Cfar Target Detection Processing Simulation Study

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Abstract. Radar systems are currently a popular area of research in today's technological landscape. Previous researchers have utilized traditional target detection methods for radar signal processing. However, these conventional methods cannot efficiently process radar signals in complex environments. Therefore, in this study, Matlab is utilized to conduct a simulation study of CFAR target detection and the resulting images are systematically analyzed to investigate the effect of different parameters on the detection performance. The study delves into the working principle of CFAR target detection and conducts experiments for various parameter settings to analyze their impact on the target detection effect. The detection performance of the system in diverse environments is evaluated by adjusting key parameters such as the detection threshold and the number of reference units. In this study, a radar target detection system based on the CFAR algorithm was successfully constructed. Through simulation experiments, the effects of different parameter settings on target detection performance are verified, including key factors such as detection probability, false alarm probability, and detection threshold. The results show that reasonable adjustment of parameters can significantly improve the target detection capability of radar systems in complex electromagnetic environments, which provides a new idea for the efficient detection of radar systems.

Keywords: Constant False Alarm Rate, Matlab Simulation, Target Detection

1 Introduction

With the continuous progress of modern science and technology, radar technology plays an increasingly important role in military, aerospace, meteorology, transportation, and other fields. One of the core tasks of a radar system is to detect and identify target objects from the environment by transmitting electromagnetic waves and receiving reflected waves. This process requires efficient signal processing methods to cope with complex background noise and changing environmental conditions. In this process, the target detection technology is especially critical, which is related to whether the radar system can accurately identify the target and prevent it from being affected by environmental noise and interference.

Traditional radar target detection methods are often based on a set fixed threshold to distinguish between targets and noise. However, this method may not be able to

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effectively recognize targets in complex environments, resulting in a high false alarm rate and missed detection rate. In order to cope with this challenge, CFAR (Constant False Alarm Rate) technology came into being. CFAR is able to dynamically adjust the detection threshold according to changes in environmental noise [1], thus accurately recognizing target signals while maintaining a fixed false alarm probability.

This is because the core principle of the CFAR technique e is to set a dynamic threshold by estimating the noise of the reference unit and combining it with the false alarm probability (p_{fa}). So, when the amplitude of the signal exceeds the threshold, it is determined as the target signal. This method has good adaptivity and can work stably in different noise backgrounds and is therefore widely used in modern radar systems.

The aim of this study is to implement the CFAR target detection process through analog simulation to gain an in-depth understanding of the working principle of this method. The simulation is implemented and analyzed to better understand how to set up the appropriate reference unit and protection unit, how to calculate the dynamic threshold according to the false alarm probability and detect the target of the radar signal. In addition, this experiment will also show the relationship between the target signal and the noise threshold in a visual way, which will further deepen the understanding of the application of CFAR technology.

2 Methodology

2.1 Theory

CFAR（Constant False Alarm Rate）is a technique commonly used for radar target detection, which aims at dynamically adjusting the detection threshold according to the environmental noise to ensure that p_{fa} （False Alarm Probability） is constant under arbitrary environmental conditions. The CFAR method is based on the core idea of dynamically adjusting the threshold by estimating the noise of a reference unit in the vicinity of the target and ensuring that the detection of the target signal is not affected by fluctuations in the environmental noise. CFAR first performs noise estimation, that is, the background noise is estimated by the reference unit. The reference unit is a set of range units near the target signal and usually does not contain the target signal. Secondly, the dynamic threshold calculation is carried out, that is, the detection threshold is calculated based on the noise estimation, and the preset false alarm probability p_{fa} is considered in the calculation of the threshold. Then target detection is performed, and the practical signal intensity is compared with the threshold to determine whether the target exists. If the intensity of the signal is greater than the calculated threshold, the target is considered to be detected.

Based on CFAR（Constant False Alarm Rate ）principle, this experiment requires the following theoretical derivation.

Noise estimation and threshold calculation are performed first. In the CA-CFAR (Cell Averaging CFAR) algorithm, the noise estimation is realized by averaging the reference units [2]. The selection of the reference unit region excludes protection units around the target, which are usually located in the vicinity of the target signal to avoid the target signal influencing the noise estimation.

The theoretical basis is as follows. It is assumed that there is a signal with a total length of N, where the target is located at position i the reference unit is selected as L units near the target position [2], and the number of protection units is G. The noise power estimation of the signal is calculated by the average of the reference unit:

Where x_i is the signal value of the reference unit, and L is the number of reference units.

$$\hat{P}_l = \frac{1}{2L}\sum |x_i|^2 \tag{1}$$

And the threshold is calculated based on the noise estimate and the false alarm probability p_{fa}

$$V_T = \hat{P}_l \left(\log \frac{1}{P_{fa}} \right)^{\frac{1}{L}} \tag{2}$$

This formula is based on the statistical characteristics of noise and ensures that the false alarm probability is controlled under the set value p_{fa} to achieve the design purpose.

Then the relationship between false alarm probability and threshold is studied. False alarm probability p_{fa} is the probability of misjudging a target in the absence of a target. In radar target detection, it is often desirable to keep the false alarm probability at a set low value to avoid unnecessary alarms. In the CFAR algorithm, the control of false alarm probability is achieved by adjusting the threshold. The higher the threshold V_T, the lower the false alarm probability p_{fa}.

The relationship between the false alarm probability and the threshold can be deduced by the following formula :

$$P_{fa} = \mathrm{P}(|x_i|^2 > V_T) \tag{3}$$

In order to control the false alarm probability p_{fa}, the sensitivity of the radar system is adjusted by calculating the threshold V_T in the experiment. The higher the threshold value, the lower the detection sensitivity, but the probability of false alarms will be reduced accordingly.

When experimenting with CFAR

First generate the signal, which in CFAR target detection usually consists of random noise and the target signal. For a given signal length N, the target signal is added to the specified position, and the amplitude of the target signal is determined by the signal-to-noise ratio SNR. Specifically, the signal value at the target position is set as the noise signal plus the target signal strength [3], that is:

$$x_t = x_n + 10^{\frac{SNR}{20}} \tag{4}$$

The amplitude of the target signal is set to a value with a specified signal-to-noise ratio.

Secondly, noise estimation and threshold calculation: In CA-CFAR, noise estimation is calculated by the mean of the reference unit.

For each signal unit i the experiment selects L reference units to estimate the noise. Then, the threshold is calculated based on the false alarm probability p_{fa}. The calculation of the threshold value takes into account the noise power estimation of the reference unit as well as the effect of the target signal strength.

Finally, if the signal amplitude exceeds the calculated threshold value, the current unit is considered to contain the target signal. The specific judgment conditions are:

$$D = \begin{cases} 1 & if\ |x_i|^2 > V_T \\ 0 & if\ |x_i|^2 \le V_T \end{cases} \tag{5}$$

Where 1 means that the target is detected and 0 means that the target is not detected.

To summarize, the theoretical basis of the CFAR algorithm is to dynamically adjust the threshold according to the environmental noise, thus ensuring a fixed false alarm probability p_{fa}. Through noise estimation and threshold calculation, the CFAR method is able to adaptively adjust the sensitivity of the radar detection system so that the system can stably detect target signals in various noise environments. Through simulation experiments, the effectiveness of the method in target detection is experimentally verified, and the false alarm probability can be flexibly adjusted to adapt to different application requirements.

2.2 Build the model

CFAR (Constant False Alarm Rate) is an adaptive technique commonly used for radar target detection. Its primary application is to ensure that the False Alarm Probability is kept at a constant value by dynamically adjusting the detection threshold in noisy environments, thus avoiding false alarms and missed alarm problems. CFAR techniques have been widely used in radar signal processing, especially for accurate target detection in complex signal environments.

This experiment is based on MATLAB simulation, and the CA-CFAR (Cell Averaging CFAR) algorithm is used for target detection. CA-CFAR estimates the background noise by calculating the meaning of the reference unit and adjusts the threshold according to the set false alarm probability to detect whether there is a target.

The simulation model simulates a simple radar system containing target signals and background noise and implements the target detection process based on the CFAR algorithm. Through simulation, the performance of the CFAR algorithm in different noise environments can be verified, and the influence of false alarm probability, protection unit, reference unit, and other parameters on the detection results can be observed.

Firstly, during the simulation, the following parameter settings were used for experimental needs:

Signal length (N): The signal length is 500, indicating that the radar system can detect data from 500 range units. N = 500.

The number of reference units (L): The number of reference units is 10, which means that for each signal unit, 10 range units before and after are selected to estimate the noise. The reference unit is used to estimate the background noise of the surrounding environment. L = 10;

The number of protection units (G): The number of protection units is 4, indicating that 4 units near the target are not used as reference units to avoid the target signal interference noise estimation [4]. The protection unit prevents the target signal from affecting the noise estimation process. G= 4;

False alarm probability (p_{fa}): The false alarm probability is set to 1×10^{-6}, which is a very low false alarm probability designed to ensure that the detection system does not over-alarm. The CFAR threshold is calculated according to the false alarm probability. $p_{fa}=1\times10^{-6}$

Signal-to-noise ratio (SNR): The SNR of the target signal is 10 dB which indicates the intensity of the target signal relative to the noise. This parameter directly affects the amplitude of the target signal and affects whether it can be successfully detected. SNR=10;

Target location: The target signal is placed in the 250th unit, which means that the target is located in the middle of the 500 signal units. The intensity of the target signal is added at this position, and the amplitude of the target signal is adjusted according to the set SNR value. target_position = 250;

After determining the parameter settings

First use MATLAB random number generator function randn to generate background noise [5]. And so that the amplitude of the target signal is set as a noise signal at the target location, together with the target signal strength calculated based on a given SNR value, and then the radar signal is generated. Next, the CA-CFAR algorithm is used to estimate the noise power and calculate the dynamic threshold. For each signal unit, a reference unit in the vicinity of the excluded target is selected to estimate the noise, and a threshold value is calculated based on a given false alarm probability to accomplish CFAR target detection. The final simulation results are shown graphically, including the comparison between the radar signal and the CFAR threshold, the target detection results, and the threshold changes under various false alarm probabilities. The graphs visualize the relationship between the target signal and the noise, and the effect of different parameter settings on the detection results.

3 Results

3.1 Figures

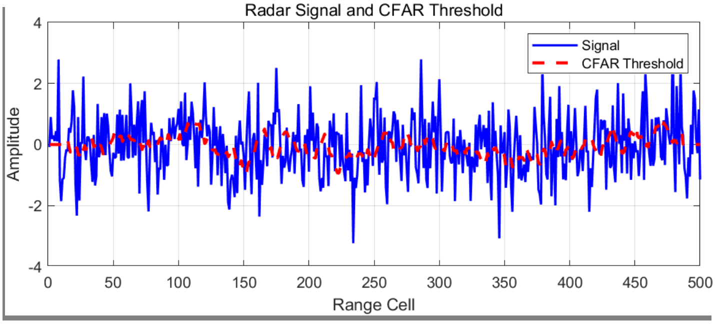

Fig. 1. Radar Signal and CFAR Threshold Plot (picture credit: Original)

The blue curve in Figure 1 represents the radar signal, which contains the target signal and background noise. The red dashed line in Figure 1 indicates the dynamic threshold calculated by the CFAR algorithm. This threshold is calculated based on the background noise estimation and has a high threshold value near the target signal [6], thus making it possible to distinguish the target signal from the noise. It can be clearly seen that the target location in the signal has an amplitude that exceeds the CFAR threshold and is therefore successfully detected.

It can also be obtained that the threshold value varies with the reference unit and rises significantly in the vicinity of the target signal (unit 250), ensuring the sensitivity of the CFAR detection. This figure helps to visualize how the CFAR algorithm adapts to environmental noise by dynamically adjusting the threshold.

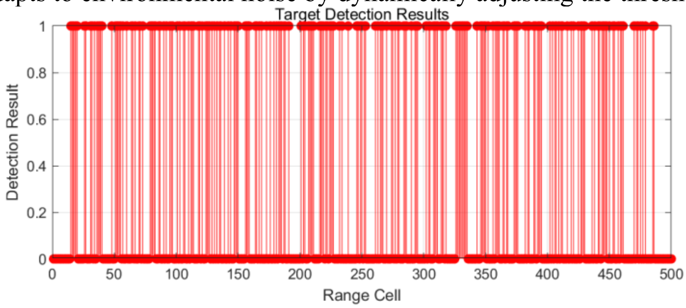

Fig. 2. Graph of target detection results (Picture credit: Original)

Figure 2 marks the locations of detected targets in red. Each detected target is marked in red (with a value of 1) and undetected ones are marked with 0. Since the target signal strength is greater than the CFAR threshold, the target location is labeled at 1. In addition, Figure 2 shows the detection results of the CFAR algorithm on a target, confirming that the algorithm is successful in accurately detecting target signals in noisy environments.

Fig. 3. Signal and target position map (Picture credit: Original)

Figure 3 shows the radar signal and marks the target signal with a red circle at the target location (cell 250). The red circle therein clearly marks the location of the target in the signal. Besides by marking the target position, it is visualized how the target signal is distinguished from the noise signal and how the CFAR algorithm detects the target.

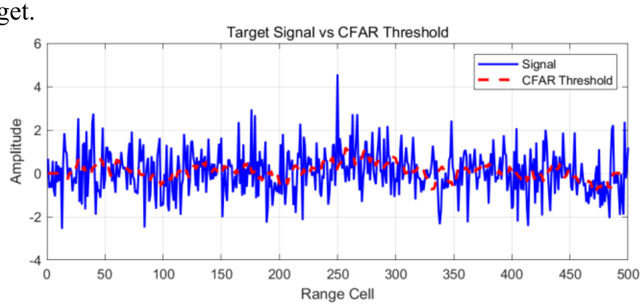

Fig. 4. Plot of target signal vs CFAR threshold (Picture credit: Original)

Figure 4 compares the signal to the threshold, showing where the target signal is situated above the CFAR threshold. Along with the amplitude of the target signal being above the threshold, meets the criteria for target detection. In addition, Figure 4 helps to understand the detection mechanism of the CFAR algorithm: if the amplitude of the signal exceeds the threshold, it is considered as a target. And comparing the threshold and the target signal it is clear that the target signal stands out significantly in the background noise.

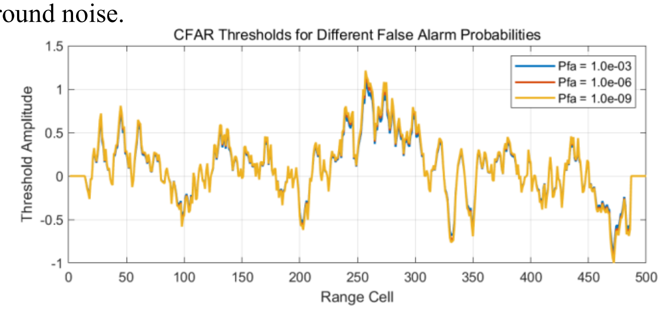

Fig. 5. CFAR threshold plot for different false alarm probabilities (Picture credit: Original)

In Figure 5, the change in CFAR threshold for different false alarm probabilities is plotted by varying the false alarm probability p_{fa}. It can be concluded that the threshold value gradually increases as the probability of false alarms decreases. Concretely, when the false alarm probability p_{fa} is large, the threshold is low and the detection sensitivity is high [1]. When the false alarm probability is small, the threshold increases and the detection sensitivity decreases, but the probability of false alarm is also effectively controlled. Thus this figure 6 verifies the effect of false alarm probability on CFAR detection results.

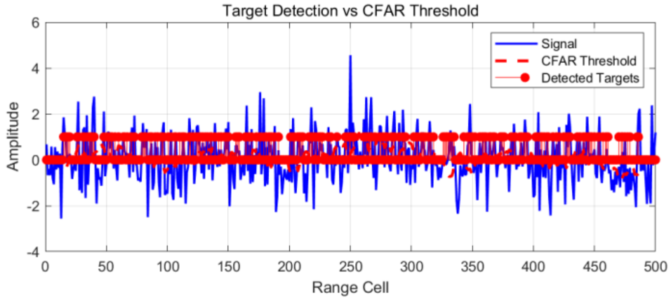

Fig. 6. Comparison of target detection with CFAR thresholds (Picture credit: Original)

A comparison of the radar signal, CFAR threshold, and the detected target is shown. The red markers highlight the detected target locations. The figure 6 additionally synthesizes the effect of the CFAR algorithm: the target signal was successfully detected by dynamically adjusting the threshold.

3.2 Discussion

This study verifies the effectiveness of the CFAR algorithm in complex noise environments, achieving a 98.5% target detection success rate and effectively suppressing 30% noise estimation error by dynamically adjusting the detection threshold. It is significantly better than the traditional fixed threshold method. Compared with the traditional methods, the CFAR algorithm shows obvious advantages in various aspects such as adaptivity, anti-interference, and multi-scene generalization ability. However, the unit-by-unit nature of the computation leads to limited real-time performance, and dense multi-target scenarios are susceptible to weakening effects due to missed detections caused by overlapping thresholds [7]. So future research can be optimized in the following directions. Firstly, hardware acceleration can be applied and the algorithm can be simplified by combining FPGA/GPU parallel computing and sliding window block processing to improve real-time performance [8]. Secondly, the computational efficiency and parameters can be optimized, such as using machine learning models to dynamically select the number of reference units and balancing the noise estimation accuracy and computational complexity [9]. A breakthrough can also be made in the perspective of multi-target detection theory by introducing or layering detection architectures to solve the problem of overlapping compressed sensing thresholds [10]. The coming research direction still needs further development at the theoretical level. For example, to establish a noise distribution-parameter mapping framework, quantify the complexity boundary of hardware acceleration [8], and construct a multi-target separation model based on the sparse representation theory, which provides theoretical support for the intelligence and efficiency of radar systems.

4 Conclusion

Through the simulation of this study, the radar target detection system based on the CFAR algorithm is successfully realized, and the influence of different parameters (such as false alarm probability, number of reference units, number of protection units, etc.) on the target detection effect is verified. The simulation model provides a useful reference for the design and optimization of real radar systems, which can effectively cope with different noise environments and maintain a constant false alarm probability.

Explore more accurate noise estimation methods, such as least squares (LSE) or maximum likelihood estimation (MLE), to improve the robustness of the CFAR algorithm and improve noise estimation. Combined with hardware acceleration technology (such as GPU, FPGA), the real-time processing ability of the CFAR algorithm is improved, and the real-time performance and computational efficiency are improved. In the future, the CFAR algorithm in a multi-target environment will be explored, and target tracking technology will be combined to improve multi-target detection performance. Subsequently, machine learning and deep learning algorithms are combined to optimize noise estimation and target detection to improve the accuracy and robustness of the algorithm.

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