Target Detection within Sea Clutter Using the Saturation Phenomenon of Fluctuation Analysis

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***Abstract*—In this paper, a novel feature based on the saturation phenomenon of fluctuation analysis is proposed for target detection in sea clutter. Because the saturation phenomenon causes the difficulties of the discrimination between sea clutter and targets by the Hurst exponent, the fluctuation curve slope, as the characteristic parameter, is suggested to describe the properties of the target and sea clutter. The tests on the real data show that the target could be effectively distinguished from the sea clutter background with the proposed approach.**

Keywords-fluctuation analysis (FA); fluctuation curve slope; saturation phenomenon; sea clutter; target detection

I. INTRODUCTION

Target detection within sea clutter is an essential problem in marine applications of radar. It is known that the fractal theory provides an alternative way to describe sea clutter properties [1] and may effectively improve the algorithm performance for target detection [2]. For years, much effort has been committed to the analysis of sea clutter by fractal geometry [3]–[6]. Self-affinity is a kind of typical fractal characteristic. Among others, the fluctuation analysis (FA) is one of the most common methods to determine the self-affinity nature of the signal in the time series analysis, as well as the stochastic process and chaos theory. With the FA, the Hurst exponent could be retrieved through studying the scaling behavior of the mean-square displacement. Hu Jing et al. indicated that the saturation phenomenon would occur while FA is applied in analysis of sea clutter, and there would be confusion between the Hurst exponents for target and sea clutters [7, 8]. In order to overcome the saturation phenomenon associated with FA, they adopted two methods: (1) treating the original time series as a "random walk" process, and (2) applying detrended fluctuation analysis method (DFA). In fact, even the saturation phenomenon occurs, certain useful information about sea clutters could be extracted still. In this paper, by analyzing the saturation phenomenon associated with FA, a novel parameter is suggested to describe the signal characteristic for the low-observable target detection in sea clutter.

II. FRACTAL PROPERTIES OF SEA CLUTTER

A. Self-affinity

Many things in the nature are not exactly self-similar, but are statistically self-affine. In time series analysis, for a time series $x(t)$, in view that the time axis and the axis of the measured values $x(t)$ are not equivalent, a rescaling of time t by a factor a may require rescaling of the series values $x(t)$ by a different factor a^H in order to obtain a statistically similar (i.e. self-similar) picture. The scaling relation

$$x(t) \rightarrow a^H x(at) \tag{1}$$

holds for an arbitrary factor a, describing the data as self-affine. The Hurst exponent H characterizes the type of self-affinity.

The scaling behavior of self-affine data can be characterized by their mean-square displacement. And the Fluctuation Analysis (FA) may retrieve the Hurst exponent H by studying the scaling behavior of the mean-square displacement $\langle x^2(t) \rangle \sim t^{2H}$ [9].

B. Fluctuation Analysis

The standard fluctuation analysis (FA) is firstly proposed by C. K. Peng et al in nucleotide sequences research. It is based on the random walk theory [10]. For a given time series $x = \{x(i), i = 1,2,\ldots,M\}$ the FA method works as follows.

First, consider the global profile, i.e., the cumulative sum of x

$$y(n)=\sum_{i=1}^{n}x(i)\quad n=1,2,...,M \tag{2}$$

where, y is usually called a "random walk" process of x, while x is an "increment" process.

Then, calculate the mean fluctuation $F(m)$

$$F(m)=\sqrt{\left\langle\left|\Delta y(m)\right|^{2}\right\rangle} \tag{3}$$

in which $\Delta y(m)=y(n+m)-y(n)$. The average $\langle\cdot\rangle$ is taken over all possible pairs of $\left(y(n+m),y(n)\right)$. The mean-square fluctuation $F^2(m)$ is related to the auto-correlation function, i.e. $F^{2}(m)=\sum_{i=1}^{m}\sum_{j=1}^{m}R_{xx}(j-i)$. If $F(m)$ satisfies the scaling law described by (4), the process under investigation is said to be a fractal process.

$$F(m)\sim m^{H} \tag{4}$$

where H is the Hurst exponent.

With the FA, one can analyze the fractal property of sea clutter. With the least-squares fitting, the Hurst exponent H could be determined as follows:

$$H=\frac{\log_2 F(m)}{\log_2 m} \tag{5}$$

The exponent $H<1/2$ indicates the time series x is anti-correlated; on the contrary, the exponent $H>1/2$ indicates x is correlated. While the exponent $H\simeq 1/2$, x is uncorrelated.

Fluctuation Analysis may cause the saturation phenomenon, that is to say the Hurst exponent obtained by FA would be close to 1.

C. Fluctuation Analysis of Sea Clutter

In this analysis, the McMaster IPIX Radar sea clutter datasets are used to study the fractal characteristics of sea clutter. More detailed information about the datasets can be got from the website of Simon Haykin [11].

The fluctuation function $F(m)$ with different scales m is obtained by FA for a time series of raw sea clutter. The typical curves of $F(m)$ in four different polarizations are plotted in Fig.1a. Obviously, the fluctuation curves $F(m)$ linearly increase with scales m. The corresponding Hurst exponent values are shown in Table I for all range units. The results indicate that the Hurst exponents of sea clutter are very close to 1, and this means there happen saturation phenomenon with FA analysis.

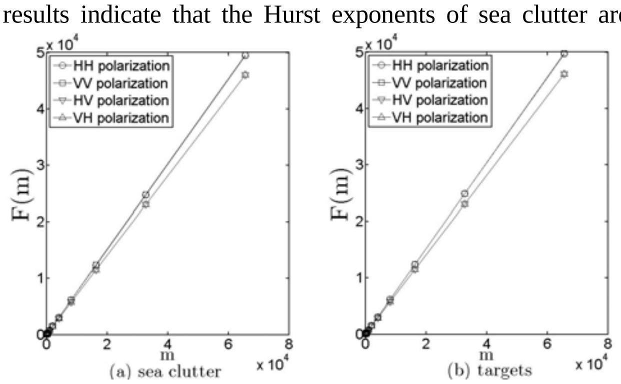


Figure 1. Mean fluctuation function curves in different polarizations.

TABLE I. HURST EXPONENTS BY FA

Range Units	#17 file	#31 file	#310 file
01	1.0000	0.9997	0.9995
02	1.0000	1.0000	0.9997
03	1.0000	0.9993	1.0001
04	1.0001	0.9969	1.0003
05	1.0000	0.9956	1.0003
06	1.0000	0.9979	1.0003
07	0.9999	0.9999	1.0000
08	1.0000	1.0001	1.0002
09	0.9995	0.9997	1.0001
10	0.9997	1.0001	1.0000
11	1.0000	0.9999	0.9995
12	1.0000	0.9998	0.9992
13	1.0000	0.9998	0.9993
14	1.0000	0.9998	0.9988

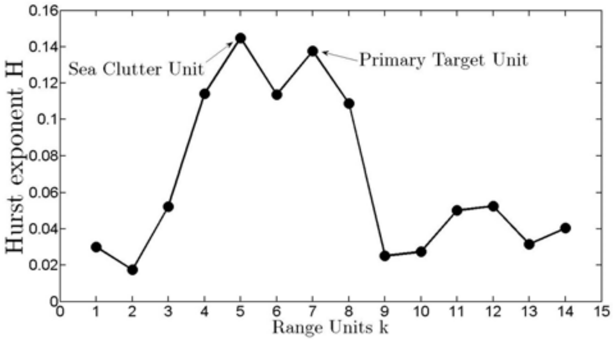
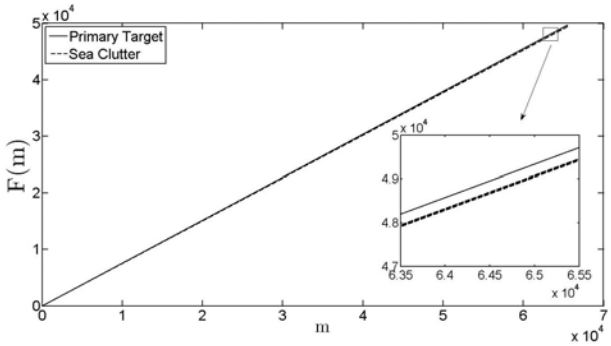


Figure 2. Hurst exponents by FA, with "random walk".

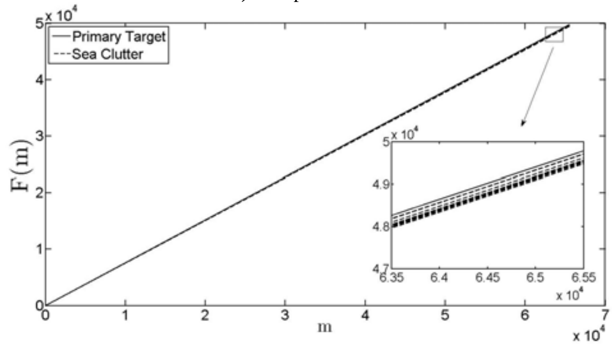
The fluctuation function curves $F(m)$ for the range units of primary targets are shown in Fig. 1b. Compared with sea clutter units, the range units of primary targets exhibit the similar scale behavior. Consequently, it would be very difficult to identify the targets from sea clutter by simply using Hurst exponent. Moreover, our tests show that, even with the "random walk" treatment, as suggested in [7, 8], the results could not be surely improved in certain situations. Fig. 2 gives one example for this kind of case. On the other hand, the saturation phenomenon may also provide some advantage for distinguishing the targets from sea clutters. Fig. 3 displays a comparison between the mean fluctuations for primary target unit and sea clutter units, with enlarged local details in the little rectangle. It could be found that the curve slopes for sea clutter units are mostly concentrated in a limited interval, and the curve slope of the target unit is lightly higher than that of sea clutter units.

III. LOW-OBSERVABLE TARGET DETECTION

A. Feature Extraction



a) HH polarization



b) VV polarization

Figure 3. Mean fluctuation function curves of target and sea clutter.

Based on the above analysis, the fluctuation curve slope may be selected as the feature parameter for low observable target detection in sea clutter.

Suppose XI^k and XQ^k are respectively the In-phase and Quadrature Components of the raw sea clutter data, where k denotes the number of range units, k=1,2,...,K. Firstly, the mean value is subtracted from the In-phase and Quadrature Component data respectively,

$$\begin{aligned}\overline{XI}^k(i) &= XI^k(i) - \frac{1}{KN}\sum_{k=1}^{K}\sum_{i=1}^{N} XI^k(i) \\ \overline{XQ}^k(i) &= XQ^k(i) - \frac{1}{KN}\sum_{k=1}^{K}\sum_{i=1}^{N} XQ^k(i)\end{aligned} \quad . \tag{6}$$

Then one can obtain,

$$\bar{X}^k = \sqrt{(\overline{XI}^k)^2 + (\overline{XQ}^k)^2} \ . \tag{7}$$

Next, with FA, calculate the fluctuation curve slope of $\bar{X}^k$. In order to increase the robustness, integrate the slope values of all range units into a feature space vector $A = [A(1), A(2), ..., A(K)]$. Define the normalized fluctuation curve slope as follows:

$$\bar{A}(k) = \frac{A(k)}{A_{mean}} \quad k = 1, 2, ..., K \tag{8}$$

where $A_{mean} = \frac{1}{K}\sum_{i=1}^{K} A(k)$.

The vector $\bar{A}$ would be finally taken as characteristic parameter for the target detection.

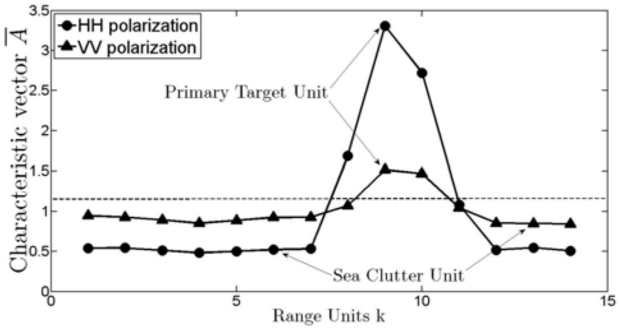


Figure 4. $\bar{A}$ values for every range unit.

B. Test Results

Fig. 4 presents the feature vector $\bar{A}$ of one dataset, with HH and VV polarizations representatively. It could be seen that there is a prominent peak at the primary target unit. Similar results could be obtained for all datasets, gathered under various circumstances. This indicates that $\bar{A}$ could be used as a typical characteristic parameter to distinguish the target from sea clutter. The frequency distributions of $\bar{A}$ values, for the primary target units and the sea clutter units both, are shown in Fig. 5, with HH and VV polarizations respectively. It could be seen that the $\bar{A}$ values for targets and sea clutters would be completely separated.

In order to further examine the performance of the proposed method, a comparison is taken with one of conventional methods, i.e. detrended fluctuation analysis method (DFA), which is an extension of FA and is often used to get over the saturation problem associated with FA.

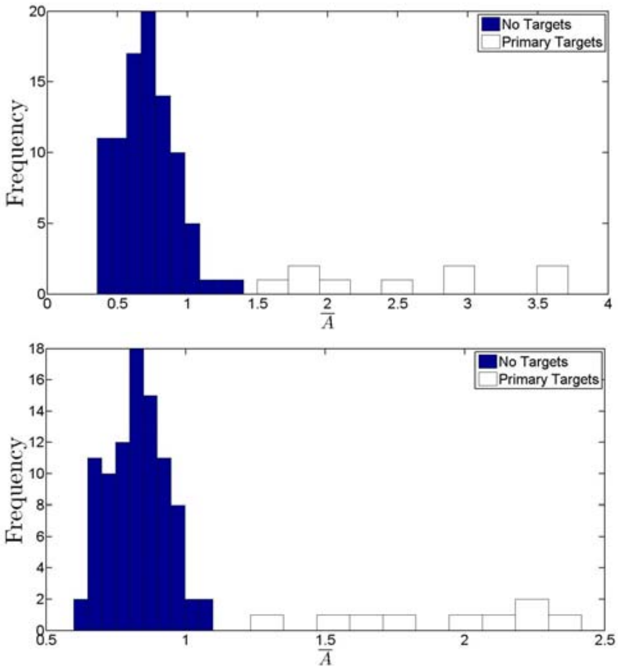


Figure 5. Frequencies of primary target units and sea clutter units for HH (top) and VV (bottom) polarizations.

TABLE II. COMPARISON OF AREA UNDER ROC CURVE (AUC)

	Proposed method	**DFA method**
HH polarization	0.9948	0.9914
VV polarization	0.9937	0.9037

In the analysis, each range unit is divided into some overlapping segments, and each segment includes 2^{15} samples. The AUC, that is area under the ROC curve, is generally used as a measurement to discriminate the arithmetic performance. The model with a higher AUC tends to give a more accurate prediction of the observation response. The AUC for the proposed method and the DFA, calculated from all of the 9 datasets, are listed in Table II. As be seen in Table II, the proposed method may have a better performance than DFA method in VV polarization, and a comparable performance with DFA in HH polarization.

IV. CONCLUSION

The saturation problem associated with FA method is analyzed. And based on this analysis, a novel parameter $\overline{A}$, i.e. normalized slope of the mean fluctuation, is suggested as the characteristic parameter to describe the fractal property of the targets and sea clutters. With the real data of IPIX Radar, the tests are carried out to verify the performance of the proposed method. And it is demonstrated that an efficacy detection of low-observed targets within sea clutters could be achieved with the proposed method.

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