CFAR DETECTOR MODELS IN RECEIVER OF THE SOFTWARE DEFINED RADAR

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Abstract: In this paper we describe software models of CA-CFAR, OS-CFAR and the TM-CFAR detectors in the receiver of the software defined radar. A comparative analysis of these CFAR detector models in terms of detection of radar targets in conditions of real clutter is performed. Software models of CFAR detector are implemented in MATLAB.

Key words: CFAR, software radar, target, real clutter.

1. INTRODUCTION

Radars always work in an environment where there are different sources of noise, such as unwanted reflections from the ground, clouds etc. In addition, there are unwanted signals from other radiation sources, which can fully occupy the display of radar and make targets very difficult to sight. Because mentioned noisy signals are nonstationary, it must be used such a detector that has a feature that automatically adjusts its sensitivity to the intensity of interference variation. In this way, false alarm probability is held constant. Detector with this feature is the CFAR (Constant False Alarm Rate) processor. Increasing the size of the window of detection reduces the losses in signal-noise ratio and improves sensitivity of the detector. In this case, the probability of false alarms is held constant by changing the scaling factor of the detection threshold.

The goal of this paper is comparative analysis of below described software models of CA-CFAR (Cell Averaging CFAR), OS-CFAR (Ordered Statistic CFAR) and the TM-CFAR (Trimmed Mean CFAR) detector because their application in developed software model of signal processing blocks of a conventional radar receiver presented in [5], [6] and [7] to improve its characteristics in terms of detection of different types of targets. An important motive for work on this problem is implementation of new features to an existing radar system.

The first part of the paper briefly describes the block for signal processing of the conventional radar in which the acquisition of real clutter is performed and mathematical models of CA-CFAR, OS-CFAR and the TM-CFAR detectors.

The second part of the paper presents the simulation results obtained by processing the signal in the projected radar receiver functional blocks.

2. BLOCK FOR SIGNAL PROCESSING

Radar, which receiver is modeled by software, operates in the C-band frequency range and is designed for detection and tracking of low-altitude targets. It is a pulse Doppler radar based on an outdated digital signal processing technology. Pulse repetition frequency is variable and signal carrier frequency too. Target speed is not measured but estimated by tracking circuit. Detected targets are previewed on a panoramic CRT display. Display refresh time is one second. Picture 1 shows the block for signal processing.

Block diagram of the realized software radar receiver (SRR), which is presented in detail in [5] is shown in picture 2. The names of the blocks and their order generally agree with the original block scheme of the used radar. The advantages of the software implementation of a radar receiver relative to the hardware implementation are its adaptability in terms of changes in signal processing algorithms in existing functional blocks, possibility of easy implementation of new blocks with new features and less expensive maintenance. This paper analyzes the operation of various types of CFAR processors and their impact on the detection of radar signals.
3. MATHEMATICS MODEL OF CFAR

CFAR (Constant False Alarm Rate) processor is used as a detector in a radar receiver to detect targets in the surveillance zone where not all parameters of the statistical distribution of clutter are known, or they are nonstationary.

3.1. CA-CFAR detector

CA-CFAR (picture 3) is optimal CFAR detector when the surveillance zone is homogeneous, i.e. when the cells of the CFAR detector have contents with identical clutter distribution.

The essential parameters of each CFAR are:
- the probability of false alarm, \( P_{fa} \),
- size of the window detection, \( 2^n \),
- average value of signals in cells, \( Z \),
- scaling factor of the detection threshold, \( T_h \) and
- detection threshold, \( S \).

CA-CFAR processes signals received from the envelope detector by averaging of signals in \( 2n \) neighboring range bins \( (X_i) \) and the resulting mean value compares with the signal in range bin which is under test \( (Y) \). The mean value of the signal in \( 2n \) adjacent range bins is given in the equation:

\[
Z = \frac{\sum_{i=1}^{n} X_i + \sum_{i=1}^{2n} X_i}{2n} = \frac{Y_1 + Y_2}{2n} \quad (1)
\]

The threshold level of detection, \( S \), is calculated for a given probability of false alarm, \( P_{fa} \). In the CA-CFAR, the false alarm probability depends on the scaling factor of the detection threshold \( T_h \) according to the following equation [1]:

\[
P_{fa} = (1 + T_h)^{-2n} \quad (2)
\]

It is easy to calculate the scaling factor:

\[
T_h = \frac{1}{2 \sqrt{P_{fa}}} - 1 \quad (3)
\]

Threshold level of detection, \( S \), is calculated as the product of the scaling factor, and average of signals \( Z \):

\[
S = T_h \cdot Z \quad (4)
\]

The calculated values of the scaling factor depending on the probabilities of false alarms are given in table 1.

<table>
<thead>
<tr>
<th>( P_{fa} )</th>
<th>( 2n = 8 )</th>
<th>( 2n = 16 )</th>
<th>( 2n = 32 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_{C4} )</td>
<td>( T_{C4} )</td>
<td>( T_{C4} )</td>
<td></td>
</tr>
<tr>
<td>( 0^4 )</td>
<td>2.162</td>
<td>0.778</td>
<td>0.334</td>
</tr>
<tr>
<td>( 0^6 )</td>
<td>4.623</td>
<td>1.371</td>
<td>0.540</td>
</tr>
<tr>
<td>( 0^8 )</td>
<td>9.000</td>
<td>2.162</td>
<td>0.778</td>
</tr>
</tbody>
</table>

A comparator in the CFAR compares value of the signals from the test bin \( (Y) \) obtained from the threshold of detection according to (4). If \( Y > S \), a decision is made that a target is detected at the test bin, with predetermined
probability of false alarm. It is assumed that there is no target in the test bin if \( Y < S \).

### 3.2. OS-CFAR detector

OS-CFAR detector is primarily designed for a situation where in the same moment in a particular area has several targets which reflective signals have similar or different amplitudes at the entrance of the detector. Block scheme of OS-CFAR is shown in picture 4. In this implementation of CFAR detectors instead of calculating the mean signal in the cells, a cell ordering is done by sorting them in ascending order of amplitude. So it gets a new set of data in the following form:

\[
X_1 \leq X_2 \leq \ldots \leq X_N
\] (5)

Choosing \( k \)-th the biggest value

\[ Z = X_{(k)} \] (6)

The main idea of the concept of OS-CFAR detector is the selection of a particular value \( X_{(k)}, k \in \{1, 2, \ldots, N\} \) of the series (5) to obtain the estimated value of average power of clutter in the observed window detection:

\[ Z = X_{(k)} \] (6)

Scaling factor of the detection threshold, \( T_{OS} \), is calculated depending on the desired probabilities of false alarm, \( P_{fa} \). The value of the probability of false alarm for the OS-CFAR detector can be calculated by the following equations [1], [2]:

\[
P_{fa} = k \binom{N}{k} \frac{\Gamma(N-k + T_{OS} + 1)\Gamma(k)}{\Gamma(N + T_{OS} + 1)}
\] (7)

\[
P_{fa} = k \binom{N}{k} \frac{(k-1)!(N + T_{OS} - k)!}{(N + T_{OS})!}
\] (8)

In equation (7) gamma function is labeled with \( \Gamma \) and it is defined as:

\[
\Gamma(x) = \int_0^\infty t^{x-1} e^{-t} dt
\] (9)

Equation (8) can be used only in cases where \( T_{OS} \) is an integer value.

The value of probability of detection \( P_D \) for OS-CFAR detector can be calculated by the following equation [2]:

\[
P_D = k \binom{N}{k} \frac{\Gamma(N-k + T_{OS} / (1+SNR) + 1)\Gamma(k)}{\Gamma(N + T_{OS} / (1+SNR) + 1)}
\] (10)

As shown in equation (10), the probability of detection depends on the choice of parameter values \( k \). The optimal value for \( k \) is that value for which the mean value of the detection threshold \( ADT \) (Average Decision Threshold) is minimal. Depending on the size of the windows detection \( N \) of OS-CFAR detector and parameters \( k \), the average decision threshold is defined as [2]:

\[
ADT = T_{OS} \sum_{j=1}^{k} \frac{1}{N-k+j}
\] (11)

It is shown that the absolute minimum of average decision threshold is for \( k \approx 7N/8 \), but in practical realizations is showed that the parameter value \( k = 3N / 4 \) is satisfactory [2], because the losses are negligible small, and there is a greater suppression of clutter. Dependence of the average decision threshold \( ADT \) of values of the parameter \( k \) is shown in picture 5 for the four different detection window sizes \( N \).

![Picture 5. Dependence of the average decision threshold
ADT of the parameter \( k \)](image)

### 3.3. TM-CFAR detector

Implementation of TM-CFAR detector is a kind of generalization of the original OS-CFAR algorithm in which the clutter power is estimated by linear combination of the content of sorted cells in observed window detection. First, we sort cells per amplitude in the window detection, and then discards \( T_1 \) smallest cells and \( T_2 \) cells with the highest amplitudes. After that it is done the summation of content in the remaining cells (picture 6). A special case of the TM filter is \( \alpha \)-TM filter that rejects equal number of cells \( (T_1 = T_2) \) with minimum and maximum amplitudes.

Variable \( Z \) is used for the evaluation of clutter power and it is calculated here as follows [3]:

![Diagram](image)
It is observed that the OS and CA-CFAR algorithms are special cases of TM-CFAR algorithm. In the OS-CFAR detector is \((T_1, T_2) = (k-1,N-k)\) and in the CA-CFAR detector is \((T_1, T_2) = (0,0)\).

\[
Z = \sum_{j=T_1+1}^{N-T_2} X_{(j)} \tag{12}
\]

The value of probability of detection \(P_D\) for TM-CFAR detector can be calculated by the following equations:

\[
P_D = \prod_{i=1}^{N-T_1-T_2} M_{DV_i}(T_{TM}) \tag{20}
\]

\[
M_{DV_i}(T_{TM}) = \frac{N!}{T_i[(N-T_1-1)(N-T_1-T_2)]} \sum_{j=0}^{T_i} \frac{N-j}{N-T_1-T_2} + \frac{T_{TM}}{1+SNR} \tag{21}
\]

\[
M_{DV_i}(T_{TM}) = \frac{a_i}{T_{TM}} + \frac{1}{1+SNR}, \quad i = 2,\ldots,N-T_1-T_2 \tag{22}
\]

4. SIMULATION RESULTS

The simulation was performed on a model SRR as described in [7]. After the acquisition of real radar data and their A/D conversion, signals of radar targets are simulated and superimposed to real clutter signal. After the signal processing in previously projected functional blocks of the SRR we analyzed the results of signal detection using different types of CFAR processors. The probability of false alarm was standard value of 10\(^{-6}\).

The detection of radar signals can be improved by increasing the size of window detection in CFAR detector, or by changing the threshold detection algorithm calculations. Main parameters of realized CFAR detector are shown in the table 2.

<table>
<thead>
<tr>
<th>Model</th>
<th>(P_{fa})</th>
<th>2n</th>
<th>k</th>
<th>(T_1)</th>
<th>(T_2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CA-CFAR</td>
<td>10(^{-6})</td>
<td>16</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>OS-CFAR</td>
<td>10(^{-6})</td>
<td>16</td>
<td>12</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>TM-CFAR</td>
<td>10(^{-6})</td>
<td>16</td>
<td>-</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

Picture 7 shows the raw video signal for one antenna revolution. Picture 8 shows a separated area from 170 to 230 degrees, where signal clutter is the strongest. Simulated targets were in the upper area.

Parameters for the first two simulated targets are given in table 3. The targets have the same azimuth and range, but their signal amplitudes \((U_t)\) are very different. In picture 9 it can be seen that all three types of CFAR detect target. But when we reduce the amplitude of the signal, it can be seen that OS-CFAR and the TM-CFAR gives better results then CA-CFAR. In the signal processing of CA-CFAR detector (picture 10) more false targets appeared as a result of very small amplitude of target signal, which value is less then amplitude of the signal clutter around.
Next, we simulated a group of targets, and the parameters are given in table 4. The group consists of four targets that are on the same azimuth at relatively close distances, so it is difficult to detect them. The targets have different signal amplitudes ($U_s$) in the level of clutter signal in the environment and different speeds. We analyzed three situations:

- the distance between two adjacent targets is 5 radar resolution cells (picture 11),
- the distance between two adjacent targets is 2 radar resolution cells (picture 12),
- the distance between two adjacent targets is 1 radar resolution cell (picture 13).

<table>
<thead>
<tr>
<th>parameter</th>
<th>$U_s$</th>
<th>$f_s$</th>
<th>$R$</th>
<th>$\theta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>target 1</td>
<td>1.5</td>
<td>2500 Hz</td>
<td>9 km</td>
<td>199°</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>9 km</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>9 km</td>
<td></td>
</tr>
<tr>
<td>target 2</td>
<td>1.3</td>
<td>2000 Hz</td>
<td>14.4 km</td>
<td>199°</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>11.7 km</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>10.8 km</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>19.8 km</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>14.4 km</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>12.6 km</td>
<td></td>
</tr>
</tbody>
</table>

In the first case, when the distance between targets is 5 radar resolution cells, all three types of CFAR detectors
operate well and successfully detect all four simulated targets.

![Detection results for group of targets (case 2)](image)

**Picture 12.** Detection results for group of targets (case 2)

In the second case, OS-CFAR detect only the first and fourth target, and the TM-CFAR gives the worst results and detects only the fourth target of the group. CA-CFAR gives quite good results and detect all four targets.

![Detection results for group of targets (case 3)](image)

**Picture 13.** Detection results for group of targets (case 3)

In the third case, the distance between adjacent targets is only one radar resolution cell. Only the CA-CFAR was able to detect all four targets with the appearance of a number of false targets. Practically, OS-CFAR and TM-CFAR were unable to carry out detection of a single target from the group. TM-CFAR detects one target scarcely and it is shown in the picture 13.

**5. CONCLUSION**

Based on the qualitative results of the analysis it can be said that the detection of targets in conventional radar can be improved by proper choice of processing algorithm in CFAR detector in accordance with the characteristics of individual targets or groups of targets and clutter characteristics. If we should detect target with a relatively weak signal, we should choose OS-CFAR or TM-CFAR. But by detection of targets at very close distances in range, priority should be given to CA-CFAR detector.

Direction of further research would be moving toward a design model CFAR detector that would optimize all the good features of the individual CFAR detector depending on the characteristics of clutter and present targets.

**References**


