Fast Imaging of a Target in Inhomogeneous Media for Pulse Radar Systems

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Abstract— **Many works have been done to develop efficient imaging algorithms for ground penetrating radars. We have developed a new imaging algorithm SEABED for homogeneous media and confirmed its performance. This algorithm has an advantage that the calculation time is quite short because it is based on a reversible transform. However, its performance for inhomogeneous media has not studied yet. In this paper, we examine the performance of SEABED for inhomogeneous media.**

Keywords— **Imaging, Inhomogeneous Media, Pulse radar, Boundary scattering transform**

I. Introduction

MINE detection is an important social issue, for which ground penetrating radars are promising candidates. It is required to develop an efficient algorithm for ground penetrating radars. Estimating target shapes using data received by a scanned omni-directional antenna is known as one of ill-posed inverse problems. Many kinds of imaging algorithms have been proposed [1-6]. Model fitting method is one of effective approaches for this problem [1, 2]. In the model fitting method, target shapes are expressed with parameters, and the parameters are updated to minimize the difference between the observed data and the estimated data. Model fitting method works well to some extent, but they have problems concerning calculation time and stability [3, 4]. Imaging algorithms based on domain integral equation is another parametric approach [5]. In their algorithm, targets and media were modeled as grids of permittivity. They solved the domain integral equation by means of various optimization algorithms such as genetic algorithms. However, they assume that antenna scans around targets, which is not realistic for our applications. Migration algorithms are well-known especially in the field of seismic prospecting [6]. Migration algorithms are applicable for general media and targets, but their resolutions are limited to the order of the signal wavelength.

The conventional algorithms in general have problems of long calculation time and instability. It is required to develop a fast and stable algorithm for radar imaging for mine detection. We have developed a new imaging algorithm SEABED for pulse radars [7]. The SEABED algorithm has a characteristic that it can quickly and directly estimate a target shape as a line, which is a remarkable advantages compared to conventional ones. We have confirmed the high performance of SEABED algorithm for homogeneous media. Inhomogeneity of underground is one of the most difficult problem to overcome for mine detection. In this paper, we examine the performance of SEABED algorithm for inhomogeneous media by numerical simulations.

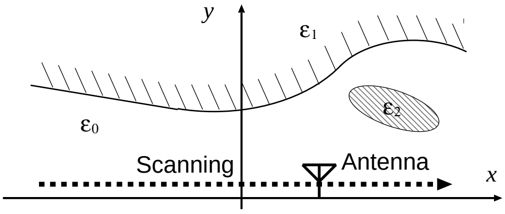

Fig. 1. The coordinates and an example of a target complex permittivity.

II. System Model

We assume a mono-static radar system in this paper. An omni-directional antenna is scanned along a straight line. UWB pulses are transmitted at a fixed interval and received by the antenna. The received data is A/D converted and stored in a memory. We estimate target shapes using the data. Fig. 1 shows the system model.

We deal with a 2-dimensional problem, and TE-mode wave. Targets and the antenna are located on a plane. We define r-space as the real space, where targets and the antenna are located. We express r-space with the parameter (x, y). Both x and y are normalized by λ, which is the center wavelength of the transmitted pulse in air. We assume $y > 0$ for simplicity. The antenna is scanned along x-axis in r-space. We define $s'(X, Y)$ as the received electric field at the antenna location $(x, y) = (X, 0)$, where we define Y with time t and speed of the radiowave c as $Y = ct/(2\lambda)$. We apply a matched filter of transmitted waveform for $s'(X, Y)$. We define $s(X, Y)$ as the output of the filter. We define d-space as the space expressed by (X, Y). The transform from d-space to r-space corresponds to imaging which we deal with in this paper.

III. SEABED Algorithm

We have already developed a non-parametric shape estimation algorithm based on BST (Boundary Scattering Transform) [7]. We call the algorithm SEABED (Shape Estimation Algorithm based on BST and Extraction of Directly scattered waves). The algorithm utilizes the existence of a reversible transform BST between target shapes and pulse delays. We have clarified that the SEABED has an advantage of direct estimation of target boundaries using inverse transform, which is a mathematically complete solution for the inverse problem.

We assume that each target has a uniform complex permittivity, and surrounded by a smooth boundary. We also assume that the propagation speed is known. Boundary Scattering Transform (BST) is expressed as

$$X = x + y\mathrm{d}y/\mathrm{d}x, \quad (1)$$

$$Y = y\sqrt{1 + (\mathrm{d}y/\mathrm{d}x)^2}, \quad (2)$$

where (X, Y) is a point on a quasi wavefront. (x, y) is a point on target boundary, and we assume $y > 0$ and $Y > 0$ [7]. We have clarified that the inverse transform of BST is given by

$$x = X - Y\mathrm{d}Y/\mathrm{d}X, \quad (3)$$

$$y = Y\sqrt{1 - (\mathrm{d}Y/\mathrm{d}X)^2}, \quad (4)$$

where we assume $|\mathrm{d}Y/\mathrm{d}X| \leq 1$. We call the transform in Eq. (3) and (4) Inverse Boundary Scattering Transform (IBST).

First, we extract a quasi wavefront from $s(X, Y)$ in SEABED. Quasi wavefronts have to satisfy the condition $\mathrm{d}s(X, Y)/\mathrm{d}Y = 0$ and $|\mathrm{d}Y/\mathrm{d}X| \leq 1$. The latter condition ensures Y in Eq.(4) to be a real number. We sequentially extract the set of points (X, Y). Next, we select quasi wavefronts with large power and eliminate undesirable components. Finally, we apply IBST to the extracted quasi wavefront and estimate the target shape.

IV. Shape Estimation in Homogeneous Media

We first show an application example of SEABED algorithm for homogeneous media. We assume a cylindrical perfect conductor with radius of 1λ as an example target. Fig. 2 shows an example of target boundary surface. The inner domain is filled with perfect electric conductor, and the outer domain is filled with air. The symbols on the bottom in this figure are the points where the data is obtained. Fig. 3 shows the received data $s(X, Y)$ which is calculated with FDTD (Finite Difference Time Domain) method. The antenna receives the signal at 39 locations with intervals of 0.125λ. We assume $\mathrm{S/N} = \infty$ for simplicity.

Fig. 4 shows the extracted quasi wavefronts from the received data. By applying IBST to the quasi wavefront, we obtain the estimated target shape as in Fig. 5. In this figure, the solid line and broken line are the true shape and estimated shape, respectively. The lower side of the target boundary is accurately estimated by SEABED algorithm. The upper side of the target is not estimated because SEABED requires the directly scattered signal. As a result, we can conclude that SEABED algorithm works well for shape estimation of a target in homogeneous media.

V. Shape Estimation in Inhomogeneous Media

A. Performance for Random Media

In this section, we investigate the estimation performance of SEABED algorithm for inhomogeneous media.

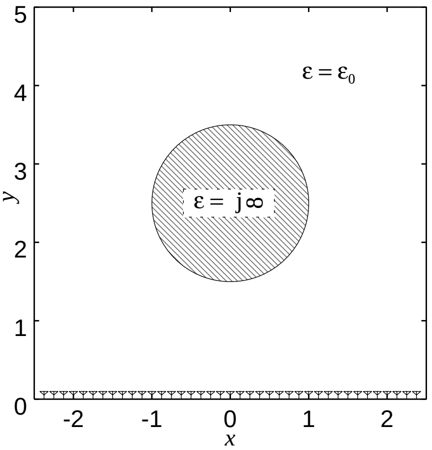

Fig. 2. Target shape example.

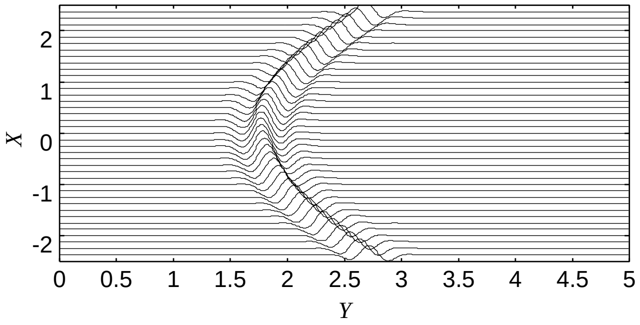

Fig. 3. Received signal in homogeneous media.

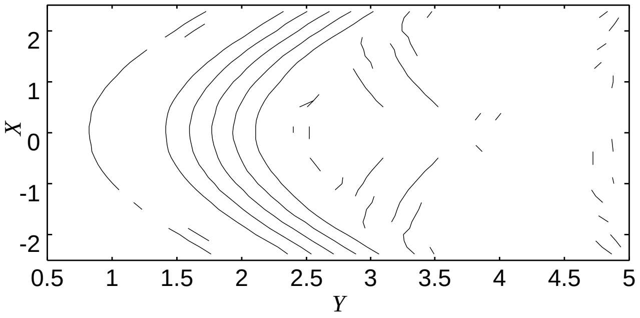

Fig. 4. Extracted quasi wavefronts in homogeneous media.

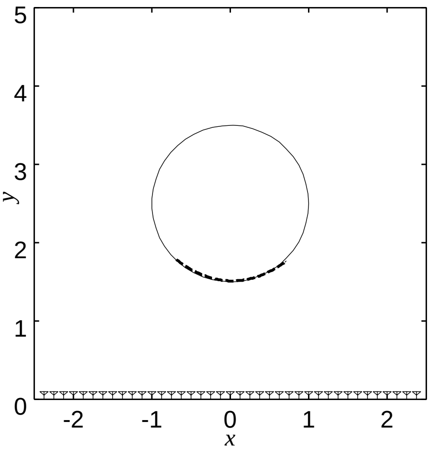

Fig. 5. Estimated target shape in homogeneous media.

The target shape is a cylindrical perfect conductor with radius of 1λ which is the same one as shown in Fig. 2. The media around the target has highly inhomogeneous dielectric, whose relative permittivity ε_{r} is shown in Fig. 6. This permittivity is obtained by applying a two-dimensional spatial LPF (Low Pass Filter) with the cut-off of the half-wavelength to a random image with a normal distribution. The distribution of the relative permittivity has the mean of 1, and the standard deviation of 0.5. We assume this mean is known as a priori information. The central round region with relative permittivity of 1 corresponds to the region of the target. Fig. 7 shows the received signal for the target in this random media. We see many undesirable components in this figure compared to the the signal in homogeneous media. Fig. 8 shows the extracted quasi wavefronts from the signal in Fig. 7. We see many undesirable quasi wavefronts together with a desirable one. However, most of the undesirable quasi wavefronts are not connected smoothly with each other, which makes their evaluation value small, which enables to eliminate the undesirable components. We apply IBST to the quasi wavefronts whose evaluatin value greater than −5dB of the maximum evaluation value. We utilize the mean of the permittivity when applying IBST. Fig. 9 shows the estimated target shape by IBST. The solid line and broken line are the true target shape and the estimated target shape, respectively. We see that the target shape is correctly estimated to some extent although the estimation is less accurate than in the homogeneous media. Additionaly, we see that the undesirable components are removed because their evaluation value become smaller than that of the desirable one. If we set the threshould of evaluation value to −10dB, the estimation image contains undesirable components caused by the random media, which show the importance of the selection of the threshould.

B. Performance for Layered Media

Next, we investigate the performance of SEABED algorithm for layerd media. The target shape is a cylindrical perfect conductor which is the same one used in the previous section. We obtain this permittivity by applying LPF for y-direction with a cut-off of half-wavelength to a random image. The mean of the relative permittivity is 1, which we assume to be a priori information. Fig. 11 shows the received signal in the layered media. We can observe many scattered wave from the layers close to the antenna. The scattered wave from the target is smooth compared to those in the random media. Fig. 12 shows the extracted wavefronts in the layered media. We see the desired component and undesirable components caused by the layers. We apply IBST to the quasi wavefronts whose evaluatin value greater than −5dB of the maximum evaluation value. Fig. 13 shows the estimated target shape in the layered media. The solid line and broken line are the true target shape and estimated target shape, respectively. We see that SEABED algorithm also works well for layered media as in this figure. However, we can observe the offset error caused by the layered media between the antenna and the target.

The imaging took 40 msec with Xeon 2.8GHz processor, which is considerably fast. The calculation time is independent of the media and the shape of targets because SEABED algorithm utilize the reversible transform. We have confirmed the efficiency of SEABED algorithm even in inhomogeneous media.

VI. SUMMARY

We investigated the performance of SEABED algorithm, which we proposed previously, for inhomogeneous media. The simulation result shows that SEABED algorithm works well even in inhomogeneous media on some conditions as follows:

- The mean of random permittivity should be known.
- The threshould for evaluation value of quasi wavefronts should be suitably selected.

Further studies are needed to overcome these difficulties. As for calculation time, the imaging took 40 msec with Xeon 2.8GHz processor. The calculation time of SEABED algorithm is sufficiently short, which enables a realtime operation with this algorithm.

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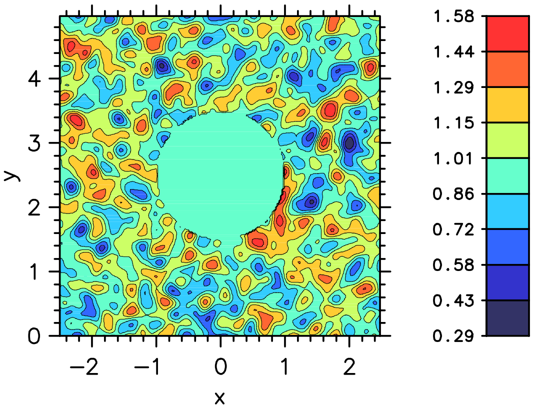

Fig. 6. Permittivityε_{r} of random media.

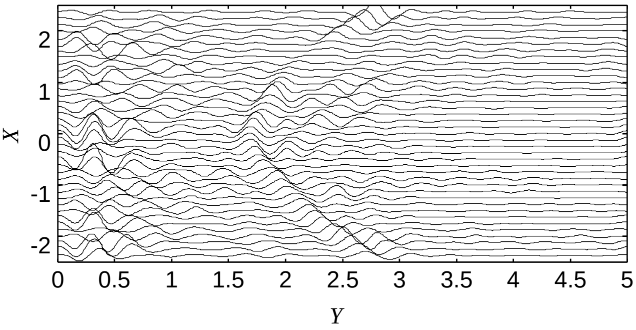

Fig. 7. Received signal in random media.

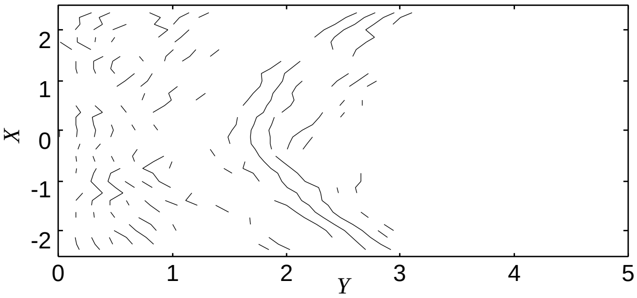

Fig. 8. Extracted quasi wavefronts in random media.

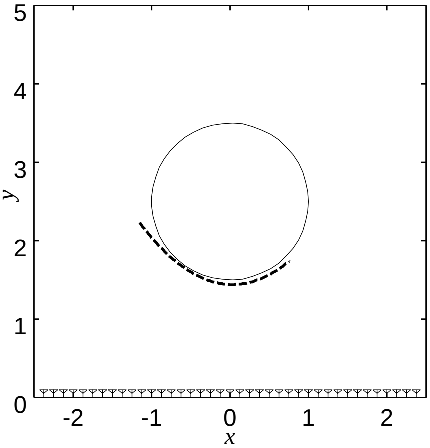

Fig. 9. Estimated target shape for random media.

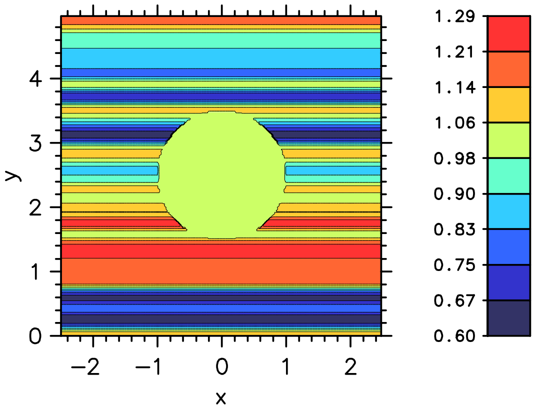

Fig. 10. Permittivityε_{r} of layered media.

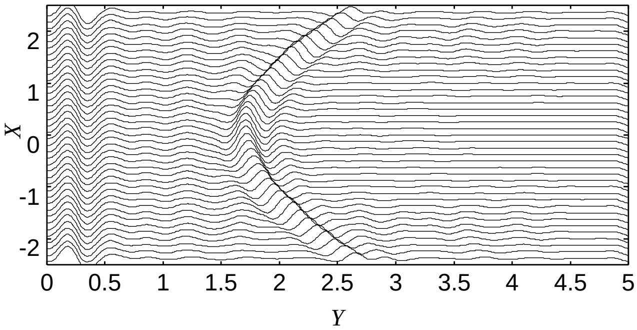

Fig. 11. Received signal in layered media.

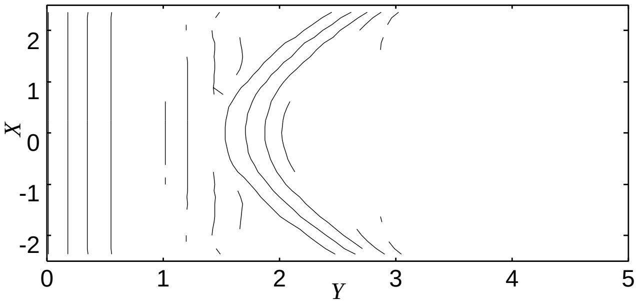

Fig. 12. Extracted quasi wavefronts in layered media.

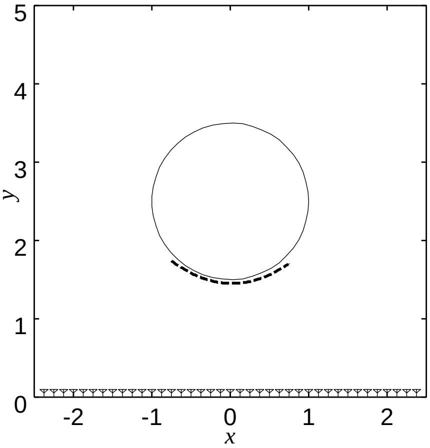

Fig. 13. Estimated target shape for layered media.