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Low-observable target detection in sea clutter based on the adaptive 3D-IFS algorithm

Wang Chungang*, Zhao Qi, Feng Wenquan

School of Electronic and Information Engineering, Beihang University, Beijing 100191, China

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ABSTRACT

This paper mainly studies the application of the fractal self-affine theory for weak target detection in sea clutter. In this paper, the adaptive 3D-IFS (3D-IFS: three-dimensional iterated function system) algorithm is presented and a novel weak target detection model is proposed based on the algorithm. To accurately extract the weak target from the complicated background of sea clutter, we use the radar echo model of the LFM radar and the target detection model to calculate the prediction error of radar echoes. Furthermore, based on extensive analysis and simulation, we identify the scale factor, polarization model and target state as three key factors that affect the detection performance of our proposed model. Using the real data from IPIX radar and C-band radar for simulations, we can see that the model has a significant performance improvement for weak target detection compared to the traditional 3D-IFS algorithm. The detection probability of the model reaches 70% at the *SCR* near −10 dB, and signal processing time of the model is approximately 0.3 s at the *SCR* near −6 dB, thus it meets the requirement for low-observable (*SCR* > −8 dB) and radial velocity about 600 m/s high speed weak target detection in sea clutter.

1. Introduction

With stealth performance enhancement of ultra-high speed for sea-skimming low-altitude or very low-altitude target, the background of sea clutter becomes increasingly complex [1], the *SCR* (Signal to Clutter Radio) of the radar echoes is more and more low (*SCR* < −10 dB). Target detection method based on the statistics theory often requires a high *SCR* (*SCR* > 5 dB) [2], sea clutter spikes will cause seriously the probability of false alarm for weak targets [3]. A large number of real sea clutter data show that it meets a chaotic characteristics, so it is possible to apply fractal theory to study target detection in sea clutter [4,5]. In 1993, Lo et al. have utilized fractal dimension to detect ship [6], but the fractal dimension can only detect the *SCR* ≥ 8 dB radar echoes. This method is equivalent in detection performance to using statistics theory. Target detection method based on fractal variable step size *LMS* algorithm is proposed according to statistics theory and fractal theories in Ref. [7], which is only effective for detecting *SCR* ≥ −2 dB radar echoes. In addition, the detection method is sensitive to initial value of system and the initial value affects the convergence rate of the prediction error, it is not beneficial to detect high-speed target. Except for the fractal dimension, fractal self-affine is another characteristic for fractal theory, the 2D-IFS and the 3D-IFS algorithm are applied to analyze self-affine characteristics of a discrete sequence [8]. Under the affine transformation, a part of a sequence is similar to its other or whole parts. The whole sequence can be transformed into a parts by defining whole sequence and selecting corresponding affine transformation, then update it until achieving a satisfactory result. Due to self-affine requiring less prior information of radar echoes, now it becomes one of the most dynamic detection methods. Heechan [9] has reconstructed the image data by fractal self-affine characteristics, but this method still requires that the image data has good fractal self-affine characteristics so that it can reconstruct this image; Mazel uses 2D-IFS and 3D-IFS algorithm to respectively model the self-affine fractal model [10]; The three-dimensional fractal interpolation functions are derived from three-dimensional iteration function system in Ref. [11,12], but the above three papers mainly focus on the IFS algorithm implementation process, the influence of the scale parameters on the prediction error is not discussed. The prediction error of chaotic discrete sequence is calculated by self-affine fractal characteristics [13]. IFS algorithm is applied to weak target detection in Ref. [14]. Unfortunately, the scale parameters by setting empirically are not also favorable to detect low SCR radar echoes. The affine antenna is designed by using the IFS algorithm and the influence of the scale parameters on the return loss is analyzed [15]. In order to

* Corresponding author. Tel.: +86 18301499427.
E-mail address: xppwcg2007@163.com (C. Wang).

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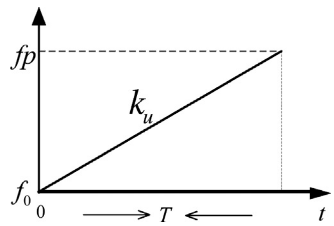

Fig. 1. Linear frequency modulation signal.

let the prediction error more obvious between the target echo and sea clutter by setting the scale parameters [16] and improve further detection performance for low SCR radar echoes, a weak target detection model based on the adaptive 3D-IFS algorithm is developed in this paper, it is considered that it is a novel method of weak target detection.

2. The formulation of problem

2.1. Radar echoes model

For the linear frequency modulation (LFM) signal, stepped frequency modulation signal (SFM) or linear stepped frequency modulation (LSFM) signal, the Doppler shift frequency induced by moving target for transmitted LFM signal is the most sensitive on radar imaging or ambiguity function than the other two signals, so this paper uses LFM signal in Ref. [17] as the radar transmitted signal, shown in Fig. 1.

Assume the radar transmitted LFM signal is $s_t(t)$, there is

$$s_t(t) = E_T \mathrm{rect}\left[\frac{t}{T}\right] \exp\left[2\pi j\left(f_0 t + \frac{k_u t}{2}\right)\right],$$
$$\mathrm{rect}(t/T) = \begin{cases} 1 & 0 < t < T \\ 0 & \text{else} \end{cases} \tag{1}$$

where the amplitude of radar transmitted signal is E_T, the carrier frequency is f_0, signal bandwidth B is $k_u T$, where k_u is modulation slope of the LFM signal and T is pulse width. When the $k_u = 0$, the wideband radar becomes narrowband general pulse radar.

Based on the signal $s_t(t)$, the radar echoes model can be presented

$$s_r(t) = \left\{E_R rect\left[\frac{t-\tau_d(t)}{T}\right] \exp[2\pi j(f_0 + f_d)(t - \tau_d(t))]\right\} * \{\gamma(t - \tau_d(t))\} \tag{2}$$

where the notation * denotes a convolution time domain, E_R is the amplitude of radar echoes, time delay $\tau_d(t) = 2(r_0 + v_1 t + a_1 t^2/2)/c$, c is speed of light, r_0 is an initial distance from target to radar, and v_1, a_1 are relative radial velocity and relative acceleration. f_d is Doppler frequency shift and $f_d = -(2/\lambda)v_1$ when $a_1 = 0$. The scattering coefficient of two-dimensional fractal sea surface model $\gamma(t)$ is from Ref. [18].

2.2. The 3D-IFS algorithm

We use the frequency f_s to sample the radar echoes $s_r(t)$ to obtain a discrete echoes sequence, and split the discrete sequence into $\boldsymbol{x}[n]$ and $\boldsymbol{y}[n]$, $\boldsymbol{x}[n]$ is first half of discrete sequence $s_r(t)$, $\boldsymbol{y}[n]$ is back half of discrete sequence $s_r(t)$,that is $s_r(n) = s_r(t/f_s) = [x[n], y[n]]$. n is the sample index of the discrete sequence and $\boldsymbol{x}[n]$, $\boldsymbol{y}[n]$ are the amplitude value of the data point at sample index n, thus the 3D-IFS algorithm is composed of three sets of parameters n, $\boldsymbol{x}[n]$ and $\boldsymbol{y}[n]$. Considering point (x, y) on the $x \times y$ plane by composing of $\boldsymbol{x}[n]$, $\boldsymbol{y}[n]$, a linear affine mapping is defined [11]

$$\boldsymbol{w}_i\begin{pmatrix} n \\ \boldsymbol{x}[n] \\ \boldsymbol{y}[n] \end{pmatrix} = \begin{pmatrix} a_i & 0 & 0 \\ c_i & d_i & h_i \\ k_i & l_i & m_i \end{pmatrix}\begin{pmatrix} n \\ \boldsymbol{x}[n] \\ \boldsymbol{y}[n] \end{pmatrix} + \begin{pmatrix} e_i \\ f_i \\ g_i \end{pmatrix}, \quad i = 1, 2, \ldots, M, \tag{3}$$

where $\boldsymbol{w_i}$ is mapping transformation. $a_i, c_i, d_i, h_i, k_i, l_i, m_i, e_i, f_i, g_i$ are mapping parameters, $\begin{bmatrix} d_i & h_i \\ l_i & m_i \end{bmatrix}$ is called contraction matrix. This contraction matrix must have all eigenvalues of modulus less than unity. We associate with Eq. (3) and obtain

$$\boldsymbol{w}_i\begin{pmatrix} p' \\ \boldsymbol{x}[p'] \\ \boldsymbol{y}[p'] \end{pmatrix} = \begin{pmatrix} p \\ \boldsymbol{x}[p] \\ \boldsymbol{y}[p] \end{pmatrix}, \ w_i\begin{pmatrix} q' \\ \boldsymbol{x}[q'] \\ \boldsymbol{y}[q'] \end{pmatrix} = \begin{pmatrix} q \\ \boldsymbol{x}[q] \\ \boldsymbol{y}[q] \end{pmatrix}, \quad i = 1, 2, \ldots, M, \tag{4a}$$

where $(p,\ \boldsymbol{x}[p],\ \boldsymbol{y}[p])$ and $(q,\ \boldsymbol{x}[q],\ \boldsymbol{y}[q])$ are two continuous interpolation points for $p < q$, $u = q - p$;

$(p',\ \boldsymbol{x}[p'],\ \boldsymbol{y}[p'])$ and $(q',\ \boldsymbol{x}[q'],\ \boldsymbol{y}[q'])$ are the address points associated with that pair of interpolation points with $p' < q'$, $v = q' - p'$, $u < v$. All the address points must lie within the interval of support of the points along M.

Substitute Eq. (4) into Eq. (3), we derive

$$\begin{pmatrix} p \\ \boldsymbol{x}[p] \\ \boldsymbol{y}[p] \end{pmatrix} = \begin{pmatrix} a_i & 0 & 0 \\ c_i & d_i & h_i \\ k_i & l_i & m_i \end{pmatrix}\begin{pmatrix} p' \\ \boldsymbol{x}[p'] \\ \boldsymbol{y}[p'] \end{pmatrix} + \begin{pmatrix} e_i \\ f_i \\ g_i \end{pmatrix} \tag{4b}$$

$$\begin{pmatrix} q \\ \boldsymbol{x}[q] \\ \boldsymbol{y}[q] \end{pmatrix} = \begin{pmatrix} a_i & 0 & 0 \\ c_i & d_i & h_i \\ k_i & l_i & m_i \end{pmatrix}\begin{pmatrix} q' \\ \boldsymbol{x}[q'] \\ \boldsymbol{y}[q'] \end{pmatrix} + \begin{pmatrix} e_i \\ f_i \\ g_i \end{pmatrix} \tag{4c}$$

From Eq. (4d) and (4c), we have

$$p = a_i p' + e_i, \quad q = a_i q' + e_i \tag{5a}$$
$$\boldsymbol{x}[p] = c_i p' + d_i \boldsymbol{x}[p'] + h_i \boldsymbol{y}[p'] + f_i \tag{5b}$$
$$\boldsymbol{y}[p] = k_i p' + l_i \boldsymbol{x}[p'] + h_i \boldsymbol{y}[p'] + g_i \tag{5c}$$
$$\boldsymbol{x}[q] = c_i q' + d_i \boldsymbol{x}[q'] + h_i \boldsymbol{y}[q'] + f_i \tag{5d}$$
$$\boldsymbol{y}[q] = k_i q' + l_i \boldsymbol{x}[q'] + m_i \boldsymbol{y}[q'] + g_i \tag{5e}$$

Thus we have

$$q - p = a_i(q' - p') \tag{5f}$$
$$\boldsymbol{x}[q] - \boldsymbol{x}[p] = c_i(q' - p') + d_i(\boldsymbol{x}[q'] - \boldsymbol{x}[p']) + h_i(\boldsymbol{y}[q'] - \boldsymbol{y}[p']) \tag{5g}$$
$$\boldsymbol{y}[q] - \boldsymbol{y}[p] = k_i(q' - p') + l_i(\boldsymbol{x}[q'] - \boldsymbol{x}[p']) + m_i(\boldsymbol{y}[q'] - \boldsymbol{y}[p']) \tag{5h}$$

Combine with Eq. (5), there are

$$a_i = (q - p)/(q' - p') = u/v \tag{6a}$$
$$e_i = (pq' - qp')/(q' - p') \tag{6b}$$
$$c_i = (\boldsymbol{x}[q] - \boldsymbol{x}[p])/(q' - p') - d_i(\boldsymbol{x}[q'] - \boldsymbol{x}[p'])/(q' - p') - h_i(\boldsymbol{y}[q'] - \boldsymbol{y}[p'])/(q' - p') \tag{6c}$$
$$k_i = (\boldsymbol{y}[q] - \boldsymbol{x}[p])/(q' - p') - l_i(\boldsymbol{x}[q'] - \boldsymbol{x}[p'])/(q' - p') - m_i(\boldsymbol{y}[q'] - \boldsymbol{y}[p'])/(q' - p') \tag{6d}$$