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# Performance comparison of detection methods for weak target based on two-dimensional fractal sea surface

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ABSTRACT

A detection method of the weak radar target is studied by applying fuzzy theory and multifractal correlation theory based on a two-dimensional fractal sea surface model. Firstly, a two-dimensional fractal sea surface model and its backscattering coefficient are introduced, the backscattering coefficient is a universal model affected by seawater permittivity, electromagnetic wave incidence angle, incident frequency, wind speed and wind direction factors. A novel two-dimensional wideband radar echo model, which is considered as a time-domain convolution of the stepped frequency signal radiated by airborne radar and the backscattering coefficient, is derived. Secondly, multifractal correlation theory is elaborated and a computation method of a membership degree of multifractal correlation spectrum is proposed, fuzzy theory and the AdaBoost algorithm are applied to the target detection. Finally, several target detection methods are compared with CA-CFAR and works of the predecessors. The results of the comparative study show its rationality of the two-dimensional wideband radar echo model and the superiority of wideband radars in detection performance, it is also seen that the multifractal correlation spectrum outperforms the multifractal spectrum in the probability of detection.



## 1. Introduction

Traditional radar echo signal models such as K-distribution, logarithmic distribution, Gaussian distribution, Rayleigh distribution etc stochastic models are mostly based on experiential data fitting or simple physical model, while fractal model can reveal the dynamic nature of the sea wave motion [1], but fractal theory provides a new way to study week target detection from the sea surface. Target detection based on fractal theory is dependent on the fact that the background of the target differs from the sea clutter's. T. Lo and Haykin [2] calculated fractal dimension [3] of the sea clutter is approximately 1.75, which is firstly applied to target detection of the sea clutter. Subsequently, Mandelbrot [4] and others have done a lot of work on the fractal dimension, founding single fractal dimension cannot adequately describe the structure and characteristic of a fractal object, and then Grassberger [5] and others systematically presented the multifractal theory, analyzing a general character of a fractal system from its parts. With the development of research, in 1990, Menuveau and Chhabra [6] generalized 'single point' statistical characteristics of the multifractal, and studied the spatial correlate characteristic of two points with the different singularity intensity, namely the 'two-point' statistics characteristic of multifractal, it is the development of multifractal theory, thus 'two-point' multifractal correlation can supply more self-similarity information than 'single point' multifractal. J. O'Neil and C. Menveau [7] studied the spatial correlation of multifractal in turbulence and analyzed the autocorrelation function. Moreover, Zhou Wen-xing [8] derived the multifractal nature and multifractal correlation of random binomial measures, the phase transition of the scaling behavior of the 'two-point' correction function is also examined. Based on the theory above, this paper firstly introduces the two-dimensional fractal sea surface model and its backscattering coefficient [9–12] and derives the two-dimensional wideband radar echo model. It explains multifractal correlation theory and compares several detection algorithms.

Because of the work environment of radars the presence of noise, multipath [13] and other factors, it is very difficult for classical statistical model to represent it exactly. However we can consider its working environment as a fuzzy environment [14]. In such uncertain situation, the sea clutter and target echo signal are similar and the boundary of two kinds of echoes overlaps seriously. Especially in the case of strong sea clutter background, using fixed threshold to distinguish will bring high probability of false alarm, which will lead to a misjudgment, so the AdaBoost

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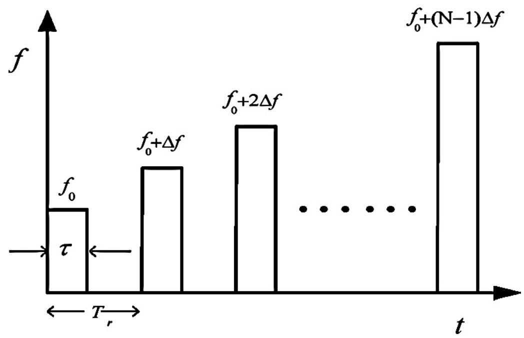


**Fig. 1.** Stepped frequency signal.

algorithm [15,16] is applied to target detection, and there is a good detection performance for the weak target. The rest of this paper is organized as follows. Detection methods of weak target from two-dimensional fractal sea surface are presented in Section 2. The experimental results and discussions are given in Section 3. Finally, the paper is concluded in Section 4.

## 2. Problem statement and radar echo model

### 2.1. Radar transmitting signal model

The stepped frequency signal [17,18] contains a string of narrowband coherent pulses. The carrier frequency of each pulse is linear stepped. Let $T$ be the pulse width, $E_T$ be the amplitude, $T_r$ be the repeated period, $f_0$ be the initial frequency, $\Delta f$ be the stepped frequency interval, $N$ be the number of frequency steps, as shown in Fig. 1.

The transmitted stepped frequency signal is

$$s_t(t) = E_T \sum_{i=0}^{N-1} \mathrm{rect}\left[\frac{t - iT_r}{T}\right] \exp[-j2\pi(f_0 + i\Delta f)t], \quad \mathrm{rect}(t/T) = \begin{cases} 1 & 0 < t < T \\ 0 & \text{esle} \end{cases} \tag{1}$$

### 2.2. Radar scattering coefficient model

In recent years, the works of electromagnetic scattering model for two-dimensional fractal sea surface focus on the electromagnetic scattering model closer to the actual. Here the two-dimensional band-limited WM surface is considered as the rough fractal surface, the functional relationship between electromagnetic scattering characteristics of the rough surface and fractal independent variables is presented by Kirchhoff approximation [19], the improved two-dimensional sea surface model [10–12] is shown as follows

$$f(x,y,t) = \sigma\eta \sum_{m=0}^{N_1-1} a^{-(d-\xi)m} \sin\left\{\frac{2\pi}{\Lambda_m}[(x+V_x t)\cos\beta_{1m} + (y+V_y t)\sin\beta_{1m}] - \Omega_m t + \alpha_{1m}\right\}$$
$$\sigma\eta \sum_{n=0}^{N_1-1} b^{(d-3)n} \sin\left\{\frac{2\pi}{\Lambda_n}[(x+V_x t)\cos\beta_{2n} + (y+V_y t)\sin\beta_{2n}] - \Omega_n t + \alpha_{2n}\right\} \tag{2}$$

where $\sigma$ is the standard deviation of the amplitude and $\eta$ is a normalization constant, $d$ is true fractal dimension, $2 < d < 3$, $a$ is the scale factor of space wave number smaller than the fundamental, $b$ is the scale factor of space wave number greater than the fundamental, $b > 1$, $a = 1/b$. $V_x$, $V_y$ are the velocity of direction $X$ and $Y$ on the observer platform, respectively, $\beta_{1m}$, $\beta_{2n}$ are the direction angle of the wave movement, $\Omega_m$, $\Omega_n$ are the angular frequency of the $m$-th and $n$-th spectral component, respectively, $\Lambda_m$, $\Lambda_n$ are sea wavelength, $\Lambda_m = \Lambda_0/a^m$, $\Lambda_n = \Lambda_0/b^n$, are sea wave number $K_m = 2\pi/\Lambda_m = K_0 a^m$, $K_n = 2\pi/\Lambda_n = K_0 b^n$, $\Lambda_0$ is the fundamental spatial wavelength, $K_0$ is the sea fundamental wavelength, N1 is the number of sinusoidal components, $\alpha_{1m}, \alpha_{2n}$ are initial arbitrary phases modeled as independent random variables uniformly distributed in the interval $[-\pi, \pi]$ $\alpha_{2n}$, $\xi$ is the positive power rate factor, $\varsigma$ is the correction factor, that is

$$\eta = \left\{\frac{2[1-\mathrm{a}^{-2(\mathrm{d}-\xi)}][1-\mathrm{b}^{2(\mathrm{d}-3)}]}{[1-\mathrm{a}^{-2(\mathrm{d}-\xi)\mathrm{N}_1}][1-\mathrm{b}^{2(\mathrm{d}-3)}] + [1-\mathrm{a}^{-2(\mathrm{d}-\xi)}][1-\mathrm{b}^{2(d-3)\mathrm{N}_1}]}\right\}^{\frac{1}{2}},$$

$$\frac{\sigma = 0.0212\varsigma U_{19.5}^2}{4}, K_0 = 0.877^2 g/U_{19.5}^2,$$

when $\xi = 3.9$, $b = 1.015$, $d = 2.62$, $\varsigma = 1.65$, when $N_1 = 400$, the improved two-dimensional fractal sea spectrum are good agreement with the global *PM* spectrum. The scatteringcoefficient of the two-dimensional fractal sea surface is

$$\gamma(t) = \pm\frac{F(\theta_1,\theta_2,\theta_3)}{A_m} \times \int_Y^X \int_Y^X e^{jk\phi(x,y,t)} \mathrm{d}x\mathrm{d}y + \left(\frac{Aa_x + Bb_x}{2C}\right) \times \sin c(kAX) \sin c(kBY) \tag{3}$$

where

$F(\theta_1, \theta_2, \theta_3) = 1/2\ (Aa_x/C + Bb_x/C + c_x)$, $A = \sin\theta_1 - \sin\theta_2\cos\theta_3$, $B = -\sin\theta_2\sin\theta_3$, $C = -(\cos\theta_1 + \cos\theta_2)$

$a_x = \sin\theta_1(1 - R_0) + \sin\theta_2\cos\theta_3(1 + R_0)$, $b_x = \sin\theta_2\sin\theta_3(1 + R_0)$, $c_x = \cos\theta_2(1 + R_0) - \cos\theta_1(1 - R_0)$

$\phi(x, y, t) = Ax + By + Cf(x, y, t)$, $\mathrm{sinc}(x) = \sin(x)/x$, $k = 2\pi/\lambda$, $\lambda$ is the wave length.

$A_m = 4XY$, $A_m$ is the area of the fractal sea surface that is illuminated by electromagnetic wave.

"±" shows the polarization mode of HH or VV.

$$R_0 = \frac{\varepsilon_i \cos\theta_1 - \sqrt{\varepsilon - \sin^2\theta_1}}{\varepsilon_i \cos\theta_1 + \sqrt{\varepsilon - \sin^2\theta}} \tag{4}$$

where $R_0$ is the Fresnel reflection coefficient, $\varepsilon_i = \{\varepsilon_{\mathrm{ref}}, \varepsilon\}$, $\varepsilon$ is the permittivity of the sea water, and $\varepsilon_{\mathrm{ref}}$ is the relative permittivity and $\varepsilon_{\mathrm{ref}} = 1$. $\theta_1$ is incidence angle, $\theta_2$ is scattering angle, $\theta_3$ is azimuth angle.

Substituting Eq. (1) into Eq. (3), statistical sum of electromagnetic backscattering coefficient of all resolution cells in $N_1$ waves