Multi-target CFAR Detection of a Digital Phased Array Radar System

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Abstract. As the core of a digital phased array radar system, a radar signal processing environment can be perfected by exploring the constant false alarm rate (CFAR) detection technology. One typical combination is selected to construct the multi-target radar echo signal by considering that its component signals have many types, and the simulated signal processed by moving target detection (MTD) module serves as the input of the CFAR detection module. The mean level (ML) and ordered statistics (OS) CFAR detectors are analyzed theoretically and simulated. Simulation results indicate that, all the true targets are validated while keeping the false alarm rate constant, but some false targets are introduced by using the smallest of (SO) and OS CFAR detectors. Based on the built radar signal generation and processing environments, a graphical user interface (GUI) of MATLAB will be developed to reveal the detected multi-targets on the radar search interface.

1. Introduction
As we know, performance evaluation of a radar system is significantly important in practical applications. However, the evaluation implemented with traditional methods becomes more difficult nowadays, and the semi-physical or all-digital simulation method can be an alternative way to accomplish design and evaluation of the radar system. As a development trend of modern radars, the phased array radar technology has been attracting attention of many countries in the past years [1-2]. For a digital phased array radar system, it is necessary to construct the signal generation and processing environments, with the purpose to build a radar simulation GUI.

In the radar signal processing environment, the CFAR detection technology plays an important role, but it was not investigated in [3] due to the space limitation. A number of studies were done on devising various CFAR detectors to validate the true targets. Zhang et al. explored new methods to elevate the target-to-clutter ratio by using full polarimetric AT-INSAR, and three novel detectors that could achieve CFAR detection were put forward [4]. Zhou et al. proposed a modified cell averaging CFAR detector based on the Grubbs criterion for target detection in non-homogeneous background, and the CFAR property with respect to the distribution parameter in exponential-distributed background was verified via Monte Carlo simulations [5]. Wang et al. studied the target detection problem in system-dependent clutter background, and three detectors with the CFAR feature were designed by using the generalized likelihood ratio, Rao and Wald tests [6]. It is found that, most of previous researchers focused on investigating the CFAR detection technology, and few of them constructed a digital phased array radar system by integrating all the signal generation and processing technologies.

In this paper, the radar echo signal is processed further by a new MTD method to illustrate the multi-target positive and negative velocity correctly. And the CFAR detection technology is
investigated to perfect the radar signal processing environment. Typically, ML and OS CFAR detectors are clarified and simulated in detail.

2. Moving Target Detection

We structured an array antenna element and a radar signal generation environment in [7], which could model and simulate radar transmission signals, radar internal noise, clutter and jamming signals, and these signals were combined linearly to generate the radar echo signal. Then we established a radar signal processing environment to measure multi-target range and velocity information in [3], which adopted pulse compression (PC), moving target indication (MTI) and MTD technologies to process the radar echo signal.

Considering that there are many kinds of clutter and jamming signals, one representative combination is chosen to generate multi-target radar echo signals in this paper. The combination is radar transmission signal, Gaussian white noise, Rayleigh distribution clutter and noise amplitude modulated jamming [7]. And the frequency domain method is more desirable for the PC effect than the time domain method; multi-target range information can be measured from the MTI result after using a double delay canceller; a new MTD method is proposed to convey the positive and negative velocity inerrably, with multi-target range and velocity measured simultaneously, as shown in Figure 1 [3]. And the Findpeaks function of MATLAB is used twice to measure multi-target range and velocity information. The measure results of multi-target range and velocity from MTD are listed in Table 1.

By comparing with the initial target range, the existing errors caused by Doppler frequency shift are small, in the order of $10^{-4}$ to $10^{-3}$. Also, the error magnitude is proportional to the moving velocity. Meanwhile, there is a constant error at 0.042 in comparison with the initial velocity, and the reason is that using the fast Fourier transform (FFT) is inevitable to cause spectrum leakage and picket fence effect with truncation and discreteness in signal collection, resulting in obvious measure errors. Therefore, the MTD result with the proposed method is leveraged as the input of CFAR detection.

![MTD result with the proposed method.](image)

Table 1. Comparison of Multi-target Motion Parameters.

| Target | Range (m)   | Velocity (m/s)   |
|--------|-------------|------------------|
|        | Initial    | MTD              | Initial    | MTD              |
| True 1 | 15000      | 15015            | 300        | 312.500          |
| True 2 | 20000      | 20010            | -100       | -104.167         |
| True 3 | 13000      | 13005            | -200       | -208.333         |

3. Constant False Alarm Rate

To detect target echo signals in a strong jamming environment, both specific signal-to-noise ratio and CFAR processing are indispensable. The CFAR detection technology aims at offering a detection
threshold to avoid the effect of noise and jamming variations, enabling the targets to have a constant false alarm probability. In this paper, two classic CFAR detection methods will be studied and emulated. Actually, they are the ML and OS CFAR detectors.

3.1. ML CFAR Detector

The basic feature of ML CFAR detection technology is averaging the clutter power around targets, to estimate the background clutter power [6,8-10]. ML CFAR can be classified as cell average (CA)-CFAR, greatest of (GO)-CFAR, and smallest of (SO)-CFAR, etc. Figure 2 shows the block diagram of ML CFAR detectors. It can be seen that, the detected unit \( x_d \) locates in the middle, and \( D \) represents its power, with the protection units flanking it. \( x_i (i=1,...,n) \) and \( y_i (i=1,...,n) \) are the front and rear reference units of the detected unit, and \( n \) represents the number of sliding window reference units. In other words, the total length \( N \) of reference sliding windows is \( 2n \). \( X \) and \( Y \) denote estimations of the clutter intensity of the bilateral reference windows. The decision criterion can be induced as:

\[
\begin{align*}
    & D \geq T Z \Rightarrow H_1, \text{ A Target exists} \\
    & D < T Z \Rightarrow H_0, \text{ No target exists}
\end{align*}
\]  

(1)

where \( Z \) is sum of the background clutter power around targets, \( T \) is the threshold factor, and \( S \) is the resulting threshold.

![Figure 2. Block diagram of the ML CFAR detector.](image)

3.1.1. CA-CFAR detector. Estimate of the ground clutter power level of CA-CFAR can be obtained by averaging all the reference units, that is

\[
Z = X + Y = \sum_{i=1}^{n} x_i + \sum_{i=1}^{n} y_i
\]

(2)

where \( Z \) is estimate of the total background clutter power. After a series of theoretical derivation, the detection probability of CA-CFAR detector is

\[
P_{fa,CA} = (1 + T)^{-N}
\]

(3)

Since \( P_{fa,GO} \) is given, \( T \) can be resolved by converting the equation (3):

\[
T = (P_{fa,CA})^{\frac{1}{N}} - 1
\]

(4)

Seen from the equation (4), \( T \) is not correlated with the variable background power, but only with the constants \( P_{fa,GO} \) and \( N \), indicating the CA-CFAR detection method satisfies the requirement of constant false alarm. Therefore, the ultimate CA-CFAR threshold \( S \) is determined by multiplying \( T \) with \( Z \).
3.1.2. **GO-CFAR detector.** In a clutter edge environment, the GO-CFAR detector is able to exhibit a good performance. As a member of ML CFAR detectors, the GO-CFAR detector regards the larger power of the front and rear sliding windows to be estimate of the background clutter power, which can be expressed as:

\[ Z = \max(X, Y) = \max\left(\sum_{i=1}^{n} x_i, \sum_{i=1}^{n} y_i\right) \]  \hspace{1cm} (5)

The false alarm probability of GO-CFAR detector can be derived as:

\[ P_{fa, GO} = 2(1+T)^{-n} - 2\sum_{i=0}^{n-1}\left(\frac{n+i-1}{i}\right)(2+T)^{-(n+i)} \]  \hspace{1cm} (6)

Equation (6) shows that T is a constant only determined by \( P_{fa, GO} \) and \( n \).

3.1.3. **SO-CFAR detector.** Under the condition that multiple interference targets exist in the unilateral sliding windows, a SO-CFAR processing method can be employed to improve the detection performance, and reduce the interference of other targets with the detected unit. Contrary to GO-CFAR, the SO-CFAR detector treats the smaller power of the bilateral sliding windows as estimate of the total clutter power:

\[ Z = \min(X, Y) = \min\left(\sum_{i=1}^{n} x_i, \sum_{i=1}^{n} y_i\right) \]  \hspace{1cm} (7)

In homogeneous clutter background, the false alarm probability of SO-CFAR detector can be deduced as:

\[ P_{fa, SO} = 2\sum_{i=0}^{n-1}\left(\frac{n+i-1}{i}\right)(2+T)^{-(n+i)} \]  \hspace{1cm} (8)

3.2. **OS CFAR Detector**

By sorting sample units in the bilateral reference windows, the OS CFAR detector can achieve a good performance in both the multi-target and homogeneous environments. The essence of OS CFAR detectors is sorting the reference units from small to large [10-12]. The basic model of an OS CFAR detector is illustrated in Figure 3, in which \( x_d \) is the detected unit, \( x_i \) \((i=1,\ldots,2n)\) is the reference unit.

![Figure 3](image)

**Figure 3.** Block diagram of the OS-CFAR detector.

The OS-CFAR detector sorts the reference units in sliding windows by power at first, that is:

\[ x_{(1)} \leq x_{(2)} \leq \cdots \leq x_{(2n)} \]  \hspace{1cm} (9)

Then, the \( k \)-th unit \( x_{(k)} \) is utilized as estimate of the background clutter power \( Z \):

\[ Z = x_{(k)} \]  \hspace{1cm} (10)
Eventually, the false alarm probability of OS-CFAR detector in homogeneous clutter background can be written as:

\[ P_{fa,OS} = k \left( \frac{2n}{k} \right) \frac{\Gamma(2n-k+1+T)\Gamma(k)}{\Gamma(2n+T+1)} \]  

(11)

![Graphs showing the result after MTD processing for CA-CFAR, GO-CFAR, SO-CFAR, and OS-CFAR detectors.](image)

**Figure 4.** CFAR detection processing results.

**Table 2. Measurement Results From CFAR Detection.**

| Range (m) | CA-CFAR | GO-CFAR | SO-CFAR | OS-CFAR | Target Attribute |
|-----------|---------|---------|---------|---------|------------------|
| —         | —       | —       | 30      | —       | False            |
| —         | —       | —       | 11625   | —       | False            |
| 13005     | 13005   | 13005   | 13005   | —       | False            |
| 15015     | 15015   | 15015   | 15015   | —       | False            |
| 20010     | 20010   | 20010   | 20010   | —       | True             |
| —         | —       | 22890   | —       | —       | False            |
| —         | —       | 25185   | 25185   | —       | False            |
| —         | —       | 26415   | —       | —       | False            |
| —         | —       | 28095   | —       | —       | False            |

Simulation results after using ML and OS CFAR detector are shown in Figure 4. Note that, all the true targets are validated with the false alarm rate kept constant, whereas certain false targets are introduced by using the SO-CFAR detector, and one false target introduced by using the OS-CFAR detector. Exact multi-target range values are worked out by using the Findpeaks function from Figure 4, and measurement results of these explored CFAR detectors are listed in Table 2 for comparison. It is apparent that, CA-CFAR and GO-CFAR detectors perform fairly well, but the SO-CFAR detector is not a good choice here.
4. Conclusions
In this paper, ML and OS CFAR detectors are analyzed theoretically and simulated to perfect the radar signal processing environment. In the future, a MATLAB GUI will be developed for the phased array radar system, with the phased array antenna element, radar signal generation and processing environments all integrated. When operating the radar simulation system, the detected targets will be revealed on the radar search interface in real time. In addition, simulation results from the digital radar system should be compared with the practical applications. It is only in this way that the radar simulation system would be desirable ultimately.

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