Distributed Target Detection in SAR Images Using Improved Chaos-based Method

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Abstract—Detection of distributed targets such as internal wave or ship wake on sea surface in Synthetic Aperture Radar (SAR) images is an important application of ocean microwave remote sensing. The chaotic characteristic of sea clutter gives some clues to targets detection on sea surface. Speckle, the inherent noise of SAR image, will affect the predictive accuracy of sea clutter adversely and reduce the detection performance of radar. In order to apply the chaotic characteristic of sea clutter to targets detection in SAR images more effectively, an improved chaos-based detection method is proposed in this paper. First, speckle noise is suppressed by undecimated wavelet transform (UWT), and then targets are detected on the basis of the chaotic characteristic of sea clutter from the denoised SAR images. Experimental results prove that the method proposed in this paper is effective for the distributed targets detection in SAR ocean images.

Keywords—chaos; undecimated wavelet transform; sea clutter; SAR images; target detection

I. INTRODUCTION

The performance of maritime surveillance radar is affected by sea clutter, the unavoidable radar returns from the sea surface. Therefore, an accurate sea clutter model is curial for detection of targets on sea surface. Traditionally, sea clutter has been modeled as a stochastic process. The statistical models used to describe the amplitude characteristic of sea clutter include the Rayleigh, Lognormal, Weibull, and K distributions\cite{1}. These models except K-distribution are built on empirical studies of sea clutter instead of any physical understanding of the clutter returns.

Contrary to the statistical approach, Haykin and Henry \cite{2} have reconstructed the dynamic model of sea clutter on the basis of chaos theory in the past decades. More precisely, sea clutter signal can be modeled by a nonlinear deterministic dynamical system. The chaos model has been applied to targets detection and its detection performance is better than that of the statistical models \cite{3}. In this paper, the distributed targets in SAR ocean images are detected on the basis of the chaotic characteristic of sea clutter.

Due to the coherent imaging principle of SAR, SAR image is inevitably corrupted by speckle noise. The traditional Chaos-based Detection Method (CDM) \cite{3} does not perform effectively in detecting objects in SAR images because of the influence of speckle. Based on the speckle removal of SAR images, an Improved Chaos-based Detection Method (ICDM) is proposed in this paper.

In the second section, the methodology of the ICDM is introduced. Then in the third section, the SAR ocean images are used to test the performance of the CDM and ICDM.

II. IMPROVED CHAOS-BASED DETECTION METHOD

A. Speckle Suppression Using UWT

The accuracy of sea clutter chaotic prediction and the detection performance of radar will be reduced because of the influence of speckle in SAR images. In order to improve the detection performance, the undecimated wavelet transform (UWT) is used to remove speckle noise. In the following, the UWT will be introduced.

Mallat and à trous \cite{4} algorithms are widely applied to discrete wavelet transform.

The mallat algorithm, a decimated wavelet transform, is very efficient from the computational point of view. Unfortunately, the decimation causes translation variance of the wavelet transform. Due to the loss of the translation-invariance property, the decimated wavelet is not optimal for the applications such as filtering, detection, or more generally, analysis of data.

In order to achieve translation-invariance, the UWT has been introduced \cite{4}. In addition to the translation-invariance, the UWT gives increased amount of information about the transformed signal compared to the decimated wavelet transform. The number of the wavelet coefficients does not shrink between the transform levels. This additional information can be very useful for the better analysis and understanding of the signal properties.

The à trous algorithm, an undecimated wavelet transform, modifies the mallat decomposition scheme by up-sampling the low-pass and high-pass filters instead of sub-sampling the filtered signal \cite{5}. The up-sampling is done by inserting zeros between each of the filters’ coefficients at each level. The scheme of the à trous algorithm is shown in Fig.1. $a_i(n)$ and $d_i(n)$ denote the approximation and detail coefficients of the
The extension of the UWT reported in Fig. 1 is straightforward. At each level, the image is decomposed into four images: the approximation (LL), and three detail (LH, HL, HH) images. Each image maintains the same resolution of the original image.

After SAR image is decomposed by the UWT, the coefficients of speckle mainly exist in detail images [6]. The approximated image is used to detect targets. In this paper, speckle suppression is approached as low-pass filtering.

The UWT is used to suppress speckle in this paper because of its two advantages. a) The translation-invariance is useful for locating the position of the detected targets; b) UWT is a redundant transform which reserves larger amount of information that is advantageous to construct an accurate sea clutter dynamic system.

B. Chaotic Predictive Model of Sea Clutter

Usually, sea clutter is a time series, \{c(n), n = 1, 2, \cdots, N\}. It conceals the essential feature of the sea dynamical system. The Takens Embedding Theorem has stated that a nonlinear dynamical system can be reconstructed to a certain extent by using just one observation of the system, and the reconstruction is independent of which signal component is used [3].

According to the Takens Embedding Theorem, there exists a diffeomorphism \(\psi: \mathbb{R}^{D_z} \rightarrow \mathbb{R}^{D_z}\), where \(D_z\) is the embedding dimension [3]. Thus we have

\[
(c(n + \tau), c(n + 2\tau), \cdots, c(n + D_z\tau)) = \psi(c(n), c(n + \tau), \cdots, c(n + (D_z - 1)\tau))
\]

Equation (1) states that each component of the left-hand side is determined by the components on the right-hand side and only \(c(n + D_z\tau)\) is new information. Hence, there exists a nonlinear function \(F\) such that

\[
c(n + D_z\tau) = F(c(n), c(n + \tau), \cdots, c(n + (D_z - 1)\tau))
\]

Equation (2) shows that reconstructing dynamics from a chaotic time series becomes a single step prediction problem. To improve the predictive accuracy of sea clutter, Haykin [9] has proposed the improved predictive equation

\[
c(n + D_z\tau) = F(c(n), c(n + 1), \cdots, c(n + D_z\tau - 1))
\]

Equation (3) offers more information for prediction than (2), so it will have a better prediction performance. In this paper, equation (3) is used as the predictive model of sea clutter.

It is well known that neural network has the inherent ability to learn a nonlinear function. We can train neural network to obtain a nonlinear function \(\hat{F}: \mathbb{R}^{D_z\tau} \rightarrow \mathbb{R}\) that approximates the unknown function \(F\) in (3). BP (back-propagation) neural network is used in this paper. The approximating function \(\hat{F}\) is optimized by adjusting the parameters of BP neural network to minimize the mean square error (MSE) between the expected output \(c(n + D_z\tau)\) and the actual output \(\hat{c}(n + D_z\tau)\) of neural network in response to the input vector \(\{c(n), c(n + 1), \cdots, c(n + (D_z - 1)\tau)\}\). Neural network is trained in a supervised manner. The objective function MSE is given by

\[
MSE = \frac{1}{N_s} \sum_{n=1}^{N_s} (c(n + D_z\tau) - \hat{c}(n + D_z\tau))^2
\]

where \(N_s\) is the number of training samples.

C. Detection of Targets in Sea Clutter

Radar detection is usually formulated as a binary decision problem given by [10]

\[
H_1: x(n) = s(n) + c(n)
\]

\[
H_0: x(n) = c(n)
\]

where \(x(n)\) is the received radar signal, \(s(n)\) is the target signal, and \(c(n)\) is the sea clutter signal.

To apply the predictive model of sea clutter to detection, the BP neural network is first trained using sea clutter \(c(n)\). When the received radar signal \(x(n)\) is exposed to this trained BP neural network, the network will generate a prediction error \(\varepsilon(n)\)

\[
\varepsilon(n) = |x(n) - \hat{x}(n)|
\]

where \(\hat{x}(n)\) is the prediction value of \(x(n)\) generated by the clutter-trained network. The detection problem in (5) will be determined as [10]

\[
x(n) \in \begin{cases} H_1 & \text{if } \varepsilon(n) > \eta \\ H_0 & \text{if } \varepsilon(n) < \eta \end{cases}
\]

where \(\eta\) is the threshold for target detection according to the prediction error of \(x(n)\).

Since the BP neural network is trained using clutter data, the BP net should produce a good approximation to the sea clutter dynamic system and generate small prediction error for an \(H_0\) signal. When a received radar signal containing one or more targets, an \(H_1\) signal, is fed into the network, it no longer...
matches this predictive model since target and clutter dynamics are usually quite different and is expected to result in a larger prediction error [10]. Therefore, we can detect target according to the prediction error of \( x(n) \).

The threshold \( \eta \) is an important parameter for target detection. In this paper, the concept of constant false alarm rate (CFAR) is used. CFAR determines the threshold by the fixed false alarm probability \( p_a \) and the probability density function of the \( H_0 \) hypothesis. For the detection method based on chaotic prediction error, \( p_a \) can be estimated numerically using the prediction error of sea clutter by a histogram [11]. \( \eta \) is determined according to (8)

\[
\int_{-\infty}^{\infty} p_a(x)dx = p_a
\]  

(8)

D. Targets Detection Procedure in SAR Ocean Images

The data in the same range bin of SAR image is taken as a received radar signal. The smooth region in SAR ocean image is called background generated by sea clutter. The main steps of the detection method proposed in this paper are as follows.

1) Compute the undecimated wavelet transform of SAR image to suppress the speckle noise. The approximation (LL) image is used in the following steps.

2) Select background region and estimate the delay time \( \tau \) and embedding dimension \( D_e \) using the data in the background region.

3) Reconstruct the sea clutter dynamical system by training BP neural network. \( k \) range bins in the background region are selected, \( k = M/N \). Where \( M \) is the number of the samples needed to train BP network, and \( N \) is the length of data in a range bin.

4) Determine the threshold of CFAR detection. The prediction error of background region is computed by the clutter-trained neural network. We can get the probability density function of the \( H_0 \) hypothesis according to the histogram of the prediction error. Then, \( \eta \) is determined by (8) at a given probability of false alarm.

5) Detect targets according to the chaotic prediction error of the region to be detected and the threshold \( \eta \), then produce a binary image, “white” is target, “black” is background.

6) Use the operations of morphological image processing to combine the adjacent targets and remove those smaller than the structuring element.

III. EXPERIMENTAL RESULT

Internal wave and ship wake in SAR ocean images are detected by the CDM and ICDM respectively.

The first experiment is the internal wave detection. The false alarm probability is set to \( 10^{-2} \). Fig. 2(a) is the SAR ocean image containing internal wave. Fig. 2(b) and (c) are the detection results of internal wave by the CDM and ICDM respectively.

The second experiment is the ship wake detection. The false alarm probability is set to \( 10^{-2} \). Fig. 3(a) is the SAR ocean image containing ship wake. Fig. 3(b) and (c) are the detection results of ship wake by the CDM and ICDM respectively.

The CDM cannot distinguish the internal wave and ship wake effectively from the background generated by sea clutter because the speckle in SAR images reduces the predictive accuracy of sea clutter. The ICDM can detect the internal wave and ship wake more accurately. Therefore, ICDM is effective to detect the distributed targets in SAR ocean images.

IV. SUMMARY

In the proposed method, the chaotic characteristic of sea clutter is the basis of targets detection from SAR ocean images. To suppress the speckle in SAR image, the undecimated wavelet transform of SAR image is performed. Then, the approximated image is used for targets detection based on the chaotic prediction error. The experimental results prove the effectiveness of the ICDM proposed in this paper.

REFERENCES


Figure 2. The detection results of internal wave in SAR ocean image. (a) SAR ocean image containing internal wave. (b) Detection result of internal wave by the CDM. (c) Detection result of internal wave by the ICDM.

Figure 3. The detection results of ship wake in SAR ocean image. (a) SAR ocean image containing ship wake. (b) Detection result of ship wake by the CDM. (c) Detection result of ship wake by the ICDM.