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Small target detection within sea clutter based on fractal analysis

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Abstract

Sea clutter refers to the signals returned from the wavy and turbulent rough sea surface. The radar returns from small targets, like submarine periscope or small boats, will be obscured by the sea clutter which makes the straightforward detection of targets, with small radar cross section, a difficult task. The conventional target detection schemes in the presence of sea clutter are mainly based on Hurst exponent, estimated utilizing the fractal characteristics of the received radar data. In the present study, a more robust signature measure is proposed based on fractal analysis of received radar data. The proposed target detection method is applied on actual sea clutter radar data and the performance is compared with the conventional Hurst parameter based method. The simulation results illustrate that the proposed method achieves better detection performance and is robust under varying sea conditions.

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Keywords: Fractal; radar; sea clutter; target detection

1. Introduction

Clutter refers to the unwanted echo signal that reach the radar, typically returned form ground or sea due to manmade or natural objects which act like pseudo targets. When radar is used for a specific application in military, we are interested in echoes from targets like armed vehicles, machineries, unmanned aircrafts, military movements etc. than any signals from other harmless obstacles. Sea clutter is the undesirable returns from wavy and turbulent ocean surfaces which is influenced by the environmental conditions like sea state, wind velocity, wave height,

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presence of tide etc. and radar parameters like viewing geometry, range resolution, transmission frequency and so on. Owing to the presence of wind and non-stationary waves, the sea clutter often exhibits a Doppler spread. The sea clutter is spikier and has high power at heavy sea conditions due to huge radar reflections which is seen as a "sunburst" in the radar display screen, obscuring the target if present in the range bin under test. Therefore, the detection of small targets with low radar cross section (RCS) which are embedded within sea clutter is a challenging task in radar signal processing. The problem is significant in the area of defence, remote sensing and coastal environmental monitoring due to various reasons such as identification of small boats, submarine periscope, low flying unmanned aircrafts and missiles, small radioactive floating objects and pieces of ice, spilled oil patches, and unauthorised fishing.

The traditional target detection techniques within sea clutter were in terms of statistical analysis based on probability density functions. Owing to non-Gaussian nature of sea clutter distribution, Rayleigh, Weibull, log-normal and compound K-distributions were employed for the analysis of sea clutter. The target detection strategies were based on the goodness-of-fit of actual radar data with the theoretical distributions. The distribution based strategies were not effective in accurately detecting targets within sea clutter. Mandelbrot introduced fractal theory for the analysis of rough and irregular objects based on self-similarity and scale invariance [1]. The fractal theory was first applied for target detection within sea clutter in [2] and [3]. The relationship between the fractal dimension of sea clutter and roughness of the sea surface was analyzed based on scattering mechanisms in [4]. Neural network model based analysis for target detection were studied in [5] and [6]. Most of the above mentioned techniques require large number of data sets to find out parameters for accurate detection of targets. An effective small target detection scheme was proposed in [7] based on multi-fractal analysis of the time series radar data. A detection strategy using integral test based on multi-fractal analysis was proposed in [8]. A joint fractal-multi-resolution based detection of small targets was proposed in [9]. [10], [11]. In [12], fractal analysis was performed in frequency domain for target detection. The performance of most of the above mentioned fractal analysis based schemes depend on sea state and viewing geometry of the radar. In [13], a better detection scheme based on normalized Hurst exponent was suggested but at the expense of training to estimate statistical parameters.

Instead of the conventional signature parameter which is the Hurst exponent, in the present study, a more robust signature measure is proposed based on fractal analysis of received radar data. The proposed technique does not require any training. The performance of the proposed method is compared with that of the conventional method based on probability of detection for various false alarm rates.

The paper is organised as follows. The system model and theoretical aspects of fractal analysis are explained in section 2. The proposed target detection strategy is discussed in section 3. The simulation results with analysis and the conclusion of the study are given in sections 4 and 5 respectively.

2. Systems model and Fractal analysis

The sea clutter data, $x = [x(1), x(2), ..., x(n)]$ can be modeled as a "random walk" process [7] obtained as the partial summation of the elements of $\boldsymbol{s} = [s_1, s_2, \cdots, s_N]$ as

$$x(n) = \sum_{k=1}^{n} s_k \tag{1}$$

where $\boldsymbol{s}$ represents a covariance stationary stochastic process with zero mean and variance, σ^2 . Consider a function, $G(m)$ given as

$$G(m) = \sqrt{\left\langle \left| x(n+m) - x(n) \right|^2 \right\rangle} \tag{2}$$

and

$$G(m) \cong m^H \tag{3}$$

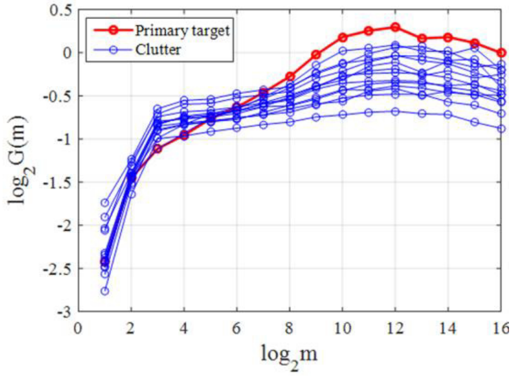

Fig. 1. Variation of $\log_2 G(m)$ versus $\log_2 m$.

where $\langle . \rangle$ represents average taken over all possible combination of $(x(n+m), x(n))$. If the scaling law given by (3) is satisfied, the process under investigation is considered to be a fractal process and the analysis is called fluctuation analysis [7]. The parameter H is called Hurst parameter. The Hurst parameter is related to the fractal dimension, D as $D = (2 - H)$ [2]. The fractal dimension will be larger and Hurst parameter will be smaller for radar returns from the natural sea clutter whereas the data corresponding to sea clutter and target will have a smaller fractal dimension and larger Hurst parameter [2],[3].

Taking logarithm with respect to two on both sides of (3) it can be rewritten as

$$\log_2 G(m) = H \log_2 m \tag{4}$$

The equation (4) represents the equation of a straight line with $\log_2 m$ in the x-axis, $\log_2 G(m)$ in the y-axis and H is the slope. The curve is fairly linear for the values of m ranging from 2^4 to2^{12}. Utilizing these facts, in the conventional fractal based target detection method [7], the clutter and target is distinguished by fitting a straight line with $\log_2 m$ in the x-axis and $\log_2 G(m)$ in the y-axis to find out the slope, H in the range $m = 2^4$ to2^{12}.

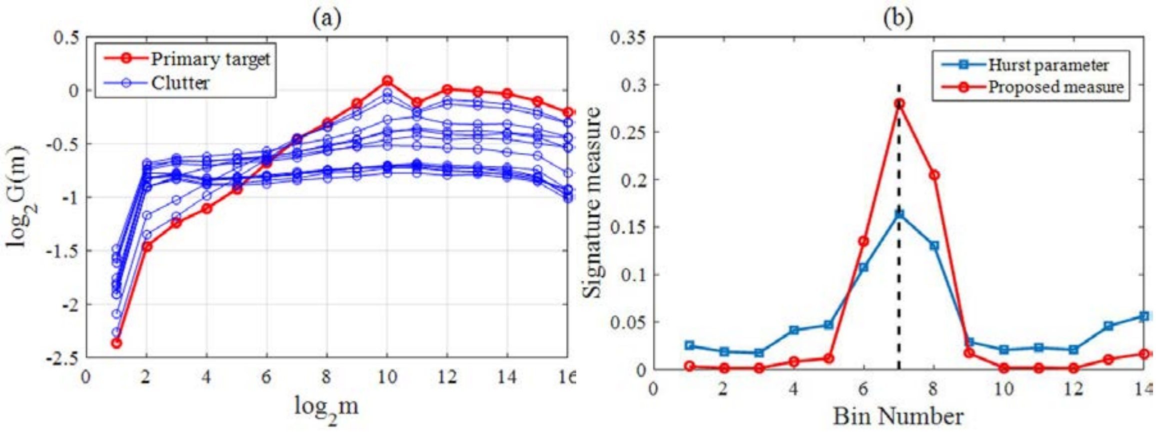

Fig. 2. (a) Fractal curves comparison; (b) Signature measure comparison, target in 7th range bin.

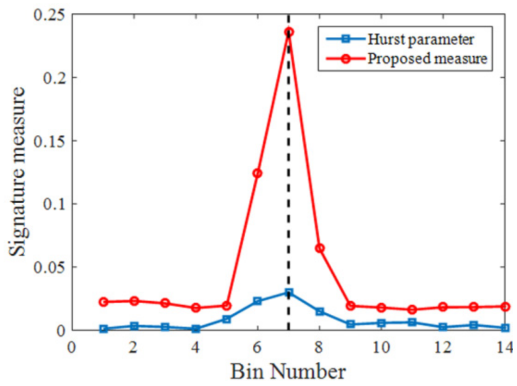

Fig. 3. Signature measure comparison, target in 7th range bin

3. Proposed signature measure

The target detection procedure followed in [7] was based on the assumption that the statistics of Hurst parameters is independent of viewing geometry and sea state. Therefore, the signature measure used in [7] has a significant variance for various range bins corresponding to pure sea clutter for the same data set. A modified target detection scheme based on normalized Hurst exponent was proposed in [13] where the Hurst parameter of the cell under test (CUT) is normalized with respect to mean and variance of Hurst exponents calculated from reference bins. Even though the method based on normalized Hurst exponent adapts to the change of sea state, it requires training data from reference range bins without target in order to find out the mean and variance. Hence in the present study, a better signature measure is proposed which is not only independent of the sea state and viewing geometry but also provides better detection performance without the necessity of any training data.

The variation of $\log_2 G(m)$ versus $\log_2 m$ for a particular data set for various range bins are shown in Fig. 1. The curves corresponding to primary range bin with strong target is shown in a different color than that without targets. It can be seen that the slope of the curves, in the range of $\log_2 m$=4 to 12, is higher for that with targets than without targets. This is used as the signature measure in conventional methods [7]. But it was observed that the slope will be different for other datasets corresponding to different sea states. It may be noticed that the curves corresponding to presence of target has large variation in the range $\log_2 m$=3 to 10 than that corresponding to pure sea clutter. The same characteristic is observed for other data sets also. Hence, in the present study, instead of finding out the slope

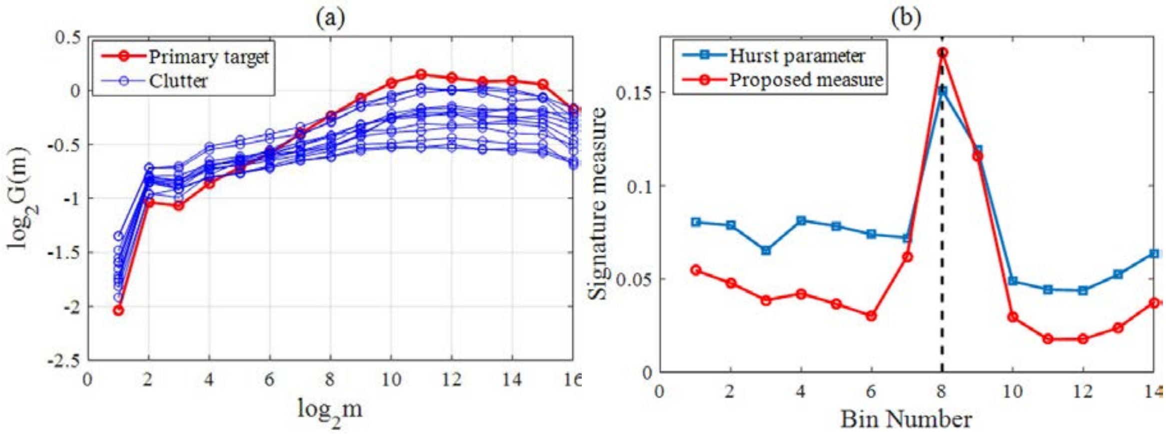

Fig. 4. (a) Fractal curves comparison; (b) Signature measure comparison, target in 8th range bin.

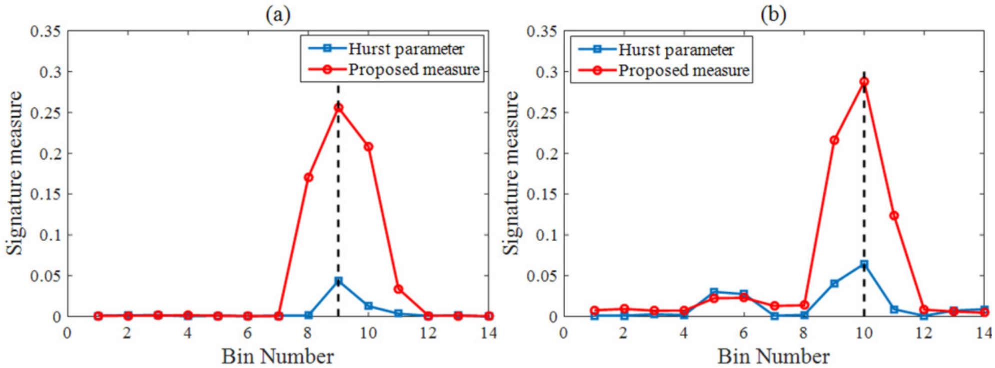

Fig. 5. Signature measure comparison (a) Target in 9th range bin; (b) Target in 10th range bin.

of the curve in the particular range, the variance of $\log_2 G(m)$ in the range $\log_2 m$ =3 to 10 is selected as the signature measure.

4. Simulation results and analysis

The performance of the target detection scheme based on the proposed signature is compared with the conventional Hurst exponent based technique using original sea clutter radar data. 14 actual sea clutter data sets are obtained from the McMaster-IPIX radar database maintained by Professor Simon Haykins ((http://soma.ece.mcmaster.ca/ipix/dartmouth/datasets.html). The experiment was carried out using IPIX X-band polarimetric coherent radar operating at a carrier frequency of 9.39 GHz with four polarization modes HH, HV, VV and VH (horizontal/vertical transmission, horizontal/vertical reception). Each dataset contains 14 spatial range bins of the four polarization modes which accounts for a total of 784 time data vectors. Each data vector consists of 2^{17}samples. Out of the 14 range bins, a particular range bin consists of a target which is made of a spherical styrofoam block wrapped with wire mesh, having a diameter of 1m. The range bin where the target is exactly present is called primary range bin. A few (two or three) range bins, nearer to the primary range bin is also hit by the target, which are called secondary bins. The radar returns from the other 10 range bins corresponds to pure sea clutter. The details about the primary range bin, secondary range bin and the observation time are also provided in the website. The variation of $\log_2 G(m)$ versus $\log_2 m$ for a particular data set for various range bins are shown in Fig. 2(a). The target is present in the 7th range bin. The signature measure comparison corresponding to Fig. 2(a) is shown in Fig. 2(b). From Fig. 2(b), it can be inferred that the proposed method not only detects the primary target bin, but also has higher value corresponding to the bin with both clutter and target than the conventional Hurst parameter. The proposed measure also has lower magnitudes at clutter only bins than the Hurst parameter. The signature measure comparison for another dataset having a target in 7th range bin is shown in Fig. 3. The proposed signature clearly distinguishes target from clutter whereas the probability of misdetection is high for conventional measure. The $\log_2 G(m)$ versus $\log_2 m$ graphs of the 14 range bins corresponding to another dataset for which the primary target is in the 8th range bin are shown in Fig. 4(a). The signature measure comparison corresponding to Fig. 4(a) is shown in Fig. 4(b). The signature measure comparison plots for datasets having primary bins as 9 and 10 are shown in Fig. 5(a) and Fig. 5(b) respectively. The proposed measure has highest magnitude at the primary bins and very low clutter floor. Even though the clutter floor of the proposed signature measure is lower than or almost equal to that of Hurst parameter, the magnitude corresponding to primary bin is significantly higher, which indicates a higher probability of detection. It is also seen that the magnitude of the proposed measure at secondary bins are also higher than the Hurst exponent. The three dimensional mesh plot of the normalized signature parameter versus the 14 range bins and the 14 datasets using conventional Hurst parameter and the proposed measure are illustrated in Fig. 6(a) and Fig. 6(b) respectively. It can be seen that the conventional parameter exhibits a higher clutter floor than the proposed signature measure. In order to analyze the detection performance, the probability of detection versus false alarm rate plots using the conventional method and proposed method are compared. The graphs obtained using received data corresponding to HH and HV polarization modes are shown in Fig. 7(a) and Fig. 7(b) respectively. The detector is applied to the primary bins which are implemented by comparing the signature parameters with a predefined threshold. The threshold for a given false alarm rate is obtained by performing Monte Carlo simulations on the clutter only data vectors. The threshold for a given false alarm rate is computed from the probability density function of the signature measure calculated from the clutter only data vectors. If H is the signature measure and

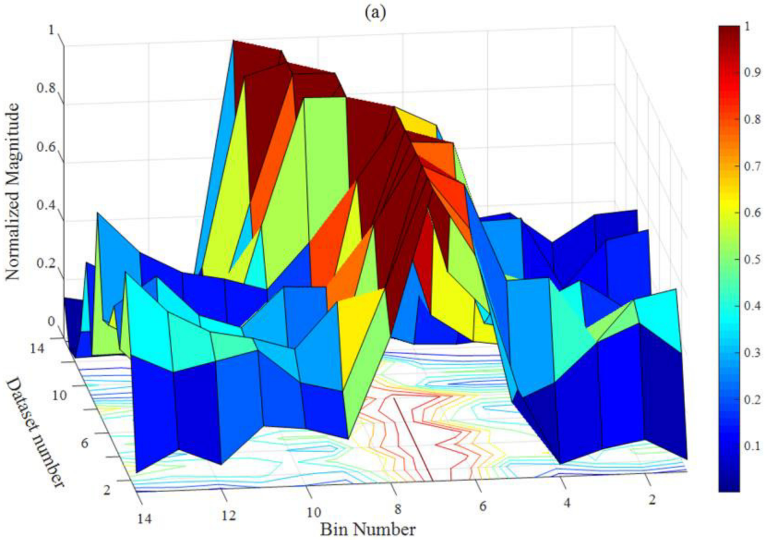

Fig. 6. (a) Mesh plot of the normalized signature parameter for conventional method

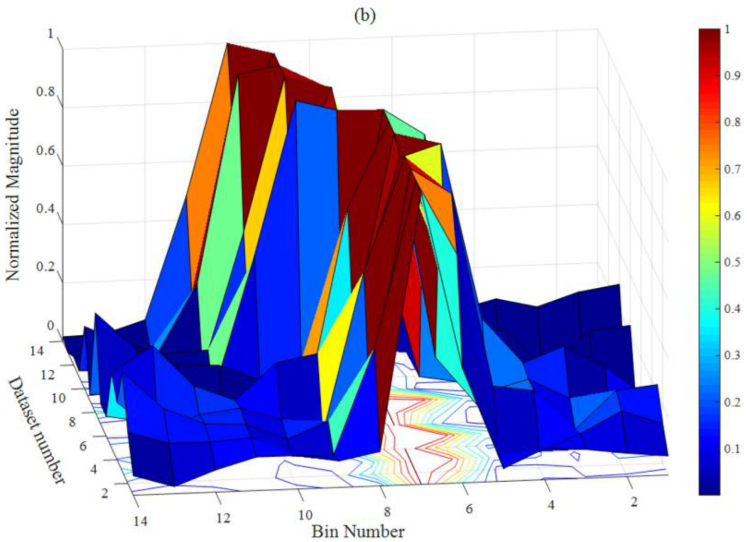

Fig. 6. (b) Mesh plot of the normalized signature parameter for proposed method

$p(H)$ is the probability density function of H, the probability of false alarm, P_{fa} at threshold τ is given as $P_{fa} = \int_{\tau}^{\infty} p(H)\,dH$. Hence that value of H_t is selected as threshold such that the area under the probability density curve from $H=\tau$ to $H=\infty$ is equal to P_{fa}. It is clear from the graphs that the proposed method exhibits significantly better detection performance than the convention method.

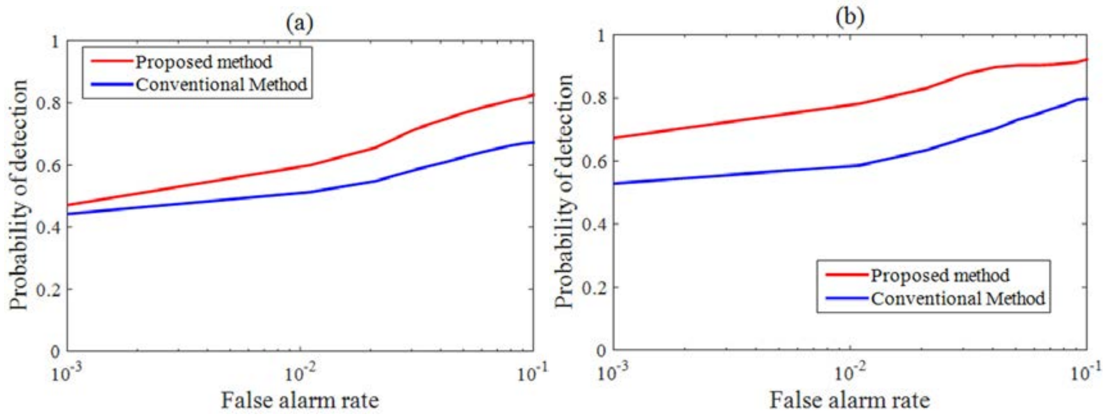

Fig. 7. Probability of detection comparison (a) HH polarization; (b) HV polarization.

5. Conclusion

A new signature measure for the detection of small targets embedded within sea clutter is proposed. Unlike the conventional methods, the proposed method is least affected by the change of sea sate and the viewing geometry of the radar and at the same time it does not require any training data set to determine the signature parameter. The robustness of the proposed method is illustrated through numerical simulations performed on actual radar data corresponding to targets within sea clutter. The variance based method has lower magnitudes for bins corresponding to actual clutter than the Hurst parameter based conventional approach. The magnitudes at the primary and secondary bins are also much higher for the variance based signature than that of the conventional measure. The proposed method also has a higher detection probability than the Hurst parameter based method. The probability of detection is higher for variance based method in the case of both like and cross polarization data and exhibits an improvement in detection probability of 0.2 for the entire range of false alarm rate varying from 0.001 to 0.1 in the case of cross polarization. Similar measure can be estimated from the spectral domain of the received data, which is considered as a future study.

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