Moving Target Detection at Sea Based on Fractal Characters in FRFT Domain

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Abstract: Radar systems that require fine target detection capabilities and yet cannot tolerate the atmospheric attenuation of higher frequency bands may also be X-band. Clutter is a term used to describe any object that may generate unwanted radar returns that may interfere with normal radar operations. Parasitic returns that enter the radar through the antenna’s main lobe are called main lobe clutter; otherwise they are called side lobe clutter. In order to effectively detect moving target in sea clutter, three methods based on fractal character differences are proposed making use of the different fluctuation of amplitude between sea clutter and moving target in fractional Fourier transform (FRFT) domain. At first, fractal model in FRFT domain is established and simulations of fractal curves of real sea clutter in FRFT domain are conducted, which indicate the fractal character i.e. self-similarity within its corresponding scale invariant interval. Then, fractal dimension, fractal fitting error and fractal dimension variance in FRFT domain are analyzed, whose differences can be used as test statistic for moving target detection respectively. In the end, X-band real sea clutter is used for verification and results present that the proposed methods outperform the traditional coherent accumulation method and fractal dimension difference method in time domain. Weak moving target can be detected, which indicates the effectiveness of the methods.

INTRODUCTION

Clutter echoes are random and have thermal noise-like characteristics because the individual clutter components (scatterers) have random phases and amplitudes. In many cases, the clutter signal level is much higher than the receiver noise level. Thus, the radar’s ability to detect targets embedded in high clutter background depends on the Signal-to-Clutter Ratio (SCR) rather than the SNR.

White noise normally introduces the same amount of noise power across all radar range bins, while clutter power may vary within a single range bin. In recent years, fractal has been widely employed for description and modeling of the roughness of sea surface [2]. Fractal characters such as Hurst exponent and fractal dimension now can be calculated easily with high accuracy. Various fractal statistics have been shown to be sensitive to the presence of targets within sea clutter [3]. Therefore, the fractal method provides an alternative framework to describe the rough property of sea clutter and an effective way to detect low observable targets [4]. The radar echo of moving target can be modeled as linear frequency modulation (LFM) signal in some circumstances and also target with complex moving condition can be seen as LFM signal within a short time [5]. Hence, researches on detection and estimation of LFM signal are of great importance to moving target detection at present. The fractional Fourier transform (FRFT) is a newly developed time-frequency analysis tool, which is more suitable for non-stationary signal processing, especially LFM signal [6], [7]. FRFT of LFM signal has a good energy concentration property and it is applicable to the detection and parameter estimation for moving target in low signal-to-clutter ratio (SCR) environment without extra prior knowledge of sea clutter [8]. Under some low SCR conditions, the fractal character differences between sea clutter and target in time domain have little improvement for detection. The radar echo of moving target after FRFT may be highly concentrated as a peak in the FRFT domain with higher SCR. On the contrary, the energy of sea clutter in FRFT domain is mainly distributed around frequency domain with a fluctuant and rough surface. The fractal differences between sea clutter and moving target at some specific scale in FRFT domain, however, is rarely studied. As a result, the fractal character of moving target at sea in FRFT
domain is analyzed, which is extremely useful to detect low observable moving target within strong sea clutter.

Related Work

In CW radars, clutter is avoided or suppressed by ignoring the receiver output around DC, since most of the clutter power is concentrated about the zero frequency band. Pulsed radar systems may utilize special filters that can distinguish between slowly moving or stationary targets and fast moving ones. This class of filters is known as the Moving Target Indicator (MTI). In simple words, the purpose of an MTI filter is to suppress target-like returns produced by clutter, and allow returns from moving targets to pass through with little or no degradation. In order to effectively suppress clutter returns, an MTI filter needs to have a deep stop-band at DC and at integer multiples of the PRF. Fig.1b shows a typical sketch of an MTI filter response, while Fig.1c shows its output when the PSD shown in Fig. 1a is the input.

Surface clutter includes both land and sea clutter, and is often called area clutter. Area clutter manifests itself in airborne radars in the look-down mode. It is also a major concern for ground-based radars when searching for targets at low grazing angles. The low grazing angle region extends from zero to about the critical angle. The critical angle is defined by Rayleigh as the angle below which a surface is considered to be smooth, and above which a surface is considered to be rough.

\[ \frac{4\pi h_{rms}}{\lambda} \sin \psi < \frac{\pi}{2} \]

Volume Clutter

Volume clutter has large extents and includes rain (weather), chaff, birds, and insects. The volume clutter coefficient is normally expressed in squared meters (RCS per resolution volume). Birds, insects, and other flying particles are often referred to as angel clutter or biological clutter. The average RCS for individual birds or insects as a function of the weight of the bird or insect is reported in the literature as

\[ (\sigma_b)_{dB_{sm}} \approx -46 + 5.8 \log W_b \]

Clutter Statistical Models

Since clutter within a resolution cell (or volume) is composed of a large number of scatterers with random phases and amplitudes, it is statistically described by a probability distribution function. The type of distribution depends on the nature of clutter itself (sea, land, volume), the radar operating frequency, and the grazing angle.

If sea or land clutter is composed of many small scatterers when the probability of receiving an echo from one scatterer is statistically independent of the echo received from another scatterer, then the clutter may be modeled using a Rayleigh distribution,

\[ f(x) = \frac{2x}{x_0} \exp \left( -\frac{x^2}{x_0} \right) ; \ x \geq 0 \]

MOVING TARGET DETECTION BASED ON FRACTAL CHARACTER DIFFERENCES IN FRFT DOMAIN

The fractal dimension obtained from \( \log 2F(m) \) versus \( \log 2m \) in FRFT domain is a significant statistic for fractal features. Analyzing the fractal curves of sea clutter and
target respectively, we find that the slope with sea clutter data in FRFT domain is smaller than that of moving target. The fluctuation degree of radar echo from moving target is lower than that of sea clutter, which leads to a higher Hurst exponent. Hence, fractal character differences of sea clutter and target in the best transform domain can be used as test statistic and then we have proposed three novel methods to detect moving target:

the fractal dimension, the fractal fitting error and the fractal dimension variance method within the scale-invariant interval. However, the best transform order \( p \) is not a known priori, with which the fractional Fourier spectrum of the LFM signal focuses well and the fractal difference will be the biggest. We take \( p \) as a variable to calculate FRFT of the signal and form a two-dimensional energy distribution on the \((p,u)\) plane. Then, a peak search with a proper threshold on this plane can achieve the goal of the determination of best transform order \( p_{opt}=1.056 \) [6] with a small acceleration.

A. Fractal Dimension Based Detection Method in FRFT Domain (Method 1)

Fractal dimension is a very efficient statistic to describe the texture property of rough surface. There is a general relation between Hurst exponent \( H \) and fractal dimension \( D \):

\[
D = 2 - H
\]

Rougher surface corresponds to larger fractal dimension, which means that the fractal dimension of sea clutter in FRFT domain is higher. The fluctuation functions of sea clutter \( \log_2 F_c(m) \) and moving target \( \log_2 F_s(m) \) in the scale-invariant interval \((m=2^5 \sim 2^{10})\) can be expressed as

\[
\begin{align*}
\log_2 F_c(m) &= (2 - D_c) \log_2 (m) + \text{const} \\
\log_2 F_s(m) &= (2 - D_s) \log_2 (m) + \text{const}
\end{align*}
\]

where the fractal dimension \( D_c \) and \( D_s \) can be obtained from the slopes of the fluctuation functions for sea clutter and moving target in the scale-invariant interval, respectively. We use fractal dimension of adjacent range bins in FRFT domain to distinguish sea clutter and moving target. If it is lower than the threshold, target can be declared. The statistic is as follows

\[
T_1 = |D_s - D_c| \geq \frac{H_0}{H_1} \eta_1
\]

Where \( \eta_1 \) is the threshold. The pre-determined threshold could, for example, be a detection threshold based on constant false alarm rate (CFAR) method, in order to provide a certain probability of detection for a given false alarm rate. The detection threshold simulation can be carried out using Matlab software in presence of clutter and moving target.

Fractal Fitting Error Based Detection Method in FRFT Domain (Method 2)

In practical applications, the fractal dimension of sea clutter in FRFT domain is strongly affected by the climate and the presence of noise. Given the fixed incidence angle and wavelength of radar, the sea backscatter in FRFT domain may exhibit different fluctuation degree, which leads to different fractal dimension. The fractal dimension of sea clutter and moving target may overlap with each other with high false alarm rate. Moreover, in heavy sea clutter, it is difficult to tell them apart only with the difference of fractal dimension. As a result, it is quite necessary to analyze some other fractal characters.

The energy of moving target can be concentrated as a peak in FRFT domain with a smoother surface without the character of self-similarity. Hence, the fitting error of fractal curves of sea clutter is smaller than that of moving target, which can be taken as test statistic.

The matching degree of fractal model in FRFT domain with real sea clutter can be expressed as the fitting error of straight line to the \( \log_2 m \sim \log_2 F \) curves.

\[
E = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (ax_i + b - y_i)^2}
\]

Obviously, a fractal detection method combining difference of fractal fitting error in FRFT domain between sea clutter and moving target is expected to furthermore increase the accuracy of detection. Target can be declared if it exceeds the given threshold. The statistic is as follows

\[
T_2 = \left| \frac{E_s - E_c}{H_0} \right| \geq \eta_2
\]

C. Fractal Dimension Variance Based Detection Method in FRFT Domain (Method 3)

Ideal fractal object satisfies the self-similarity at all scales, which means that the fractal dimension is independent of scales. Given a series of sea clutter in FRFT domain, we can get the fluctuation function \( \log_2 F_s(m) \) at different
scales $m$. It can be found that the fractal feature of sea clutter in FRFT domain coincides well with that of theoretical fractal model in the scale-invariant interval $(m=2^5 \sim 2^{10})$. However, the fractal curves do not rise with scale in a linear way, which indicates that the fractal feature of moving target varies with the time scale. The peak formed by signals of moving target may cover the scattered amplitude of sea clutter in FRFT domain. When the width of peak and scale is close enough, the change of amplitude will be the biggest, which demonstrates the break of fractal dimension. Hence, we can calculate the fractal dimension at different scales in FRFT domain and employ the changes of fractal dimensions with scales for target detection. The $x, y$ coordinate of fractal curves in FRFT domain can be expressed as follows

$$x_i = \log_2(m_i), \quad y_i = \log_2 F(m_i), \quad i = 1, \ldots, 11$$

$$D_{\Delta i} = \frac{\log_2 F(m_i) - \log_2 F(m_{i-1})}{\log_2 (m_i) - \log_2 (m_{i-1})} \approx \frac{y_i - y_{i-1}}{x_i - x_{i-1}}$$

the fractal dimension differences at different scales in FRFT domain and we find that there is little difference between bins without target. This is because sea clutter can be regarded as the sum of single frequency signals and the energy of sea clutter can’t be focused in FRFT domain.

**Simulation Results**

In our study we have discussed different types of power signal problems such as voltage sag, voltage swell, momentary interruption, lower length transient, up chirp and combination of gaussian signals and their corresponding magnitude vs. time are analyzed with MATLAB software. The chosen sampling rate is 3.84 kHz.

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**Fig. 1 (a) Momentary Interruption (b) Modified ST time frequency contour (c) Modified ST magnitude response**
Fig. 3 (a) Voltage Transient (b) Modified ST time-frequency contour (c) Modified ST magnitude response

Fig. 4 (a) Simultaneous Disturbances (b) Modified ST time-frequency contour (c) Modified ST magnitude response

Fig. 5 (a) Simulated Gaussian signal (b) Modified ST time frequency contour (c) Modified ST magnitude response

Fig. 6 Scalogram for the simulated Gaussian signals.
Fig. 7 (a) Simulated Gaussian signal with 25dB noise
(b) Modified ST time-frequency contour
(c) Modified ST magnitude response

CONCLUSION

In this paper, moving target detection in sea clutter is studied and three novel methods are proposed based on the fractal character differences in FRFT domain. The results of simulation with real sea clutter indicate that the methods are effective and possess the following merits: 1) the energy of signals is accumulated in the best transform domain with higher SCR; 2) better detection performance in heavy sea clutter environment; 3) accurate parameters estimation. It needs some clarification that the detection performance of the proposed methods will be better if there exist moving targets with fast speed at sea than the performance with the primary target in sea data.

REFERENCES

[3] Jian Guan, Ningbo Liu, Jian Zhang, and Jie Song, “Multifractal correlation characteristic for radar detecting...


