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Parameter Estimation of Three-dimensional Scattering Centers Based on State Space and ESPRIT Method

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Abstract

For the problem of radar target three-dimensional scattering centers parameter estimation, a new method that based on state space method and spectrum estimation method (3D-SS-ESPRIT) is proposed. According to the 3D-GTD model theory, we obtained the high-frequency radar target parameter signal model, via constructing generalized Hankel matrix, we estimated 3D scattering centers parameters based on the state space method and reconstructed the high-frequency radar target characteristic data. Numerical simulations show that the proposed method is an efficient and reliable method to estimate these parameters, compared to convention 3D spectrum estimation method, the proposed method gain better estimation, reconstruction property and has better stability.

Keywords: *scattering centers; GTD model; state space method; target characteristic*

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1. Introduction

The efficient compression, storage and utilization of radar target electromagnetic scattering data are a hot topic in current research. The concept based on electromagnetic mechanism model is a good entry point. So far, the research based on one-dimensional or two-dimensional electromagnetic model is more in-depth, but it cannot achieve high-efficiency compression of the target full-space target characteristic data [1]; the researches based on three-dimensional electromagnetic model, mainly some modern spectral estimation methods, are relatively few, which time complexity is high and the reconstruction effect on the complex target partial region is not ideal [2].

The state space method is a model-based feature decomposition method of modern control theory. It has the advantages of low requirements on system stability, and can be used to process target characteristic data with different scattering center intensity, signal frequency and angle dependence and is suitable for extracting parameters with complex structural targets [3]. In this paper, by constructing the generalized Hankel matrix with a reference of spectrum estimation method [4], the state space method in the literature [5] is extended to three-dimensional, and the three-dimensional scattering center parameter estimation and RCS reconstruction of complex targets are completed.

2. 3D-GTD Model and It's Simplification

For the 3D-GTD model, the electromagnetic scattering data of the radar target is related to the frequency f, the incident azimuth φ and the incident pitch angle θ [6]. Assume that the target 3D coordinate system is as shown:

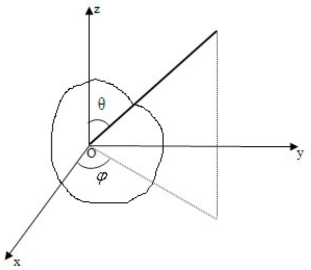


Fig. 1. Target three-dimensional coordinate system definition

The target 3D echo signal can be written as:

$$E(f,\theta,\varphi)=\sum_{i=0}^{s-1}A_i(f,\theta,\varphi)\cdot\left(j\frac{f_n}{f_c}\right)^{\alpha_i}\exp\left[-j\frac{4\pi}{c}f_n(x_i\cos\varphi\cos\theta+y_i\sin\varphi\cos\theta+z_i\sin\theta)\right]+w(f,\theta,\varphi) \tag{1}$$

where $E(f,\theta,\varphi)$ represents the scattering echo, A_i is the scattering intensity of the ith scattering centers, f_c is the center frequency, f_n is the step frequency, α_i is the type factor, (x_i, y_i, z_i) is the coordinate of the ith scattering center, and $w(f,\theta,\varphi)$ is the zero-mean three-dimensional complex Gaussian white noise.

In order to improve the calculation accuracy, spatial resampling processing is required. We can get the resampled echo in the frequency domain discretized as:

$$\begin{aligned}E'(m,n,k)&=\sum_{i=0}^{s-1}A_i\left(j\frac{f}{f_c}\right)^{\alpha_i}\exp\left[-j4\pi\left(f_m^{(x)}x_i+f_n^{(y)}y_i+f_k^{(z)}z_i\right)\right]+w(m,n,k)\\&\approx\sum_{i=0}^{s-1}A_i j^{\alpha_i}e^{-\alpha_i}\cdot(1+\alpha_i\frac{\Delta f}{f_c})^m\exp\left[-j4\pi\left(f_m^{(x)}x_i+f_n^{(y)}y_i+f_k^{(z)}z_i\right)\right]+w(m,n,k)\end{aligned} \tag{2}$$

3. 3D Scattering Centers Parameter Estimation Based on State Space

State space theory focuses on the mathematical modeling of linear systems with inputs, outputs and internal state variables. The relationship of these variables can be represented by a set of first-order differential equations. In the system, the estimation of unknown parameters can be obtained by analyzing the impulse response of the system. Since the state space method uses matrix representation, the complexity of the system description is independent of the state variables and the number of input and output variables. The relationship between variables inside and outside the system can be revealed, which makes the calculation efficiency and accuracy improved [7].

For wideband radar targets, the discrete state space equation of the echo can be expressed as:

$$\begin{aligned} x(n+1) &= Ax(n) + Bu(n) \\ y(n) &= Cx(n) + u(n) \end{aligned} \tag{3}$$

where $n = 0,1,2,\cdots, x(n)$ is its state vector, **A** is the system state change matrix, which defines the evolution of the system state from time *n* to *n + 1*, **B** is the input quantity versus state influence matrix, specifies how the input affects the current state, **C** is the state-to-output influence matrix, defines the current system How states are mapped to output. Suppose there is a zero initial pulse input:

$$u(n) = \delta(n) = \begin{cases} 1, n = 0 \\ 0, n \neq 0 \end{cases}, x(0) = 0 \tag{4}$$

Therefore, the target's 3D discrete signal model is rewritten to conform to the state space model:

$$\begin{aligned} \hat{g}_{m,n,k} &= \sum_{i=0}^{s-1} \Gamma_i (1+\alpha_i \frac{\Delta f^{(x)}}{f_c})^m \exp\left(-j4\pi\left(m\Delta f^{(x)}x_i + n\Delta f^{(y)}y_i + k\Delta f^{(z)}z_i\right)\right) = \begin{bmatrix} \Gamma_1 & \Gamma_2 & \cdots & \Gamma_s \end{bmatrix} \\ &\bullet \begin{bmatrix} \beta_1 e^{-j4\pi\Delta f^{(x)}x_1} & 0 & \cdots \\ 0 & \beta_2 e^{-j4\pi\Delta f^{(x)}x_2} & \cdots \\ \vdots & \vdots & \vdots \end{bmatrix}^m \begin{bmatrix} e^{-j4\pi\Delta f^{y}y_1} & 0 & \cdots \\ 0 & e^{-j4\pi\Delta f^{(y)}y_2} & \cdots \\ \vdots & \vdots & \vdots \end{bmatrix}^n \begin{bmatrix} e^{-j4\pi\Delta f^{(z)}z_1} & 0 & \cdots \\ 0 & e^{-j4\pi\Delta f^{(z)}z_2} & \cdots \\ \vdots & \vdots & \vdots \end{bmatrix}^{\mathrm{k}} \begin{bmatrix} 1 \\ \vdots \\ 1 \end{bmatrix} \triangleq CA_x^m A_y^n A_z^k B \end{aligned} \tag{5}$$

where $\Gamma_i = A_i \, e^{j\frac{\pi\alpha_i}{2} - \alpha_i} \, e^{-j4\pi(f_0^{(x)}x_i + f_0^{(y)}y_i + f_0^{(z)}z_i)}$, $\beta_i = 1 + \alpha_i \Delta f^{(x)} / f_c$, the diagonal matrices A_x, A_{y} and A_z have three-dimensional coordinate information of the scattering center.

Since the three-dimensional model has many parameters to be estimated, the traditional three-dimensional spectrum estimation method needs to construct three data smoothing matrices using three types of scanning sequences; the state space method only needs to construct one data smoothing matrix. The simultaneous solution of the three-dimensional variables can be completed, which effectively reduces the computational complexity and also improves the stability of the results [8]. Let the target discrete echo signal after resampling can be represented by a matrix with a size of $M \times N \times K$ and take $P = 2M/3$, $Q = 2N/3$, $L = 2K/3$. First construct the following generalized Hankel matrix:

$$H = \underset{m,n,k}{H}\left\{\hat{g}_{m,n,k}\right\} = \underset{k}{H}\left\{\underset{n}{H}\left\{\underset{m}{H}\left\{\hat{g}_{m,n,k}\right\}\right\}\right\} \tag{6}$$

where $\underset{m}{H}\left\{\hat{g}_{m,n,k}\right\}$ means constructing a Hankel matrix with a size of $P \times (M-P+1)$ by changing m while n and k are constant,

$$\underset{m}{H}\left\{\hat{g}_{m,n,k}\right\} = \begin{bmatrix} g_{0,n,k} & g_{1,n,k} & \cdots & g_{M-P,n,k} \\ g_{1,n,k} & g_{2,n,k} & \cdots & g_{M-P+1,n,k} \\ \vdots & \vdots & \ddots & \vdots \\ g_{P-1,n,k} & g_{P,n,k} & \cdots & g_{M-1,n,k} \end{bmatrix} \tag{7}$$

$\underset{n}{H}\left\{\underset{m}{H}\left\{\hat{g}_{m,n,k}\right\}\right\}$ means constructing a generalized Hankel matrix via changing n while k is constant by taking $\underset{m}{H}\left\{\hat{g}_{m,n,k}\right\}$ as the element, thus we can get $\underset{k}{H}\left\{\underset{n}{H}\left\{\underset{m}{H}\left\{\hat{g}_{m,n,k}\right\}\right\}\right\}$. Decompose the generalized Hankel matrix H into the product form of the observation matrix $\mathbf{O_1}$ and the control matrix $\mathbf{C_1}$

$$H = O_1 C_1 \tag{8}$$

where

$$O_1 = \begin{bmatrix} CA_x^0 A_y^0 A_z^0 \\ CA_x^1 A_y^0 A_z^0 \\ \vdots \\ \hdashline \vdots \\ \hline CA_x^0 A_y^0 A_z^1 \\ CA_x^1 A_y^0 A_z^1 \\ \vdots \\ \hdashline \vdots \\ \hline \vdots \end{bmatrix}, C_1 = \begin{bmatrix} \left(A_x^0 A_y^0 A_z^0 B\right)^T \\ \left(A_x^1 A_y^0 A_z^0 B\right)^T \\ \vdots \\ \hdashline \vdots \\ \hline \left(A_x^0 A_y^0 A_z^1 B\right)^T \\ \left(A_x^1 A_y^0 A_z^1 B\right)^T \\ \vdots \\ \hdashline \vdots \\ \hline \vdots \end{bmatrix} \tag{9}$$

Taking singular value decomposition for **H**, $H \overset{svd}{\Rightarrow} U_1 \Sigma_1 V_1^H$, using the information theory method, the cover disc method or the singular value comparison method to determine the number s of scattering canters [9], we can get:

$$\tilde{O}_1 = U_{1S}\sqrt{\Sigma_{1S}}, \tilde{C}_1 = \sqrt{\Sigma_{1S}} V_{1S}^H \tag{10}$$

Based on the $\tilde{\mathbf{O}}_1$ matrix solved by the above formula, each matrix separated by a broken line is defined as a primary matrix according to the definition in the equation (10), and each group of solid-separated matrices is defined as a secondary matrix. Six new matrices are defined by removing some generalized rows in these matrices: starting from the $\tilde{\mathbf{O}}_1$ matrix, the remaining matrices obtained by removing the first row and the last row of each primary matrix are defined as $\tilde{\mathbf{O}}_{1x+}$ and $\tilde{\mathbf{O}}_{1x-}$, and each secondary matrix is removed. The residual matrices obtained by the first and last level matrices are respectively defined as $\tilde{\mathbf{O}}_{1y+}$ and $\tilde{\mathbf{O}}_{1y-}$, and the residual matrices obtained by removing the first and last second order matrices are respectively defined as $\tilde{\mathbf{O}}_{1z+}$ and $\tilde{\mathbf{O}}_{1z+}$. Defining the generalized inverse of $\tilde{\mathbf{O}}$ as $\tilde{\mathbf{O}}^{\dagger}$, there is,

$$\tilde{A}_x = \tilde{O}_{1x-}^{\dagger}\tilde{O}_{1x+}, \tilde{A}_y = \tilde{O}_{1y-}^{\dagger}\tilde{O}_{1y+}, \tilde{A}_z = \tilde{O}_{1z-}^{\dagger}\tilde{O}_{1z+} \tag{11}$$

4. Simulation Results

Simulation conditions: A tail with a tail ball cone, the signal uses step frequency, the frequency range is 9-10GHz, the incident pitch angle range is 0~90°, the azimuth angle range is 0~180°, and the high frequency electromagnetic method is used for simulation. The three-dimensional spectral estimation method (3D-ESPRIT) and 3D-SS-ESPRIT method are used to estimate the three-dimensional scattering center parameter set of the target.

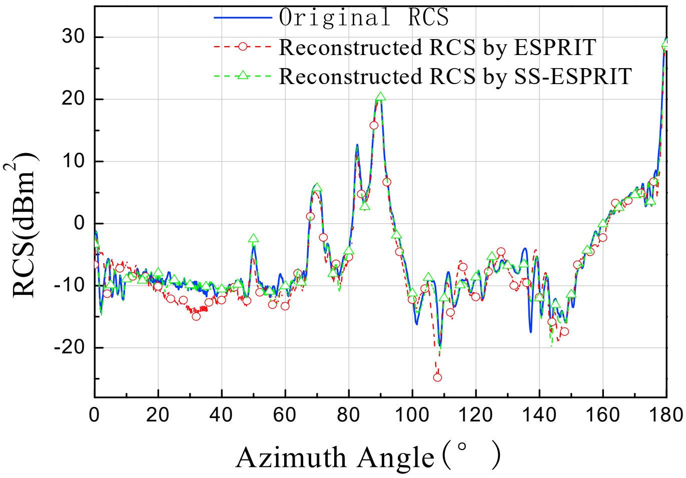
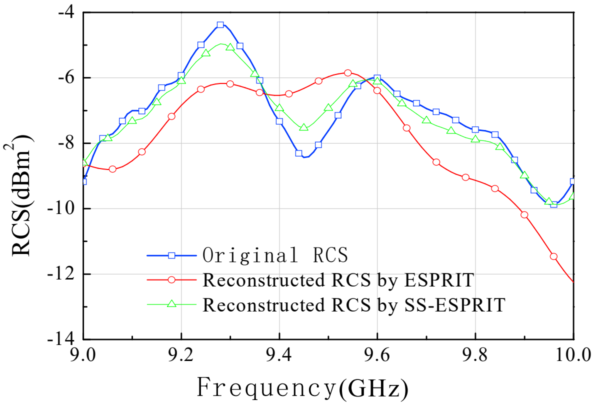
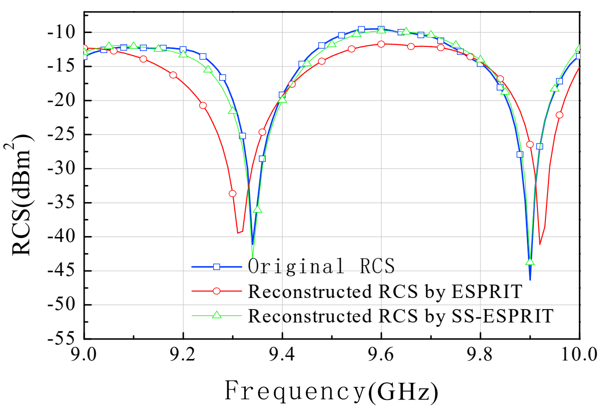


Fig. 2. Reconstruction RCS result with 90° incident pitch angle at 9.5 GHz



a) Azimuth angle 125°



b) Azimuth angle 150°

Fig. 3. Sweep frequency RCS reconstruction comparison result with 90°incident pitch angle

Fig.2. is a comparison of point frequency RCS based on the scattering center parameter set estimated by the two methods under the condition of incident elevation angle of 90° and 9.5 GHz. Fig. 3 is a comparison of the swept-frequency RCS based on two methods at different pitch angles with an incident pitch angle of 90°. Table 1 shows the statistical table of the frequency-swept RCS reconstruction error based on two methods in the range of the incident pitch angle of 88~92° and the azimuth angle of 0~180°. The above results show that compared with the 3D-ESPRIT method, based on the 3D-SS-ESPRIT algorithm, the 3D scattering center extraction and RCS reconstruction of non-rotationally symmetric targets can be effectively performed.

Table 1. omnidirectional RCS reconstruction error statistics with incident elevation angle of 88~92°

Methods	Reconstruction Error (dB)
3D-ESPRIT	2.8355
3D-SS-ESPRIT	0.9857

5. Conclusions

In this paper, a three-dimensional rotation invariant method based on state space method (3D-SS-ESPRIT) is proposed. Using the state space idea, the accurate estimation of the scattering center parameters of non-rotationally symmetric targets is realized. The system introduces the establishment of the target three-dimensional signal model, the construction of the generalized Hankel matrix and the solution of the state space equation, and completes the reconstruction of the three-dimensional electromagnetic scattering data. Simulation experiments show that the proposed method has better stability, parameter estimation performance and reconstruction accuracy than traditional 3D spectrum estimation methods.

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