_{2,j} = (x_{2,j}, z_{2,j})\ \ (j = 1, ..., N_2)$. Third, the relative permittivities for each dielectric medium calculated are determined as for each range point $\boldsymbol{q}_{\mathrm{R,k}}$

$$(\hat{\epsilon_{1,k}}, \hat{\epsilon_{2,k}}) = \underset{\epsilon_{1,k},\epsilon_{2,k}}{\arg\min} \left|\left| R_k - \tilde{R}(\epsilon_1, \epsilon_2; \boldsymbol{q}_{R,k})) \right|\right|^2, \tag{1}$$

where $\tilde{R}(\epsilon_1, \epsilon_2; \boldsymbol{q}_{R,k})$ is the estimated propagation delay. Finally, using all the transmissive range points $\boldsymbol{q}_{\mathrm{R,k}}$, the optimal relative permittivity is determined as

$$(\epsilon_1, \epsilon_2) = \frac{\sum_{k=1}^{N_{\boldsymbol{q},2}} S_{\mathrm{R}}(\boldsymbol{q}_{\mathrm{R,k}})(\hat{\epsilon_{1,k}}, \hat{\epsilon_{2,k}})}{\sum_{k=1}^{N_{\boldsymbol{q},2}} S_{\mathrm{R}}(\boldsymbol{q}_{\mathrm{R,k}})}, \tag{2}$$

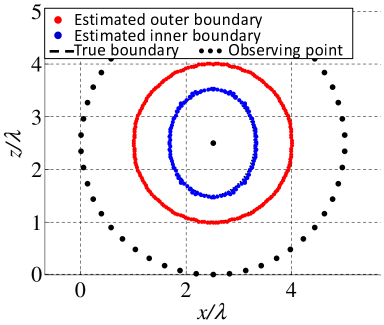

Fig. 3. Dielectric boundaries estimated from the relative permittivity obtained using the proposed method.

where $N_{\boldsymbol{q},2}$ is the total number of range points $\boldsymbol{q}_{\mathrm{R}}$.

## IV. EVALUATION BY NUMERICAL SIMULATION

The double-layered dielectric object is assumed as shown in Fig.1. The received signals are generated employing the FDTD (Finite-Difference Time-Domain) method. The relative permittivities of the outer and inner dielectric media are set to 5.0 and 3.0, respectively, and the conductivity of each medium is set to $0.01\mathrm{S/m}$. The final estimated relative permittivities for the outer and inner dielectric media determined using Eq. (2) are 5.29 (relative error of 6%) and 2.95 (relative error of 2%), respectively. Figure 3 shows the reconstructed outer and inner boundaries when the extended envelope method is applied using each permittivity obtained with the proposed method. The root-mean-square errors (RMSE) of the outer boundary and inner boundary are respectively $6.2 \times 10^{-3}\lambda$ and $2.9 \times 10^{-2}\lambda$. These results demonstrate that the proposed method accurately estimates the permittivity and the inner boundary of a double-layered medium, while assuming the GO approximation.

## V. CONCLUSION

This paper proposed a method of accurately estimating the permittivity of a double-layered homogeneous dielectric medium. FDTD based simulations demonstrated that the proposed method accurately estimates each permitivity and the inner boundary within accuracy on the order of 1/20 of the wavelength of the transmitting signal.

## REFERENCES

[1] A. Franchois, C. Pichot, "Microwave Imaging-Complex Permittivity Reconstruction with a Levenberg-Marquardt Method." *IEEE Trans. Antennas & Propagat.*, vol. 45, No. 2, pp. 203–215, Feb., 1997.

[2] A. Boryssenko, O. Boryssenko, A. Lishchenko, and V. Prokhorenko, "Inspection of Internal Structure of Walls by Subsurface Radar" *IEEE Aerospace & Electronic Systems Magazine*. vol. 48, No. 48, pp. 1993–2004, Apr., 2010.

[3] R. Souma, S. Kidera and T. Kirimoto, "Accurate Permittivity Estimation Method with Iterative Waveform Correction for UWB Internal Imaging Radar," *IEICE Trans. Electron.*, vol. E96-C, no. 5, pp. 730–737, May, 2013.

[4] S. Kidera, T. Sakamoto, and T. Sato, "Accurate UWB Radar Three-Dimensional Imaging Algorithm for a Complex Boundary Without Range Point Connections," *IEEE Trans Geosci & Remote Sens.*, vol. 48, no. 7, pp. 1993–2004, Apr., 2010.

[5] S. Kidera, T. Sakamoto, and T. Sato, "A Robust and Fast Imaging Algorithm with an Envelope of Circles for UWB Pulse Radars," *IEEE Trans. Commun.*, vol. E90-B, no. 7, pp. 1801–1809, Apr., 2007.