Comparative Study of Various CFAR Algorithms for Non-Homogenous Environments

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Abstract. Based on the radar field environment, the detection process is generally based on the adaptive threshold required to detect the received radar cell signal. Many algorithms are used to design this adaptive threshold to satisfy a Constant False Alarm Rate (CFAR) in line with detection criteria in non-homogenous environments. Although CFAR algorithms have increasingly become a vital factor in the detection process, the performance of these algorithms differs according to their treatment of the received radar bins. In cases of targets in a clutter edge and multi-targets, the performance of the GO-, VI-, OSSO- and OSGO-CFAR algorithms are better than the performance of the CA-CFAR algorithm, while the CA-CFAR and OS-CFAR algorithms lose such targets. In this context, the SO-CFAR has a higher $P_{fa}$ than the above algorithms for small targets in a clutter edge. OSSO-, OSGO, VI, and CMLD also have higher $P_{D_S}$ based on their outcomes than the other algorithms in the same $P_{fa}$ in non-homogenous environments. However, CA-CFAR is simpler and has less complexity than the other algorithms. MATLAB 2015b was used to evaluate the performance of these different types of CFAR algorithm.

1. Introduction

A comparison between the received range cell of a radar signal of the specified threshold is an essential step in the detection process in the radar system. Therefore, to maximise detection probability in such processes for a fixed probability of false alarms, a Neyman-Pearson test is used. In this context, the adaptive threshold has a value related to the realistic background cases that can be achieved by means of a constant false alarm rate (CFAR), which contributes to maximising the requirements of the detection probability.

Thus, the CFAR process, which is built into the detection algorithm, is based on

$$X > H_1 \cdot TZ$$

(1)

where

$H_0$ and $H_1$ are the absence and presence of a target, respectively;

$X$ is the test cell value (nonnegative random variable);

$Z$ is the estimated noise power, as a window cell value (nonnegative random variables); and

$T$ is the scaling factor.

The general CFAR detector processor is shown in figure (1) [1]:
Based on the content of leading and lagging windows, the CFAR algorithms are estimated against the background field of operations. To declare the presence or absence of the target, each data sample must be tested. This test is based on a comparison between the value of the CUT and the estimated threshold; if the value of the CUT exceeds that threshold, the processor declares a target at the appropriate range and Doppler bin [2].

In this context, the differences between the CFAR detectors are based on a reference cells processing procedure and scaling factor. The threshold of any CFAR detector can thus be presented in the following form:

\[ V_T = TZ \]  \hspace{1cm} (2)

The relationship between the \( P_{fa} \), threshold and the background variance can also be defined as [3]

\[ P_{fa} = \exp \left( -\frac{V_T^2}{2\sigma^2} \right) \]  \hspace{1cm} (3)

where \( \sigma^2 \) is the background variance.

There are many types of CFAR algorithm, and no single example can satisfy all actual operating conditions, whether these conditions are homogeneous (single target) or non-homogeneous (multiple targets and clutter edge), as seen in figure (2) [4].
Some of the CFAR types are closer to achieving the highest detection levels, however, improving their suitability for the field of radar operations, while others are less appropriate in the same field. This paper thus presents a comparative study of many types of CFAR in nonhomogeneous environments in order to evaluate their performance according to the field of radar operation and related performance.

2. CFAR Algorithms

The CFAR Algorithms are classified according to their treatment of the content of the range cell in processors. Despite the progress made by CFAR algorithms, all these algorithms are based on the same Cell Averaging (CA-CFAR) detector proposed in 1968 by Finn and Johnson [5]. This displayed optimal performance under homogeneous conditions, and it is poor in non-homogeneous conditions [6]. The principal limitation of this basic type is that when the clutter reaches the CUT, at that instant the threshold is not high enough to reject it because this threshold is evaluated based on the low-level noise power; thus, $P_{fa}$ is increased. To overcome this degradation, Hansen and Sawyers [7] presented an adaptive CFAR algorithm that could handle radar detection in a non-homogeneous environment without excessive false alarms due to clutter. This algorithm was based on a comparison between the CUT and the greatest of the two windows (leading and lagging) as selected in the process stage of CFAR processing. This algorithm is called a "greatest of" logic selection (GO-CFAR). A target is declared only if the amplitude of the CUT exceeds the greater of the two windows. Therefore, two independent thresholds are calculated, and the largest one is selected.

$$Z_{GO} = \text{MAX}(Y_1, Y_2)$$

The equations of the threshold are

$$V_T = \frac{T \bar{X}}{2n} = \frac{T \bar{X}Z_{GO}}{2n}$$

where;

$Y_1 = \sum_{i=1}^{n} x_i$, for the leading window;

$Y_2 = \sum_{i=n+1}^{2n} x_i$, for the lagging window;

$n$ is the window size; and

$T$ is the scaling factor.

Thus, the false alarm probability is given as [8]

$$P_{fa} = 2(1 + T)^{-n} - 2 \sum_{i=0}^{n-1} \left( \begin{array}{c} 2n-i-1 \\ i \end{array} \right) \times (2 + T)^{(n+i)}$$

In this context, the detection probability will be significantly affected and degradation will occur where there is interference from multiple targets. In essence, the closely spaced targets can mask each other. Therefore, the smallest Of-CFAR (SO-CFAR) was recommended by Trunk [9], with the threshold equation set as

$$Z_{SO} = \text{MIN}(Y_1, Y_2)$$
However, when the interfering targets exist in both CUT sides as windows and clutter edge, the performance will deteriorate [6,10]. Consequently, to overcome this limitation, a combination of the minimum and maximum Cell Average-CFAR (CMMA-CFAR) detector was proposed in [11] to maintain a higher rate of detection by adjusting the threshold in a time-based manner proportional to noise intensity.

For more accurate operation in multi-target environments, the Order Statistic (OS)-CFAR processor has also been presented. Here, the noise power estimation is based on the selection of the $K$th largest cell in a reference sliding window of size $N$ [12]. Minimal loss is thus achieved when the $K = \frac{3}{4}N$, and the probability of detection, $P_D$, is

$$P_D = \prod_{i=0}^{k-1} \frac{N-i}{N-i+n+1}$$

(8)

where the scaling factor is

$$T = (P_{FA})^{-1/K} - 1$$

(9)

and the threshold value is

$$Z = T \times X_{(k)}$$

(10)

However, there are two important limitations to OS-CFAR; these are an excessive false alarm rate at clutter edges, and a longer processing time [13]. Therefore, to reduce the processing time and improve the performance of the CFAR processor, two modifications have been proposed for OS-CFAR by Antonio R. Elias [14]. The first is the Ordered Statistic Greatest of CFAR (OSGO) for clutter edge environments, while the second is the Ordered Statistic Smallest of CFAR (OSSO), which is suitable for clutter edge and multi-target environments. In this context, the processing time for OS-CFAR is required to be at least $N (N - 1)/2d$ times the calculation required, while the sorting time can be shortened to $N \log 2(N)$ by using the quick sorting method [15]. In the case of the number of interfering targets being unknown, the generalised censored mean level detector (GCML-CFAR) offers robust performance, as it censors targets samples after determining their number [16]; however, performance may deteriorate in the clutter-edge environment. In this context, to overcome the degradation of GCML-CFAR caused by clutter edges and multiple target situations, the GTL-CMLD detector was presented by [17]. Robust performance is achieved in the presence of both interfering targets and clutter power transitions using this detector, and it is worth mentioning that this good performance is continuous as long as the interfering targets are in both sliding windows (leading and lagging). The sliding windows do affect the performance, in that a higher number of cells in the sliding windows tend to produce better performance. [3]. In this context, to reduce computation complexity, [15] presented an ADOS algorithm which depends on the mean of the decision condition instead of the mean of the iterative data only in the front part before the CUT; this avoids computing the mean over the whole, potentially large, data volume. The condition for stopping iterations can also be obtained by finding the maximum or minimum value of the remaining data after stopping iterations, which decreases the number of iterations required. Hence, this method can further improve computation speed.

3. **Results and Discussion**

To monitor the response of each CFAR's algorithms within the non-homogenous field of operation, non-homogenous received signals (clutter edge and multi-target) were entered into each type of CFAR; the threshold behaviours according to that input signal are shown in figure 3.
It is clear from this figure that the OSGO-, VI-, and CMLD-CFAR algorithms outperform others in their treatment of nonhomogeneous environments, based on their behaviors against the variation of the input signal. The response rate of the OSGO and VI outperforms against the other CFAR algorithm by 5 to 7 dB in a clutter edge environment, while in multi-target, the GO, OSGO, and VI offer advancements of 2 to 5 dB. In this context, the OSSO and OS cannot separate the closest targets.

According to the observed behaviors of the CFAR types, their \( P_D \)s have been calculated as shown in figure 4; this figure represents the probability of detection (\( P_D \)) against signal to noise ratio. The overperformance of the OS-CFAR types and VI- types is understandable, and in this context, OS-types have been stepped, as the OSSO and OSGO lines show in figure 4; simultaneously, the SO-, OS-CFAR types overperform at low SNR.

A summarisation of the CFAR-types, as given in Table 1, clarifies the response of CFAR types in multi-target and clutter edge field of operation.
**Table 1.** The summaries of the various CFAR response

| CFAR Type | Homogeneity | Multiple target | Clutter edge |
|-----------|-------------|-----------------|--------------|
| CA        | Homogenous  | Poor            | Poor         |
|           | Non-Homogenous | Poor in detect closely spaced targets | Poor |
| GO        | Homogenous  | Multiple targets (detect closely spaced targets) | Poor |
| SO        | Non-Homogenous | Multiple targets (detect closely spaced targets) | Poor |
| VI        | Homogenous  | Multiple targets best in multiple targets | Good         |
| CMLD      | Non-Homogenous | Multiple targets best in multiple targets | Good |
| OSGO&OSSO | (requires only half the processing time of OS) | Non-Homogenous | Good |

(If there are simultaneously one or more clutter edges and a multiple target situation, the performance of GCML-CFAR will be degraded)

4. **Conclusion**

From the above evaluation, it has become clear that the OS types VI, and CMLD have higher P_D levels according to their replies than other algorithms in same P_Fa and non-homogenous environments; similarly, the SO-CFAR has a higher P_Fa than the above algorithms for small targets in clutter edge environments. The P_D of the OS overperforms compared to other OS type algorithms by 0.75 at SNR=5dB, up to 0.1 at 20 dB. Therefore, for clutter or multi-target situations, the OS and VI types offer optimal performance.

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