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A Coarse-to-Fine Approach for Ship Detection in SAR Image Based on CFAR Algorithm

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Abstract—Among ship detection methods for SAR image, constant false alarm rate (CFAR) is the most important one. However, several factors, such as detector parameter and distribution of ocean clutter, affect the performance of CFAR detection. This paper proposes a novel hierarchical complete and operational ship detection approach based on detector parameter estimation and clutter pixel replacement, which is considered a sequential coarse-to-fine elimination process of false alarms. First, a simple barycentric algorithm is adopted to estimate target-window size, and the morphology method is used to estimate false alarm rate for CFAR detector. Second, a clutter pixel replacement approach based on the statistical features of sea clutter is presented to obtain statistically independent, stationary, and Weibull distributed random data for CFAR detector to remove all false alarms. Experimental results of the detection methods on a SAR image dataset show that the proposed approach is effective in reducing false alarms and obtains a satisfactory ship detection performance.

1. INTRODUCTION

Using SAR, one can obtain high-resolution images under all weather, day and night and long distance conditions. Ship detection in SAR images is one of the important aspects of the SAR application and it is the basic and most important step in automatic target recognition (ATR). Usually, ship detection aims at discerning region of interest on SAR images acquired in the airborne or satellite platform. In civilian areas and military applications, the fast and accurate detection of target in SAR images is very important.

Many studies have been carried out on how to detect ships in SAR images of the sea [1]. As for medium and high-resolution SAR images, some researchers focus on an appropriate choice of radar cross section (RCS) threshold. In fact, the RCS of ships is usually higher than the surrounding sea clutter because of the effect of multiple bounces of incoming radar waves from the ship's superstructure. There is considerable amount of existing work on the choice of pixel value threshold, such as biparameter constant false alarm rate (CFAR) detector, Gamma-distribution based CFAR detector [2] and maximum-entropy threshold detector.

The CFAR algorithm is one of the powerful and common algorithms to compute the threshold adaptively. In the CFAR detection schemes, the threshold level is calculated when the background clutter is of an estimated Gaussian distribution, K-distribution, 2-D joint log-normal (LN) distribution, or G0 distribution [3–5]. However, a major problem for the CFAR algorithm is how to determine an appropriate probability density function that can model background clutter well. Because of the complex ocean environment, the ocean clutter statistical distributions estimated could sometimes fail to provide a reasonable fit to the amplitude statistics of the clutter. Although a lot of effort is being spent on improving these weaknesses, the efficient and effective method has yet to be developed.

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In this paper, an effective coarse-to-fine method for ship detection is proposed by using parameters estimation and clutter pixel value replacement. The estimate of probability of false alarm and target window size are carried out to increase the efficiency of CFAR detection. SAR data contains clutter which is non-stationary and heterogeneous with unknown distribution which reduces the CFAR detection accuracy seriously. Therefore, we propose a clutter pixel value replacement method of SAR images and especially introduce how to process the clutter data with Weibull distribution [6]. Finally, ship detection is achieved by assigning each pixel of the SAR image to the ship class or background class according to the biparameter CFAR.

The structure of the paper is as follows. Section 2 describes the proposed coarse-to-fine approach for ship detection (see Figure 1), and presents the estimate method of probability of false alarm (PFA) and target window size, and proposes a model of clutter pixel value replacement. Section 3 provides some experimental results of the proposed approach for SAR images. Section 4 contains some conclusions plus some ideas for further work.

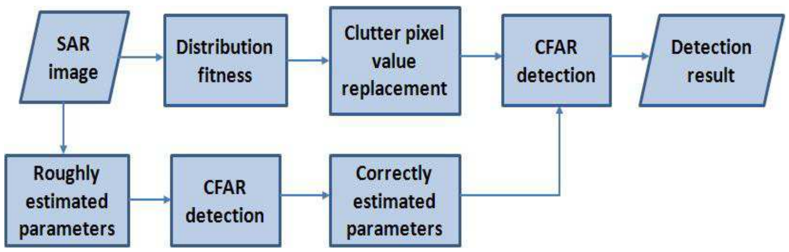


Figure 1. Flow of the CFAR detection algorithm.

2. PROPOSED ALGORITHM

In this section, a logarithmic transformation is used to reduce the two-parameter Weibull probability density function to a location-scale type distribution [6]. Supposing a SAR image pixel x, it is the Weibull distribution. Assuming that $y = \ln x$, we get the distribution

$$W(y) = \beta(\ln 2)(e^y/\alpha)^\beta e^{-(\ln 2)(e^y/\alpha)^\beta}, \quad y \in \mathbb{R} \tag{1}$$

or

$$W(y) = ((\ln 2)/b)e^{(y-a)/b} e^{-(\ln 2)e^{(y-a)/b}}, \quad y \in \mathbb{R} \tag{2}$$

where $a = \ln \alpha$ and $b = \beta^{-1}$. Thus, an effective biparameter CFAR is achieved when the clutter is locally homogeneous.

Whether the pixel tested belongs to the target region or not is judged by the rule defined in the following. The biparameter CFAR detector works on the logarithm of the pixel of SAR image X_0 as

$$\frac{\ln(X_0(m,n)) - \hat{\mu}}{\hat{\sigma}} \geq \tau(P_{fa}) \tag{3}$$

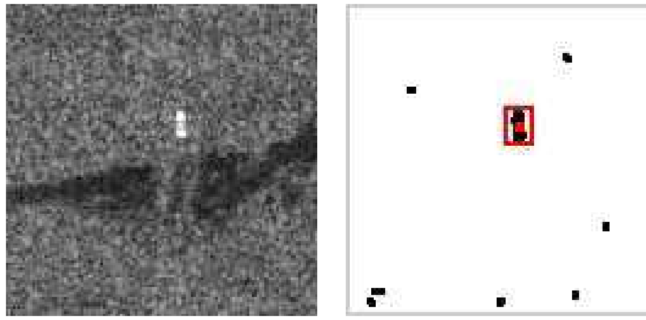
where $\hat{\mu}$ and $\hat{\sigma}$ are the estimated mean and standard deviation of the clutter on the local regions of the SAR data $\ln X_0$, and the threshold $\tau(P_{fa})$ is calculated by the parameters of the assumed Weibull distribution model and the PFA P_{fa}.

2.1. Clutter and Target Window Parameters

In the biparameter CFAR algorithm of the ship detection of SAR images, the detector uses the actual PFA and three moving windows: target window, protect window and background window. Here, the sizes of the target window and PFA will be estimated using a coarse-to-fine approach.

The main steps of the targetwindow estimation algorithm are as follows:

(a) Set the initial value. Here for specifying biparameter CFAR procedure the initial parameters, PFA $P_{fa} = 10^{-k_0}$ and target-window (h_0, w_0) are roughly estimated by standard deviation (shape parameter) of the clutter the radar spatial resolution and the size of region of interest.



(a) (b)

Figure 2. Estimated target-window. (a) Original image. (b) Rectangular window and barycentric coordinate (point inside the rectangular window).

(b) Calculate the new height and width of target-window (see Figure 2). For the SAR image X_0, with a size of $M \times N$, the biparameter CFAR operator is used to get the detection result, a binary image X_1. Here, we posit that target candidates tend to occur in groups, i.e., a high value of a pixel as a possible target will affect the probability of a neighboring pixel having a high value. On the binary image X_1, we calculate the size of the largest single-connected region, such as the following:
1) Removing isolated pixels (individual 1s that are surrounded by 0s) on binary image X_1

$$X_1(m,n) = \begin{cases} 0 & \sum\limits_{i,j\in\Gamma} X_1(m+i,n+j)\cdot X_1(m,n) = 1 \\ X_1(m,n) & \text{otherwise} \end{cases} \tag{4}$$

where $\Gamma = \{-1, 0, 1\}$.
2) Performing dilation operation [7] on binary image X_1 after removing its isolated pixels.

$$[\delta_\Gamma(X_1)](m,n) = \max_{i,j\in\Gamma} X_1(m+i,n+j) \tag{5}$$

where δ_Γ is the dilation operator.
3) Finding the row and column indices $\{(m_i,n_i)|i\in\Omega\}$ of the nonzero entries in the binary matrix X_1, where the index set $\Omega = \{1,2,\ldots,I\}$.
4) Calculating barycentric coordinates (integer coordinates of the largest region with a simply-connected interior) (m_{i_0}, n_{i_0}) according to the Equation (6) and Equation (7).

$$\tau_i = \sum_{j\in\Omega, j\neq i} \left[(m_i-m_j)^2 + (n_i-n_j)^2\right]^{-1/2} \quad i\in\Omega \tag{6}$$

$$i_0 = \arg\max_{i\in\Omega}\{\tau_i\} \tag{7}$$

where, each τ_i is a distance value using the Euclidean metric, and i_0 is a index.
5) To start the search from (m_{i_0}, n_{i_0}) and adopt the depth-first search strategy to search for the boundary pixels in a largest simply-connected region. Here, depth-first search is a systematic way to find all the boundary pixels reachable from (m_{i_0}, n_{i_0}).
6) Assigning the height and width (h_1, w_1) according to the boundary pixels in the largest simply-connected region.

The main steps of the PFA estimation algorithm are as follows:

(a) Set $J = 0$.
(b) Detect targets. For the SAR image X_0, the biparameter CFAR operator is used to get a binary image X'_J. Here, the parameters $P_{fa} = 10^{-(k_0+J)}$ and (h_1, w_1) are used
(c) Find the number of isolated pixels.

$$X''_J(m,n) = \begin{cases} 1 & \sum\limits_{i,j\in\Gamma} X'_J(m+i,n+j)\cdot X'_J(m,n) = 1 \\ 0 & \text{otherwise} \end{cases} \tag{8}$$

Let n_J denote the number of isolated pixels (non-zero pixels) in the image X''_J.

(d) Set $J = J + 1$. If a stopping condition ($n_J \leq \kappa n_0$, the scale factor parameter $\kappa \in (0, 1)$) is not met, it repeats step (b) and (c). Otherwise, the output result $P_{fa} = 10^{-k_1}$, where $k_1 = k_0 + J$.

For the estimated parameters (h_1, w_1) and $P_{fa} = 10^{-k_1}$, a binary image X_2 with possible targets is obtained from X_0 using the biparameter CFAR algorithm. Here, a possible target pixel has a high value.

2.2. Clutter Pixel Value Replacement

The correct formulation of the CFAR-based detection schemes for a target in the presence of clutter needs a faithful and mathematically tractable clutter model. In this subsection, we will focus on the clutter-pixel-value replacement in SAR image.

The pure sea clutter image X_3, obtained by the SAR image X_0 and the binary image X_2 through removing the region of possible targets and taking the interpolating operation, is converted into a number of sliding $h_1 \times w_1$ image blocks, denoted by X_3^i $(i = 1, 2, \ldots, MN)$.

CFAR methods assume an underlying distribution in the derivation of detection results. However, when it is assumed that clutter data follow a specific distribution, it takes risk. If such a distribution does not hold, then the detection results obtained may be invalid. The Kolmogorov-Smirnov (K-S) goodness-of-fit test based on statistical theory is widely used in checking distribution assumptions In this subsection, the K-S test [8] is used to answer the question: Are the data X_3^i $(i \in \{1, 2, \ldots, MN\})$ from the hypothesized Weibull distribution. Assuming that the significance level η, and the data $X_3^{i_0}$ from the Weibull distribution, then we obtain

$$X_4(m,n) = \begin{cases} X_0(m,n) & X_2(m,n) = 1 \\ \bar{x}_3^{i_0} & X_2(m,n) = 0 \end{cases} \tag{9}$$

where, $\bar{x}_3^{i_0} = x_3^{i_0} \bar{\mu}_{m,n} / \bar{\mu}_3^{i_0}$, $x_3^{i_0}$ is a pixel value drawn randomly from the matrix $X_3^{i_0}$, $\bar{\mu}_3^{i_0}$ is the mean of image block $X_3^{i_0}$, and $\bar{\mu}_{m,n}$ is the mean of $h_1 \times w_1$ neighbourhood centred on the pixel coordinate (m, n) of image X_0.

2.3. Target Detection

In this section, we use the biparameter CFAR procedures against the modified clutter, modeled as Weibull distributed process. The biparameter CFAR scheme against Weibull clutter performs an estimate of the detection threshold by means of a linear combination of a fixed number of ordered statistics drawn from the reference sample.

The targets of the SAR image X_4 is detected with biparameter CFAR operator using the correctly estimated parameters (h_1, w_1) and $P_{fa} = 10^{-k_1}$. Its detection result is denoted as X_5, a binary image.

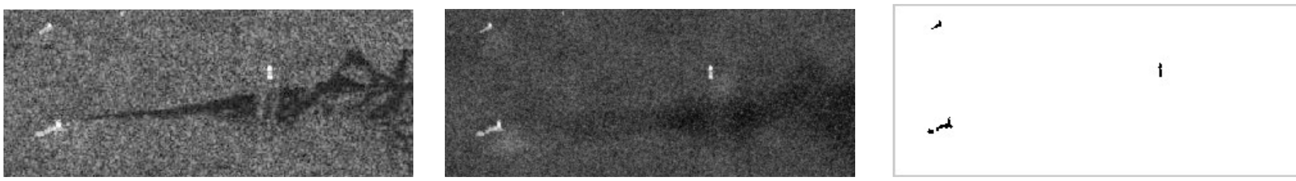
3. RESULTS AND DISCUSSION

3.1. Experimental Results

In order to assess the effectiveness of the proposed approach, we considered the real SAR images. In all the experiments, the significance level $\eta = 0.05$, the scale factor parameter $\kappa = 0.1$, the roughly estimated $(h_0, w_0) = (25, 25)$ and $P_{fa} = 10^{-5}$ are used. An input ERS (European Remote Sensing Satellite) [9] SAR image is shown in Figure 3(a), with a size of 320×131 pixels. The detection result (as shown in Figure 3(c)) shows the qualitative result for the input SAR image.

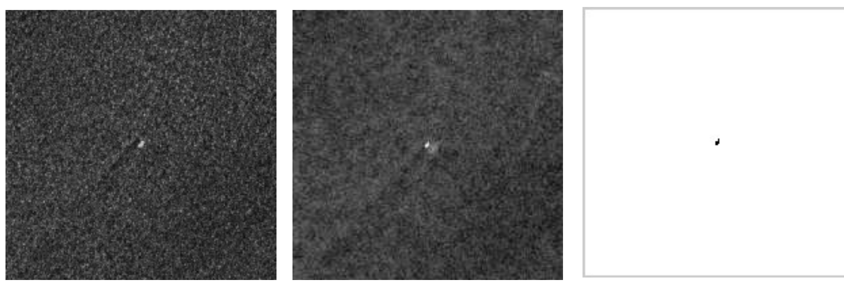
An input RADARSAT [10] image is shown in Figure 4(a), with a size of 200×200 pixels. A medium sized ship, believed to be the car ferry is visible. Another input RADARSAT SAR image is shown in Figure 5(a), with a size of 172×172 pixels. The detection results (as shown Figure 4(c) and Figure 5(c)) show the qualitative results for the input SAR images.

Comparing the detection results using the aforementioned images, the conventional biparameter-CFAR detector is greatly affected by speckle. It tends to have many false alarms (as shown in Figure 6). In the experiments, the PFA parameters are selected as shown in Table 1.



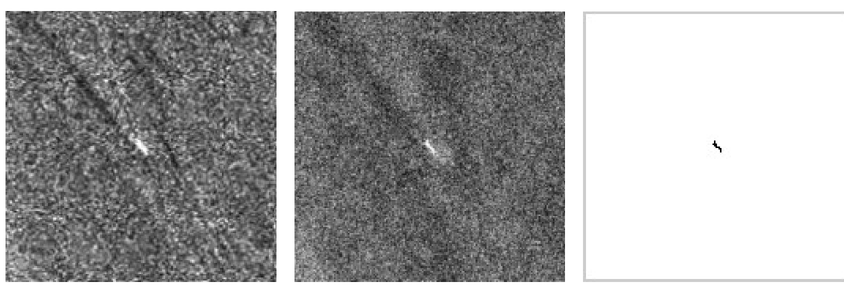
(a) (b) (c)

Figure 3. (a) Original image. (b) Image with clutter pixel value replacement. (c) Detection result with proposed method.



(a) (b) (c)

Figure 4. (a) Original image. (b) Image with clutter pixel value replacement. (c) Detection result with proposed method for image (a).



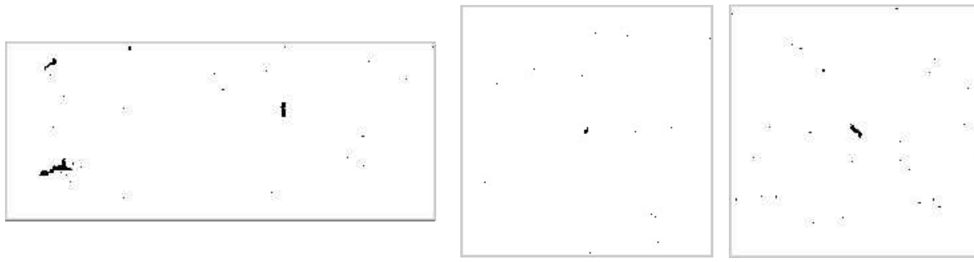
(a) (b) (c)

Figure 5. (a) Original image. (b) Image with clutter pixel value replacement. (c) Detection result with proposed method for image (a).

Table 1. Parameters estimation for biparameter CFAR.

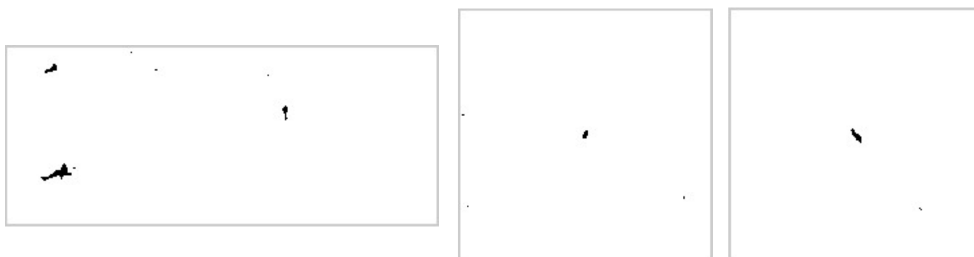
Symbol	Title	Figure 3(a)	Figure 4(a)	Figure 5(a)
h_1	Target Height	17	13	15
w_1	Target Width	35	13	13
P_{fa}	Probability of False Alarm	1.0000e-007	1.0000e-009	1.0000e-009

In [5], a method is proposed via correlation-based joint CFAR, which requires correct estimate of parameters. In the experiments, we use the real SAR images (as shown in Figure 3(a), Figure 4(a) and Figure 5(a)), and the PFA parameters are selected as shown in Table 1. Some detection results for comparison (with the proposed coarse-to-fine method) are shown in Figure 7.



(a) (b) (c)

Figure 6. Detection results with biparameter CFAR. (a) Detection result for image Figure 3(a), ($P_{fa} = 10^{-7}$). (b) Detection result for image Figure 4(a), ($P_{fa} = 10^{-9}$). (c) Detection result for image Figure 5(a), ($P_{fa} = 10^{-9}$).



(a) (b) (c)

Figure 7. Detection results with correlation-based joint CFAR for SAR images without subsequent morphological operations on binary images. (a) Detection result for image Figure 3(a), ($P_{fa} = 10^{-7}$). (b) Detection result for image Figure 4(a), ($P_{fa} = 10^{-9}$). (c) Detection result for image Figure 5(a), ($P_{fa} = 10^{-9}$).

3.2. Efficiency Discussion

The scene content, which interferes with target acquisition performance, is background clutter. Because of the finite spatial resolution of the SAR system, each gray-scale resolution element in the SAR image is generally composed of a large amount of electromagnetic scattering response from the ocean surface [11]. They produce inhomogeneous, non-stationary and random returns, and generate spiky characteristics in statistics. Thus, the performance of CFAR detectors can be severely degraded in the presence of inhomogeneous and non-stationary clutter. To overcome this problem, a coarse-to-fine approach for ship detection from SAR image based on biparameter CFAR detector is proposed. In the coarse detection stage, PFA is roughly estimated by experience and standard deviation (shape parameter) of the clutter, and target-window is roughly estimated by the radar spatial resolution and the size of region of interest. The detection results, with some false alarms, are achieved by biparameter CFAR and coarse estimation of parameters.

In the fine detection stage, the application of clutter pixel value replacement for modelling the global behaviour of homogeneous and stationary clutter has been proposed in this paper. The detection process is based on the correct parameter estimation and clutter pixel value replacement, without resorting to the choice of proper distribution for the complex statistical characteristics of ocean clutter. Therefore, the detection results, with no false alarms, can be achieved by biparameter CFAR and correct estimation of parameters. Numerical experiments based on real radar ocean clutter data also confirm the effectiveness of the proposed detection method.

4. CONCLUSION

A coarse-to-fine technique for ship detection is developed by using parameter estimation and clutter pixel value replacement. Weibull distribution is a commonly used model for the gray intensity distribution of sea clutter which determines the effect of CFAR detection. The proposed method uses Weibull distribution model to generate radar clutter of stationary distribution. Detection results show that the proposed algorithm is effective in identifying meaningful region of interest and performs quite well on combating the clutter.

We are currently working on extending this paper by studying the clutter reconstruction with the point scattering model of the SAR data acquisition system for the ship detection. Moreover, we will evaluate such assertions from a system engineering viewpoint.

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