Cell Averaging - Constant False Alarm Rate Detection in Radar

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Abstract – *Constant False Alarm Rate (CFAR) Detection is an adaptive algorithm used in Radar systems to detect the target echoes against a background of noise and clutter. The role of the constant false alarm rate circuit is to determine the threshold above which any returning signal or echo can be considered probably to be originated from a target. In most radar systems, the threshold is set to achieve a required false alarm rate (or equivalently, probability of false alarm). Cell – Averaging CFAR (CA - CFAR) is a type of CFAR detection where the threshold is estimated by scanning a block of cells around a cell-under-test (CUT) and calculating the average power level. In CA – CFAR, a target is declared to be present if the power level in the CUT exceeds the average power level found from adjacent block of cells. This paper shows the principle of CA – CFAR detector, threshold factors for CFAR detection, factors affecting CFAR detection and CFAR loss. Simulations are done using MATLAB for analyzing CFAR loss and target masking.*

***Key Words*: CFAR, CA-CFAR, radar threshold detection, CFAR loss, target masking**

1. INTRODUCTION

Target detection is a most important task of a radar system. It compares the signal to a threshold. Therefore it is important to come up with an appropriate threshold. In general, the threshold is a function of both the probability of detection and probability of false alarm. In many systems, to avoid the cost of false alarms, it is desirable to have a threshold that maximizes the probability of detection and keeps probability of false alarms below a pre-set level [1].

Constant False Alarm Rate (CFAR) detection can be defined as a property of gain or threshold controlled devices specially designed to suppress false alarms caused by noise, clutter or Electronic Counter Measures (ECM) of varying levels. It refers to a common form of adaptive algorithm used in radar systems to detect target returns against a background of noise, clutter and interference.

In the radar receiver the echoes typically received by the antenna are amplified and then passed through a detector circuitry that extracts the envelope of the received signal. This signal is proportional to the power of the echo and comprises of wanted echo and the unwanted power from internal receiver noise, external clutter and interference.

The role of the CFAR circuitry is to determine the power threshold above which any echo can be considered to probably originate from a target. If the threshold is too low, then more echoes will be detected which increases the number of false alarms. If the threshold is too high, then few echoes will be detected and the number of false alarms will also be low. In most detectors, the threshold is set in order to get a required probability of false alarms. CFAR detection is essential if the output data is fed directly to the automatic data processor. The CFAR process forms an estimate of noise and interference level where target detection is carried out, and to set the detection threshold based on this estimate.

If the background against which targets are to be detected is constant with time and space, then a fixed threshold level can be chosen that provides a specified probability of false alarm (P_{fa}), controlled by the probability density function (pdf) of the noise, which is usually assumed to be Gaussian. The probability density function is then the function of the Signal-to-noise Ratio (SNR) of the target echo. In most field systems, clutter and interference sources means that the noise level changes. In this case, a varying threshold can be used, where the threshold is altered to maintain a constant P_{fa}. There are two approaches in the estimation of false alarms:

- Cell-Averaging CFAR
- Time-averaging CFAR

The former meaning averaging the output over adjacent cells, and the latter meaning averaging the output of detection cell itself over several scans.

1.1 Cell-Averaging CFAR Principle

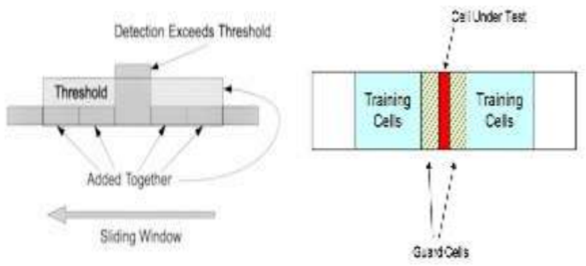


Figure 1.1: Cell – Averaging CFAR principle

A basic principle of cell averaging approach is shown in Figure 1.1 [1]. The center cell is the 'Cell-Under-Test' (CUT). The cells on both sides of CUT are the 'guard cells.' The adjacent cells' output are added and multiplied by a constant to establish a threshold. Detection occurs when the CUT output exceeds the threshold.

In CFAR, when detection is needed for a CUT, the noise power is estimated from neighboring cells. Then the detection threshold, T, is given by [2]

$$T = \alpha \cdot P_n \qquad (1.1)$$

where, P_n is the noise power and α is the scaling factor, called the threshold factor.

From equation (1.1) it is clear that the threshold changes with the data. So, with an appropriate α, P_{fa} can be maintained constant, hence the name CFAR.

In CA - CFAR detection schemes, the threshold level is calculated by estimating noise level around the CUT. This can be found by taking a block of cells around the CUT and calculating the average power level. To avoid corrupting this estimate with power from the CUT itself, the cells immediately adjacent to the CUT - referred as guard cells - are ignored. A target is declared present in the CUT if it is greater than all its adjacent cells and greater than the local average power.

The cell averaging CFAR detector is probably the most used detector. In a CA - CFAR detector, noise samples are extracted from the training cells around the CUT. The noise estimate may be computed as [2]:

$$P_n = \frac{1}{N} \cdot \sum_{m=1}^{N} x_m \qquad (1.2)$$

where N is the number of training cells and x_m is the sample in each training cell. Figure 1(b) shows the relation among the cells for a one - dimensional case.

With the above CA - CFAR detector, assuming the data passed into the detector from a single pulse, the threshold factor can be written as [1]:

$$\alpha = N.(P_{fa}^{-\frac{1}{N}} - 1) \qquad (1.3)$$

where, P_{fa} *is* the desired false alarm probability

1.2 Time-Averaging CFAR

In time-averaging CFAR, the threshold is set based on the average of the output of the *CUT* itself over a number of scans. It is very advantageous in ground clutter. However, it is not adequate for electronic countermeasures, such as lasers or infrared, that deceive the radar which may be a serious threat when it comes to security. This time-averaging CFAR may lead to the suppression of slowly moving targets unless long scan periods are used.

1.3 Constant False Alarm Rate Receiver

The threshold at the output of a radar receiver [3] is chosen so as to achieve a desired false-alarm probability. If changes in the false alarm rate are gradual, an operator viewing a display can adjust the gain manually. But this manual control is too time consuming and it is imprecise for automatic systems. So, there is a need to have some automatic, instantaneous means to maintain a constant false-alarm rate.

A CFAR may be obtained by observing clutter background in the vicinity of target and adjusting the threshold level according to the measured background. The Figure 1.2 shows the cell-averaging CFAR which uses a tapped delay-line to sample the range cells to either sides of the CUT.

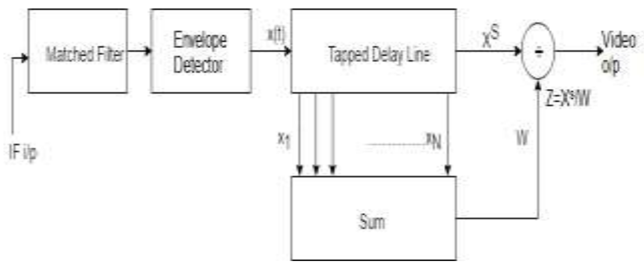


Figure 1.2: CA-CFAR receiver

The spacing between the taps is equal to the range resolution. The outputs from the delay line taps are summed. This sum is multiplied by an appropriate constant gives threshold level to achieve a desired P_{fa}.

Effective number of reference cells, m_{eff}, is calculated as:

For 'm' cell-averaging,

$$m = \begin{cases} m, & sq.\,law\ detector \\ \frac{(m+k)}{(1+k)}, & k = 0.09\,for\ envelope\ detector \\ & k = 0.65\ for\ \log detector \end{cases} \quad (1.4)$$

where m is the number of taps.

According to the figure 1.2 and equation 1.3, envelope detected outputs of m-adjacent cells are available at the tapped delay line with center-tapped at the CUT. The m-reference taps are averaged to form an estimate 'W' within the radar beam. The ratio of the detection cell amplitude, 'X^s', to the average is the video output. Then the threshold is scaled to the estimate of local noise. Thus the threshold varies continuously according to the noise or clutter within the range of the *CUT*.

Typically, the number of taps used in CA-CFAR might vary between 16 and 20. The CFAR uses the output of the sampled cells to estimate the unknown amplitude of background clutter. Since the number of samples are less, the background is not completely known. If the target echo is large, energy can exceed into the adjacent cells and affect the measurement of background. The hazards that can be seen in cell-averaging CFAR are, formation of target may act to suppress all the detection, and if the formation occupies more reference cells, threshold is so high that no target can be detected. So, the threshold can be adjusted according to the reference cells.

2. Constant false alarm rate detection

Radar threshold detection assumes that the interference level is known and constant. This allows to accurately set the threshold that gives the desired P_{fa}. The CFAR detection is a set of techniques designed to provide predictable detection in realistic interference cases.

2.1 The effect of unknown interference power on false-alarm probability

For a square-law detector with a target in white Gaussian noise, the probability of false alarm for a single sample is [1]

$$P_{fa} = e^{-T} \quad (2.1)$$

where T is the detection threshold.

By solving the above equation and analyzing it in terms of un-normalized data sample z and with the square-law detector, the threshold is

$$T = -\beta^2 \ln P_{fa} \quad (2.2)$$

and the probability of false alarm is

$$P_{fa} = e^{-T/\beta^2} \quad (2.3)$$

To tune the square-law detector, an acceptable value of P_{fa} must be chosen, then the threshold is computed from equation (2.2).

To set the threshold accurately, knowledge of interference power level is required. When the interference is the receiver noise, it is possible to measure the interference power level and the threshold can be adjusted. However, practically, this interference varies over time due to temperature and component aging.

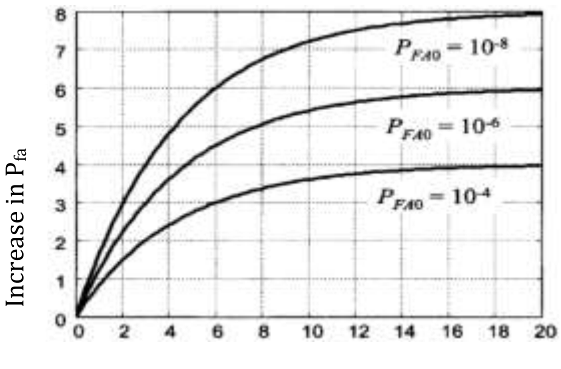
If this interference power is affected by external sources, the variability of power level is much severe. In conventional radars, the total interference power can be affected by *electromagnetic interference* (EMI). If the interference is ground clutter, its power level varies according to the terrain, weather conditions and seasons. For example, deserts have low reflectivity, frozen snow has a very high reflectivity. If the interference is a hostile electromagnetic emission directed at the radar system, then the power level can be extremely high.

In any of the above mentioned cases, the P_{fa} varies from the intended value. Let P_{fa0} be the intended probability of false alarm when the actual interference power level is β_0^2. Then, $T = -\beta_0^2 \ln(P_{fa0})$. Now suppose the actual power level is β^2. Using equation (2.3), assuming power level of β_0^2 from equation (2.2), P_{fa} will be,

$$P_{fa} = \exp\left(\frac{\beta_0^2 ln P_{fa0}}{\beta^2}\right) = \exp\left(\ln P_{fa0}^{\left(\frac{\beta_0^2}{\beta^2}\right)}\right)$$
$$= P_{fa0}^{(\beta_0^2/\beta^2)} \quad (2.4)$$

and increase in false alarm probability will be a factor of

$$\frac{P_{fa0}}{P_{fa}} = P_{fa0}^{\left[\left(\frac{\beta_0}{\beta}\right)^2 - 1\right]} \quad (2.5)$$



Noise Power increase (dB)

Figure 2.1: Increase in P_{fa} for a fixed threshold doe to increase in β^2

International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395-0056
Volume: 05 Issue: 07 | July 2018 www.irjet.net p-ISSN: 2395-0072

Figure 2.1 is the plot based on the equation (2.5) for three different values of P_{fa}. The figure shows that for a small increase in noise power, there is an unintended increase in P_{fa}. Such changes will have an impact on radar performance.

2.2 Cell-averaging CFAR

2.2.1 Effect of varying false alarm probability (P_{fa})

The reason for a major increase in P_{fa} as seen in figure 2.1 is that the threshold was set based on incorrect value of noise power level. As the interference power increases, number of false alarms also rise. It may seem that the P_{fa} difference between 10^{-6} and 10^{-8} is insignificant. But considering a pulse repetition frequency of 10 kHz and 200 range cells, and if each cell is tested the system makes (10,000 * 200) = 2,000,000 which is 2 million detection decisions per second. With $P_{fa}=10^{-8}$, false alarm occurs once every 50 seconds. If P_{fa} increases to 10^{-6}, the system detects 2 false alarms every second.

2.2.2 The CA - CFAR concept

To have a consistent performance, constant false alarm rate is preferred. To achieve this, the interference power level is determined from data in real-time, so that the threshold can be set to maintain the desired P_{fa}. A device that maintains constant P_{fa} is called the *CFAR processor*.

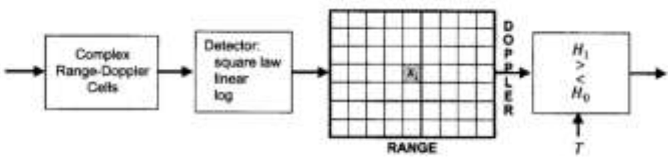


Figure 2.2: General radar detection processor

The Figure 2.2 shows a generic processor used in radar detection. This detector is for a system that detects using range cells. The individual cells are pixels in a 2-D image. The detector tests each cell for the presence of target. The CUT, denoted by x_i, is compared against the threshold set by the interference power. If the value of data in x_i exceeds the threshold value then the target is said to be present. Likewise, value of data in each and every cell is compared against the pre-set threshold level. Target is said to be present in the cells whose value exceeds the threshold value. The detection decision is made in this manner.

To set the threshold for *CUT*, x_i, the interference in the same cell must be known. Since it may be variable, it is estimated from the data present in x_i, The CFAR processing approach uses two assumptions [1]:

- The neighbouring cells contain interference with same statistics as the *CUT*, so that they are representative of interference that is competing with the target.
- The neighbouring cells do not contain any targets; they are interference only.

In these conditions, interference level in the *CUT* can be estimated from samples in the adjacent cells.

2.2.3 CFAR reference windows

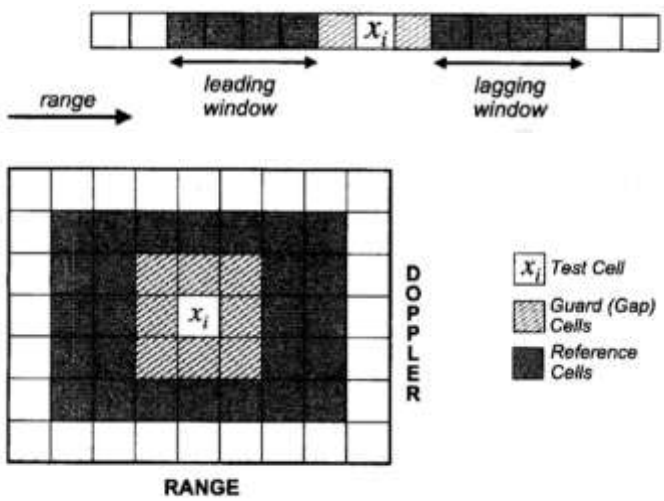


Figure 2.3: CFAR Windows. (a) 1-D Window for Range-Only Processor; (b) 2-D Window for Range-Doppler Processor

The samples cells average technique is shown in Figure 2.3. Figure 2.3 (a) shows a one-dimensional data vector of range cells with the CUT, x_i, in the middle. The data in the gray cells to either sides of x_i are averaged to estimate the interference. These cells are reference cells. The cross-hatched cells immediately adjacent to the CUT are the guard cells. These cells are not considered for averaging. Because if the target is present in the guard cells, it might straddle the range cells. Thus the first assumption is satisfied. If the system range resolution is such that the anticipated targets could extend over multiple range cells, then more than one guard cells are skipped from averaging. This combination of CUT, reference cells and the guard cells is referred to as the CFAR Window.

Figure 2.3 (b) shows the two-dimensional equivalent to the one-dimensional case explained above. In this case, the averaging is done for the Range-Doppler matrix. The components remain the same. The *CUT* is in the centre surrounded by guard cells. These guard cells are surrounded by the *range cells.*

2.2.4 CFAR loss

To quantify the CFAR loss in CA - CFAR case, the number of samples averaged is to be calculated and is denoted by χ_N, [1]

$$\chi_N = \frac{\left(\frac{P_D}{P_{fa}}\right)^{1/N} - 1}{1 - P_D^{1/N}} \quad (2.6)$$

As N → ∞, the estimate of interference power converges to the true value.

$$\chi_\infty = \frac{ln(P_{fa}/P_D)}{ln(P_D)} \quad (2.7)$$

The CFAR loss is then the ratio of number of samples averaged to the true value

$$CFAR\ loss = \frac{\chi_N}{\chi_\infty} \quad (2.8)$$

2.2.5 CA - CFAR limitations

The cell-averaging CFAR depends on two major assumptions:

- Targets are separated at-least by reference window size, so that no two targets are in the same reference cell at the same time
- All of the reference window noise samples are independent and identically distributed, and that distribution is the same as that of the interference component in the cell containing target. i.e., the interference is homogeneous.

2.3 Target Masking

When one target is in the test cell, another target is located among the reference cells. This situation is called target masking. Assuming that the power level of the target in the reference cell exceeds that of the surrounding interference, its presence raises the threshold estimate. The target in the reference window masks the target in the test cell since the increased threshold causes a reduction in detection probability; i.e., the detection of the target in test cell itself is missed. So, a higher SNR is required to achieve the specified P_D. Precise analysis of effect of presence of target in the reference cells is simple but complex in practice. However, a relatively simpler estimate that shows the effect of interfering target can be derived [1].

Consider a single interfering target with power γ_i that contaminates only one of the 'N' reference cells. The SNR of this interferer is $\chi_i = \gamma_i/\beta^2$. The expected value of new threshold is:

$$E\{T'\} = E\left\{\frac{\alpha}{N}\left(\gamma_i + \sum_{i=0}^{N-1} x_i\right)\right\} = \frac{\alpha.\gamma_i}{N} + \alpha\beta^2 = \alpha.\left(1 + \frac{\chi_i}{N}\right).\beta^2 \quad (2.9)$$

The elevated threshold decreases the probability of detection as well as the probability of false alarm. New value of P_D is:

$$P_D' = \left[1 + \left(P_{fa}^{-1/N} - 1\right)\left(\frac{1 + \chi_i/N}{1 + \chi}\right)\right]^{-N} \quad (2.10)$$

If $\chi_i \to 0$ or $N \to \infty$ then $P_D' = P_D$.

One more way to characterize the effect of interfering target is by increasing the SNR to maintain the original value of P_D. Let χ' be the value of SNR needed to achieve original P_D using the elevated threshold T'. The equation below expresses P_D in terms of original value of χ and threshold multiplier α

$$P_D = \left(1 + \frac{\alpha}{N \cdot (1 + \chi)}\right)^{-N} \quad (2.11)$$

The same relationship can be applied to determine the probability of detection P_D' with the threshold multiplier α' and SNR χ'. Thus P_D' equals P_D if

$$\frac{\alpha}{N \cdot (1 + \chi)} = \frac{\alpha'}{N \cdot (1 + \chi')} \quad (2.12)$$

The threshold multiplier α' is given by,

$$\alpha' \equiv \alpha \cdot (1 + \frac{\chi_i}{N}) \quad (2.13)$$

Using the equation (2.13) in (2.12) will give

$$\chi' = \left(1 + \frac{\chi_i}{N}\right) \cdot (1 + \chi) - 1 \quad (2.14)$$

The equations (2.10) and (2.14) are only approximations. A more careful analysis would be by finding the probability density function in the presence of interfering target, and then using this value to find the values of P_D and P_{fa}. But this approach is complicated because the interfering target changes the pdf of the cell containing it. To avoid this, the expected value of threshold is used in the equations. [2]

3. Simulation Results

Simulations are carried out using MATLAB to plot the response for CA – CFAR loss and target masking.

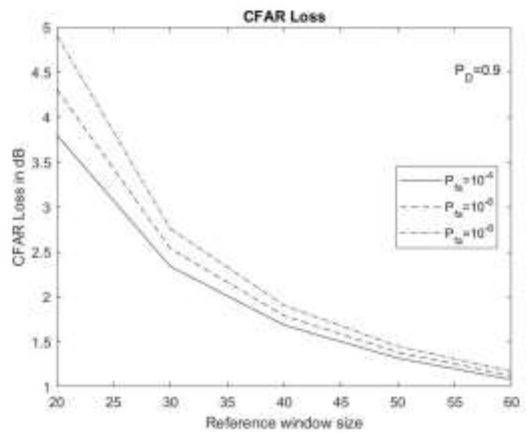
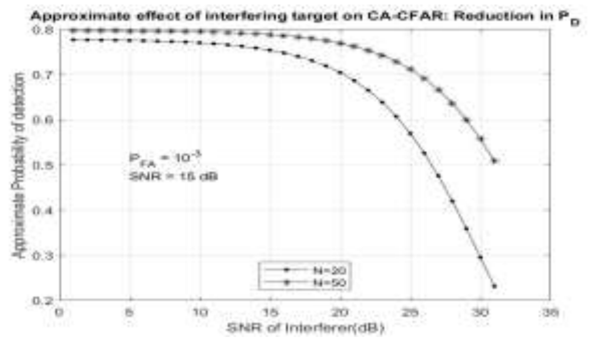
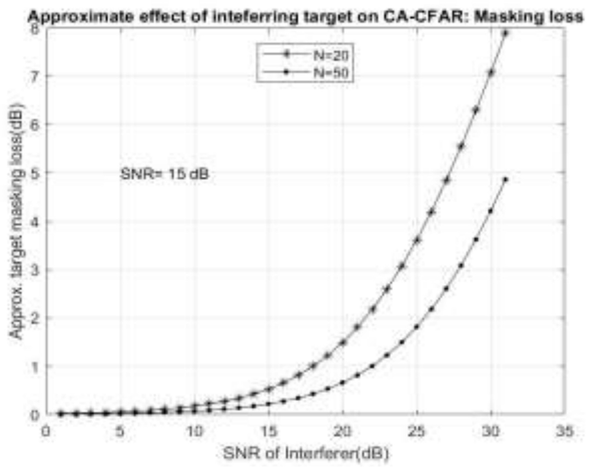


Figure 3.1: CA - CFAR loss for target in Gaussian interference with $P_D = 0.9$

The Figure 2.4 is plot based on equation (2.8) for a detection probability of 0.9 and three different values of P_{fa}. The loss is more when the number of cells is less and the loss reduces as the number of reference cells increase.



(a)



(b)

Figure 3.2: Approximate Effect of Interfering Target on CA – CFAR. Threshold Set for $P_{fa} = 10^{-3}$: (a) Reduction in P_D; (b) Equivalent Masking Loss.

Figure 3.2(a) is plot based on equation (2.10), where $P_{fa} = 10^{-3}$ and N is either 20 or 50 cells. The plots show that the probability of detection reduces with interfering target. Figure 3.2(b) plots the approximate target masking loss for the same conditions as in figure 3.2(a), and it shows that the masking loss increases with SNR of interfering target, but with more range cells, the loss can be reduced

4. CONCLUSIONS

The concept of constant false alarm rate detection in radar and the threshold requirements for the CFAR detection are understood. The principle of cell-averaging CFAR detection is studied and the effects of unknown parameters on the performance of CFAR detector and their limitations are seen. Simulations are carried out using MATLAB for CA-CFAR loss and target masking.

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