Abstract

In ship detection, a key aspect is to keep a low level constant false alarm rate combined with a high detection probability in presence of clutter background, caused by reflections from wave tops on the sea, rain, snow or fog. Generally, the Constant False Alarm Rate (CFAR) algorithm is applied, which is based on the assumption that clutter background can be modeled using a Gaussian distribution, generating a high level of false alarms in presence of non-Gaussian clutter. This problem has been addressed under two independent approaches: Modeling the environment noise (sea clutter) with independent non-Gaussian models or using variations of CFAR detection algorithm. Both approaches provide good results only for specific characteristics of clutter. In this paper we discuss a hybrid approach for target detection that use three probabilistic models of clutter associated to sea state (Gauss, Weibull and K distributions), detection algorithms with adaptive threshold for CFAR, classification algorithms that associate a noise model with a specific CFAR algorithm according to the sea state, and low level morphological operations to generate an image of targets. The goal of this approach is provide an automatic mechanism to associate a clutter model with a specific CFAR algorithm according to sea state in order to obtain radar images without clutter. The proposed detection approach is evaluated by high level simulation. Results are presented and discussed.

Keywords: CFAR algorithm, Sea clutter, Target detections.

1. Introduction

The problem of ship detection by radar echoes, involves the appropriate separation of the sea clutter, caused by the reflection from wave top on the sea, which were considered as noise with Gaussian distribution. Joined to this hypothesis, the use of detection algorithms based in the comparison of noise levels versus a fixed threshold causes a considerable increment of false detections [1]. In the last years, with the utilization of high resolution radars, it became evident that the clutter cannot always be modeled with Gaussian distribution, since the increment in the amplitude of the waves is modeled as peaks in the distribution that surpass the comparison fixed threshold in the detection, causing an excessive number of false alarms. In recent investigations on sea clutter modeling, adaptive models have been used with other distributions such as Weibull, Rayleigh and K [2], which diminish the number of false detections. However, sea clutter constantly changes over time and none of the previous distributions can model it completely. The adaptive models have variable shape parameters that can be adjusted to the existing sea conditions, according to the Beaufort scale^1 and in this way it is possible to associate an adaptive model to a group of sea states.

The detection algorithms have been developed with adaptive threshold in order to maintain a low level constant false alarm rate; such is the case of CFAR algorithms. Several modifications have been proposed to CFAR algorithms that improve their performance to different clutter conditions. Among the main variations of CFAR algorithms are the Cell Averaging CFAR (CA-CFAR), Greatest Off CFAR (GO-CFAR) and Smallest off CFAR (SO-CFAR).

The outputs of the traditional CFAR processor are the detected targets, including false detections. In our approach we include an additional processing stage that uses morphological operations like erosion and

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^1 The Beaufort scale is used as a measure of the wave height, classifying the sea in 10 levels with wave height of 0 feet to 45 feet
dilation, to reduce the false alarms and to produce an image of targets with a minimum quantity of clutter. In this way, we can extend the range of action of CFAR algorithms to the Beaufort scale if the shape parameter in clutter distribution is involved. Generally, CFAR algorithms have been used in combination with just one clutter model at a time. In this proposed approach three clutter models are combined with variants of CFAR and using a statistical analysis of data, the best combination of clutter model and CFAR algorithm for a sea state is selected appropriately.

The content of this paper is as follows: Section 2 describes the related works and results obtained in clutter modeling, CFAR detection and image processing techniques for detection. Section 3 presents the proposed approach for ship detection, combining clutter models with variants of CFAR and morphological operations. Section 4 provides some results obtained with the proposed approach, which are then discussed in section 5. Finally, some conclusions are presented in section 6.

2. Related Work

In this section we present previous work related to clutter models, detection algorithms with CFAR and image processing.

2.1. Sea clutter models

Some of the recent work that has been used as basis for the present work is briefly described in this section. Cowper and Mulgrew [3] carried out a study of the main modeling techniques of clutter, showing the decrease of false alarms when using stochastic models of high resolution like the K distribution. Davidson and Ouchi [4] worked on a numeric analysis of Laplace on the clutter to accelerate the processing time to compute the parameters of the clutter in order to increase the detection probability of the CFAR algorithm. Haykin and Bakker [5] carried out a dynamic nonlinear analysis of the clutter, using models with K distribution and models with chaos theory, which describe in an appropriate way the complex and not lineal dynamics of the sea. The last approach involves a high computational cost, however if we use the models proposed, i.e. K, Weibull and Gaussian, we can apply a combination of them to have a more accurate model of sea behavior.

2.2. CFAR detection

This sections discusses some work relate to target detection. Chong and Zhu [6] proposed the use of a Gaussian model, together with CFAR, using sliding data windows for detection. This approach achieves good results just for the case of sea state with level 0. The authors also propose the use of a model with a K distribution for the clutter in order to obtain good results in complex sea conditions. Drumheller and Lew [7] worked with a processor of false alarms with little sensibility to the thresholding parameters. They used a CFAR modification to predict an appropriate value of threshold, although they report that the modifications are valid only for a K distribution with an interval in their shape parameter. S. Watts in [8] details a study of CFAR algorithms, showing their performance using clutter models with K distribution to estimate the threshold detection, which should be obtained using the statistical analysis of clutter with a normalized distribution. For the proposed approach in our work, we select the type of CFAR sugested in previous works, CA-CFAR, GO-CFAR and SO-CFAR, combined with the three clutter models discussed on section 2.1.

2.3. Radar image

The use of image processing techniques, like erosion and dilation, are commonly used for processing radar images. In this field, S. Kuttikkad and R. Chellopa [9] proposed techniques for detection of targets in synthetic aperture radar images (SAR), using modifications of CFAR algorithms to detect both small and big targets, using non Gaussian models of clutter, mainly using Weibull and K distribution. Lombardo and Sciotti [10] applied image processing techniques as segmentation, erosion, and dilation for ship detection in SAR image of low and high resolution. In this way they solved the problem of uncontrolled increase of false alarms suffered by standard CFAR in non homogeneous images. Kaplan and Murenzi [11] proposed combination of CFAR with parameter estimation using statistical model and fractals, adding image processing applied to SAR images. They show the convenience of to use a combination of statistical model to estimate the CFAR threshold.

Although our approach is not mainly intended for high resolution data, such as those obtained with SAR, we can apply a combination of CFAR and image processing algorithms to reduce the number of false alarms generated by standard CFAR, according to results presented by Lombardo and Sciotti.

3. Hybrid Approach

Our hybrid approach includes three clutter models (Gaussian, Weibull, K) to classify sea states, CFAR
algorithms (CA, GO and SO) to detect and maintain a constant false alarm rate, statistical analysis to associate a clutter model with a CFAR type according to sea state, and low level morphological operations (erosion and dilation) to reduce the false alarms.

The proposed approach begins with the processing a range profile, which is defined as the amplitude of the echoes reflected by the targets for a single transmitted pulse. It is obtained as a function of time and is proportional to the range of targets. The amplitude of a sample in a range profile is called range cell. For this range profile, it is necessary to calculate the mean, variance, standard deviation, correlation coefficient and shape parameter, which are then compared with the parameters of the known models of clutter to select the appropriate CFAR algorithm to the sea state. As a result, a matrix with range cells that represent detected targets with false alarms is obtained. Finally, we can apply image processing techniques like erosion and dilation to the data on the matrix, to generate an image of targets free of clutter. Figure 1 shows the block diagram of the proposed hybrid approach.

3.1. Clutter Models

It has been mentioned that sea clutter is produced by the reflections of the electromagnetic waves on the surface of the sea, but the sea state changes continually over time, which makes complicated to establish a relationship between the clutter and the sea state, since this depends on speed of the wind, waves and capillarity of the waves, and other atmospheric conditions.

A technique of clutter suppression consists on adjusting a comparison threshold according to the level present of clutter. However the problem of this technique is that it rejects the same clutter level in the whole range profile. To incorporate automatic clutter suppression, it is necessary to incorporate an accurate model of the clutter. Because clutter is a random phenomenon, it can be described in probabilistic terms, i.e. by a function of density of probability (pdf) or a distribution of probability [12].

From the literature review, we know that the Weibull, Rayleigh, Gaussian and K distributions of probability are used to describe the behavior of the clutter. The Rayleigh distribution has the pdf shown in equation 1. This distribution produces a set of values with a high mean value, which makes it a good option to describe range cells with high amplitude values.

\[
f(x) \sim \frac{2x}{X_0} \exp\left(-\frac{x^2}{X_0}\right)
\]

Equation 2 shows the Weibull pdf that is an adaptive model that incorporates a shape parameter. The Rayleigh distribution is a special case of the Weibull distribution with shape parameter 2. The mean value of the Weibull distribution varies according to the shape parameter, making possible to describe range cells with values that can represent sea states of 1 to 3 [2].

\[
f(x) = \frac{a}{x^b} \exp \left(-\frac{x^b}{\beta}\right) e^{-\left(\frac{x^b}{\beta}\right)}
\]

The K distribution is a compound distribution, that allows us to model clutter for different sea states. It is used mainly to model high levels of clutter, present in sea state of 4. In the equation 3 their probability density function is shown.

\[
f(x) = \frac{b^\nu}{\Gamma(\nu)} (x^\nu e^{-x}) \times \text{Gamma Function}
\]

Finally, a sea state of 0 that has almost not disturbances can be modeled with a Gaussian distribution [2].

3.2. Adaptive CFAR

The proposed CFAR processor will allow increasing the probability of target detection by maintaining constant the number false alarms. This processor takes a window of data from the range profile. With this data, it determines if the central cell (cell under test) is a target, comparing its value with a threshold. The threshold is obtained as the sum of the mean of neighbor cells and the standard deviation, according to employed pdf, multiplied by a factor, which is
determined by the statistical model of clutter. Equation 4 shows how to calculate the threshold, note that the K factor depends of shape parameter in the distribution.

\[ T = \mu + K\sigma \] (4)

Figure 2 shows the CFAR processor applied to a data window with M values, where the central cell is the cell under test. It is important to notice that on both sides of the cell under test exist guard cells, which are not included on the computing process. The data window slides along the ranges profile to determine if each one of the range samples belongs or not to a target.

In the proposed approach we used three types of CFAR: CA-CFAR, GO-CFAR and SO-CFAR. The basic difference among the variants of CFAR is the way they obtain the mean \( \mu \) that is used to calculate the threshold. Additionally, the input data is normalized to the mean value to maintain uniformity in the data window.

To determine the way of selecting the appropriate model to the clutter type, it is necessary to determine the correlation coefficient, mean and standard deviation of the current range profile. These parameters are compared with the known clutter parameters in order to select the model that best approaches to the calculated values.

The goal of combining a clutter model with a specific CFAR is to obtain the minimum probability of false alarms combined with the maximum probability of detection; this goal is obtained by adapting thresholds to the observed clutter. Figure 3 shows the mechanism employed for detection, according to Neyman Pearson theory [1]. It can be seen the plot of pdf for clutter and targets. The separation of detection and false alarms is delimited by a threshold. The shadowed area in the pdf of targets represents the probability of detection. Note that a tail of the pdf of clutter is also on the shadowed area and represents the false alarms.

3.3. Morphological operations

The results of applying the CFAR processor according to the clutter type are combined in a matrix of detected targets. For this experiment, we used a square matrix of 4096 cells and a probability of false alarm of \( 10^{-4} \), that implies that exist 16777 false alarms, which are translated into isolated pixels or small groups of pixels when they are seen as an image. To eliminate these false targets, low level morphological operations are used. First, an erosion algorithm is applied to the matrix of targets, so that the noise that represent the isolated pixels are eliminated, a dilation algorithm is then applied to emphasize the groups of pixels that represent possible targets.

Erosion and dilation are two fundamental morphological operations. The number of pixels added or removed from the objects in an image depends on the size and shape of the structuring element used to process the image. The data matrix represents the range of targets, therefore the size and shape of the structuring element is very important to prevent the elimination of small targets. To deal with this problem, different sizes of the structuring element are used, according to the scale in which data was acquired. For example if a range profile that represents a range of 1.5 nautical miles is used, a 3x3 matrix is used (figure 4a). Using this matrix, targets with an area not bigger than 1m\(^2\) can be eliminated. For larger distances, the size of the structuring element can be increased (figure 4b).

\[
\begin{bmatrix}
1 & 1 & 1 \\
1 & 1 & 1 \\
1 & 1 & 1
\end{bmatrix}
\]

range < 1.5nm

\[
\begin{bmatrix}
0 & 0 & 0 & 0 \\
0 & 1 & 1 & 0 \\
1 & 1 & 1 & 1 \\
0 & 1 & 1 & 0
\end{bmatrix}
\]

range < 24nm

\[ a) \quad b) \]
4. Results

4.1 Clutter models

To determine a correct distribution for a specific sea state, we have carried out some simulations with samples generated with Weibull, Gaussian and K distributions.

The results shown in figure 5 were obtained using the K distribution. By modifying the shape parameter and mean constant equal to one, data with a high amplitude value were obtained (echoes with high power). This data can be used to represent the high top waves present in sea state of 4.
Figure 6 shows data with Weibull distribution for three values of the shape parameter. The amplitude of data is smaller than the amplitude obtained with the K distribution. This distribution can be used to model sea state with level 2 or 3. Finally, we can use the Gaussian distribution, as shown in Figure 7, to model sea state with levels 0 or 1.

![Figure 6](image6.png)

**Figure 6. Range profile with Weibull distribution.**

### 4.2. Detection in Range profile

For the CFAR processor, the variants of CA, GO and SO were programmed incorporating clutter models. This allows obtaining adaptive thresholds according to the sea state. Figure 8 shows the results obtained when the traditional CA-CFAR with Gaussian model is employed. The figure shows five range profiles together with their corresponding calculated threshold. It can be clearly the large number of false alarms. The range profiles contain real data, obtained when radiating with a pulse transceiver of 10Kw.

![Figure 8](image8.png)

**Figure 8. Threshold obtained with traditional CFAR.**

Figure 9 shows five range profile and their corresponding calculated threshold obtained when applying the algorithm CA-CFAR with normalized data and shape parameter of clutter distribution. We can observe a diminution on the number of false alarms in accordance with those discussed in 3.2.

![Figure 9](image9.png)

**Figure 9. Threshold obtained with the proposed approach.**

### 4.3. Detection in Radar Images

The range profiles shown in figures 8 and 9 are shown in figure 10 as a digital image. Figure 10a shows the original data as seen by a radar display. Figure 10b, 10c and 10d shows the result to applying the CFAR variants algorithms. Figure 10e shows the result of applying the proposed CFAR algorithm that incorporates clutter models. Finally, figure 10f shows the results after processing the image using low level morphological operations. It can be observed that a large number of the false alarms present in figure 10b, 10c, 10d were eliminated from figure 10f, obtaining an image of targets with low level of sea noise. The structuring element used to perform the morphological operations is the one shown in figure 4a.

![Figure 10](image10.png)

**Figure 10. Range profiles as digital image.**

### 5. Discussion

In the aspect of clutter modeling, the results obtained by simulating the different probability distributions show that it is possible to associate a sea state or group
6. Conclusions

Different models of clutter are required in order to characterize the sea state in a precise form. Thus, it is necessary to have some sort of database of models of sea clutter to cover all the possible states of the sea. However, simulations show that the proposed approach that includes just a few models performs satisfactorily. In traditional CFAR with Gaussian clutter models, the normal value of false alarms is $10^{-2}$ or $10^{-3}$ for best conditions. By including variants of the CFAR algorithm and using the clutter models to calculate the detection threshold, the level of false alarms can be reduced to $10^{-4}$. By applying morphological operations it is possible to reduce even more the number of false alarms that CFAR produces.

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References


An analysis of the selected CFAR algorithms shows that by including the shape parameter of the probability distribution associated to the clutter it is possible to increase the detection probability while maintaining a constant number of false alarms.

The results obtained with the proposed detection approach, show that the minimum size of detected targets is restricted by size and shape of structuring element. E.g. a 3x3 matrix represents an area from 0.6m$^2$ in a range of 1.5nm (2.5Km). When the range is increased, the minimum area of detected targets also increases.

Figure 10. Images obtained with the proposed approach.

