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A CONSIDERATION ON THE RADAR IMAGE RECONSTRUCTION USING AN ARBITRARY ARRAY

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1 Introduction

The radar image reconstruction technique is expected to play an important role in various fields such as the detection of the underground objects[1].

Diffraction tomography is one of the promising methods of the image reconstruction[2]. Although it can retrieve an accurate image when targets are observed from all directions, the image seriously deteriorates when the observational direction is restricted. This is due to the large deficit region in the wave number space caused by this limitation, and an appropriate interpolation is necessary to get an accurate image.

In the present study we propose an algorithm applicable to arbitrarily arranged antenna arrays by using the method of nonlinear least-squares fitting.

2 The Simulation Model

Figure 1 shows the simulation model used in the present study. A simple 2-dimensional model was adopted in order to examine the fundamental properties of the inverse scattering problem. As shown in the figure, 5 antennas are placed linearly at a fixed interval, and radiate cylindrical waves. Each antenna is used both for transmission and reception. The combination of transmitting and receiving antenna pairs provide 25 time series data.

The medium is assumed to be homogeneous and to have a low-pass frequency characteristics with no loss in the pass-band. The interval between antennas is chosen as $\lambda_c/2$, where λ_c is the wavelength at the cutoff frequency. The target consists of a limited number of isotropic point scatters. Frequency characteristics of the antenna, the transmitter, the receiver, and the medium determine the received waveform in such a case. Image reconstruction is made on the assumption that the overall characteristics are known. Figure 2 shows an example of the received pulse waveform.

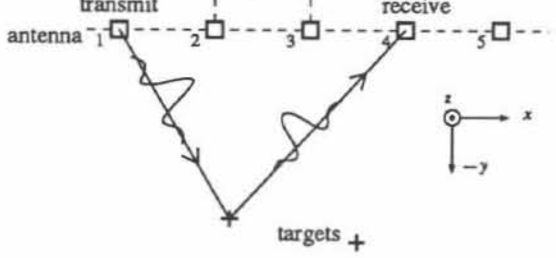


Fig. 1. Simulation model

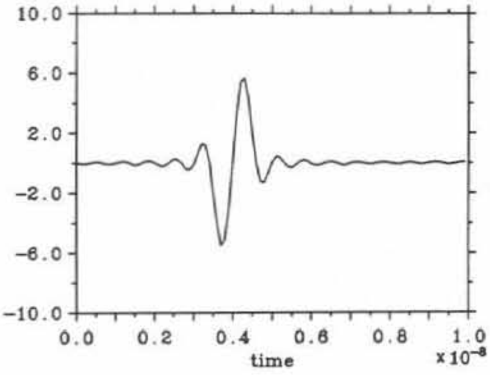


Fig. 2. Received waveform from a single point target.

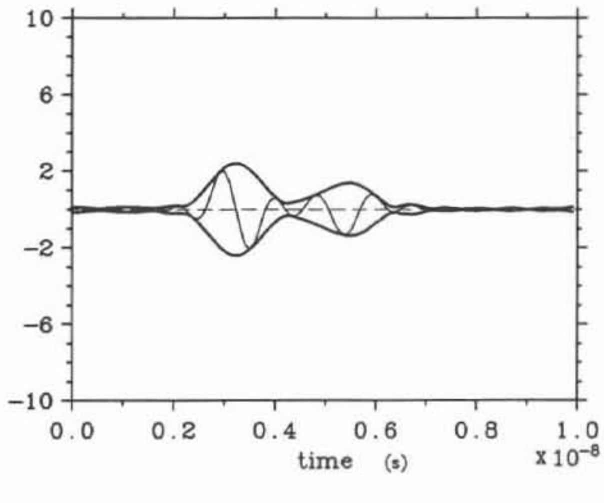


Fig. 3. Received wave form from two point targets.

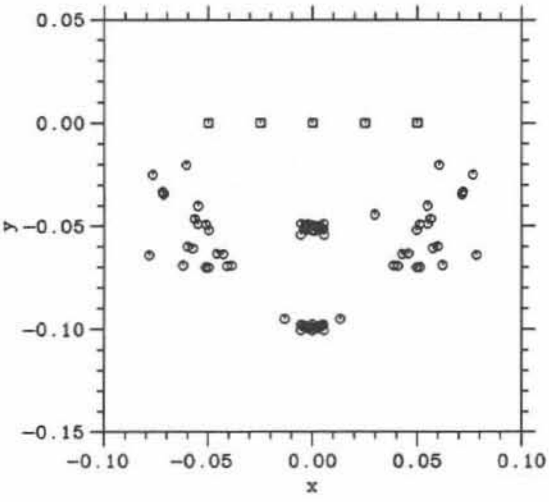


Fig. 4. Estimation of the target position.

The received time series for each pair of antennas can be computed if the number of targets, their position, and their complex reflection coefficient are given. These parameters are determined by fitting the estimated time series to the model ones using a nonlinear least-squares fitting algorithm.

3 Initial Value Determination

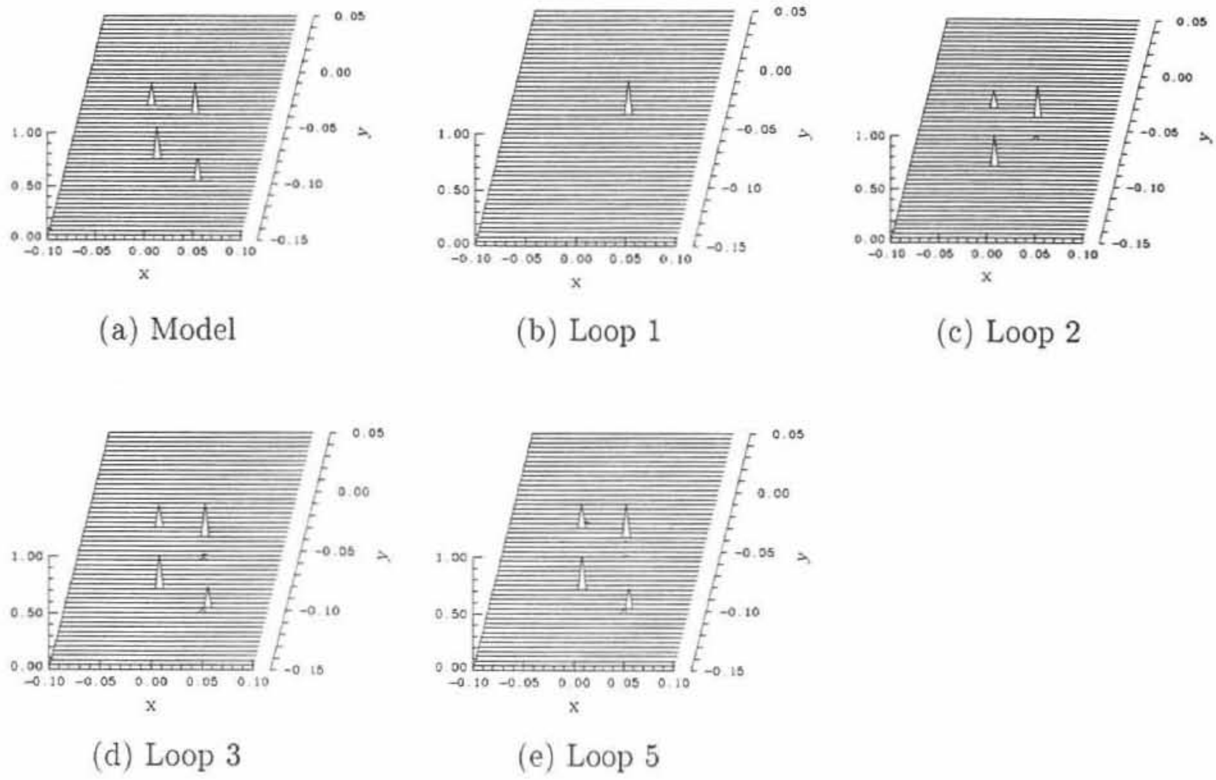
The nonlinear least-squares fitting is an iterative algorithm, which requires a proper set of initial values for all of the variables. In this paper, initial values are determined from the delay time of the received pulse.

In the observation, time series data are available for each pair of transmit/receive antennas. The thin line of Figure 3 shows an example of a simulated time series of the received signal. The thick line is the instantaneous envelope[3] computed from this signal. The existence of two pronounced peaks in the envelope indicates that the data contains scattering from two point targets. Delay time of each echo is estimated as 3.2 ns and 5.5 ns, respectively.

One-dimensional information on the position and reflection coefficient of the target are extracted from these delay times. The received pulse with 3.2 ns delay has an odd functional waveform relative to the corresponding peak of the envelope, and the pulse with 5.5 ns delay has an even one. By examining such phase of the received pulses, the phase of the reflection coefficient can be determined. In the case of Fig. 2, the pulse with 3.2 ns delay has real reflection coefficient and that with 5.5 ns has purely imaginary one.

After estimating the number and the delay time of the echoes from individual time series, the location of the targets are determined in the plane which contains the array.

The target should be located on an ellipse whose semi-major axis corresponds to the extracted delay time. Since such ellipse can be drawn for each time series data, the location can be estimated by the cross point of two ellipses. Figure 4 plots all possible combinations of the one-dimensional estimates. Two real targets are located at $(x, y) = (0.0, -0.05)$ and $(0.0, -0.10)$. Although there are many spurious points generated by incorrect combinations, this figure indicates that it is reasonable to judge that the targets



(a) Model (b) Loop 1 (c) Loop 2

(d) Loop 3 (e) Loop 5

Fig. 5. The iteration algorithm applied to a 4-point model.

are present where the concentration of the estimated points is sufficiently high.

The result of this algorithm is used as the initial guess for the nonlinear least-squares estimation.

4 Iteration Algorithm

Here we consider a more complicated model which consists of four targets with different reflectivity as shown in Figure 5(a). The procedure described in the previous section detected only one target which gives the largest contribution to the received time series. A conventional nonlinear least-squares fitting algorithm based on the modified Marquardt method is then applied to the data by minimizing the variance of the estimated and received time series for all transmitter/receiver combinations. Although the algorithm fixes the number of targets, it does improve the estimate of the location and the reflectivity of the detected target. Fig. 5(b) shows the result of the fitting.

In order to detect other three targets, we apply the fitting algorithm to the residual time series which is obtained by subtracting the estimated time series from the original one. Since most of the effect of the largest target is removed from the residual time series, smaller targets can be retrieved by the initial guess algorithm with the aid of the nonlinear fitting algorithm. This iteration algorithm is repeated until the residual becomes small enough or the estimates becomes unchanged. Fig. 5(c), (d), and (e) shows the estimated model after the second, third, and 5th iteration, respectively.

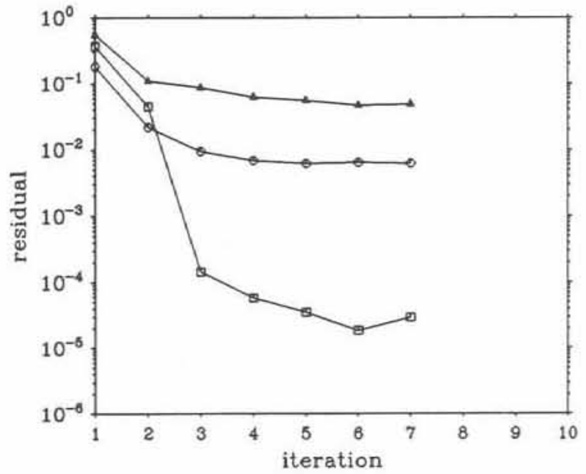


Fig. 6. Transition of the residual.

As shown in these figures, all of the four targets are found in the third iteration, and further iterations do not essentially alter the estimate. There are also spurious targets in these estimates, but their magnitude is always small. Figure 6 shows how the magnitude of the residual changes with increasing iteration. The line marked with □ is the residual when no noise is present in the given time series.

The residual decrease rapidly at the third loop when all of the targets are detected, and finally reaches to the order of 10^{-5}. The line marked with ∘ and △ is a residual transition in the presence of noise, with the signal-to-noise ratio (SNR) of 20dB and 10dB, respectively. Final level of the residual, and thus the minimum detectable magnitude of the target, is determined by the SNR as shown by these curves. When the SNR is 10dB, one target could not be detected. Ratio of the undetectable target and the standard deviation of the noise was 3.5.

5 Conclusion

We proposed a method of image reconstruction which can be applied to an arbitrary antenna array. The principle of the method is to fit the theoretically generated time series to the observed one for all combinations of the transmitter/receiver in a least-squares sense. The theoretical time series is computed on the assumption that the target consists of a limited number of point scatterers.

Since the fitting algorithm becomes nonlinear, we developed a practical way of obtaining the initial guess for the fitting. We employed an iterative algorithm which enabled the detection of targets with smaller reflectivity. We examined the behavior of the algorithm via a simple numerical simulation for the case of a linear array consisting of five elements. Although the present algorithm assumes a homogeneous medium, it is in principle applicable to a case of point scatterers embedded in a weakly inhomogeneous medium.

References

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