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PERFORMANCE ANALYSIS OF A MODIFIED CFAR BASED RADAR DETECTOR UNDER PEARSON DISTRIBUTED CLUTTER

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Abstract

An adaptive target detector in radar system is used to extract targets from background in noisy environment of unknown statistics. The constant false alarm rate (CFAR) is well known detection algorithm that is being used in almost every modern radar. The cell averaging CFAR is the optimum detector in homogeneous clutter environment when the refence cells have identically independent and exponentially distributed signals. The performance of CA CFAR degrades seriously when clutter power substantially varies in non-homogeneous background. To overcome the performance degradation, a non-linear compression technique based CFAR has been introduced for adaptive thresholding to meet the challenges of target detection from various degrees of Pearson distributed non-homogeneous clutter. Extensive MATLAB simulations have been done using various levels of clutter input to show the effectiveness of the proposed design. Improvement in Signal-to-Noise ratio (SNR) has been achieved using Swerling I model for Rayleigh fluctuating target in the backdrop of heavy clutter.

Keywords:

CFAR, SNR, Pearson Distributed Clutter, Adaptive Target Detector, Swerling Model

1. INTRODUCTION

Detection of target from the backdrop of ever varying clutter environment is always a difficult task for radar designers. It is desired that the radar system should process the received echo signals from uncertain noisy environment keeping false alarm rate constant to maintain signal-to-clutter ratio (SCR) almost constant. A solution for that was a constant false alarm rate (CFAR) technique to set the threshold adaptively as per the variation of clutters [1-3]. The cell averaging (CA) CFAR is the best radar detector in homogeneous clutter environment [4]. But the performance of CA CFAR is poor in non-homogeneous interference as compared to other CFAR detectors [5, 6]. In this paper, an improved adaptive radar detector has been designed keeping in view a known clutter covariance matrix for estimation of filter parameters and simultaneously various clutter maps for non-homogeneous clutters. To identify specific target amongst randomly varying clutter environment and to avoid receiver overloading, a modified CFAR algorithm based design has been introduced to operate in Pearson distributed clutter [7-10] environment using a non-linear compression method to lower the false alarm of the receiver significantly as well as to increase the probability of detection [11].

Normally radar receivers with adaptive moving target detectors (AMTD) are equipped with bank of filters to mitigate clutters [12]. But strong un-cancelled clutters always remain associated with the target at the output which creates false alarm as well. Therefore detection threshold is needed to be computed in such a way that it can be applied to the detection logic as per the strength of the clutter. Since environmental conditions are always changes, the threshold value must be continuously updated based on the statistical estimation of clutters in order to maintain constant false alarm rate (CFAR). In this regard, a good many numbers of methods have been proposed in implementation of various CFAR techniques [13-15]. In many of the research papers have proposed independently and identically distributed (i.i.d.) sampling method for estimation of interference or clutter power in optimized radar detector [16]. But a large number of i.i.d. samples required estimating the noise covariance matrix which inevitably leads to performance deterioration in non-homogeneous clutter environment. A substantial bulk of work is available in literature about radar target detection in heavy-tailed compound-Gaussian clutter [17-19]. Practically, target always positioned itself amongst the point, area or extended clutter. This background clutter changes with time and as per positions of the antenna. This manifests inevitable requirement of adaptive signal processing technique to apply adaptive threshold as per clutter situation to maintain a constant false alarm rate (CFAR). The output of square law detector of the radar can be modeled as positive alpha stable ($P\alpha S$) as far as power and energy of the signal is concerned. Pierce [20] has shown that non-homogeneous signals like sea clutter is also follow Pearson distribution. Keeping in view of nature of interference in non-homogeneous environment, a non-linear compression based CFAR detector has been proposed.

The remainder of this paper proceeds as follows. In section 2, a mathematical review for detection criteria of CFAR technique has been discussed explaining improvement in probability of detection by deriving the Marcum's Q function. In section 3, design of CFAR under Pearson distributed non-homogeneous clutter environment is explained. The performance analysis of the proposed design using MATLAB simulation thoroughly discussed in section 4. Finally, the concluding remarks are provided in section 5.

2. MATHEMATICAL REVIEW FOR RADAR DETECTION CRITERIA

The Constant-False-Alarm-Rate (CFAR) circuit in radar signals processing plays a vital role to suppress moving clutter available with required echo returns. The clutters are generated due to weather phenomena like cloud, rain, haze and so on. Radar receiver is very sensitive to signal-to-clutter ratio (SCR). The SCR is also depends on the threshold of the radar. When threshold is fixed, the false alarm rate increases significantly with increase in clutter level. As a result, the detection system becomes hugely inaccurate to make a decision between a target and clutter. Therefore, radar uses constant false-alarm-rate to identify target in any weather conditions. The CFAR detection technique is based on the statistical estimation of clutters or interferences.

Now we can define clutter to noise (CNR) as,

$$F = \frac{\sigma_c{}^2}{\sigma_n{}^2} \tag{1}$$

The variance of noise and clutter power is,

$$\begin{aligned}\sigma^2{}_{\alpha\beta} &= \sigma^2{}_n \sum_{j=0}^{n-1} (w^2{}_{\mathrm{Re}\, j} + w^2{}_{\mathrm{Im}\, j}) \\ &+ \sigma^2{}_c \sum_{j=0}^{n-1}\sum_{i=0}^{n-1} (w_{\mathrm{Re}\, j} w_{\mathrm{Re}\, i} + w_{\mathrm{Im}\, j} w_{\mathrm{Im}\, i})\rho(i-j)\end{aligned} \tag{2}$$

Here ρ is called clutter correlation coefficient and whereas σ^2_n and σ^2_c are variances of system noise and clutter.We get the following from Eq.(2).

$$\sigma^2{}_{\alpha\beta} = \sigma_n{}^2 P_{avg} 1 + \sigma_c{}^2 P_{CA}$$

$$\sigma^2{}_{\alpha\beta} = \sigma_n{}^2 P_{avg}[1 + (\sigma_c{}^2 / \sigma_n{}^2) P_{CA} / P_{avg}]$$

$$\sigma^2{}_{\alpha\beta} = \sigma_n{}^2 P_{avg}(1 + \frac{F}{I.F}) \tag{3}$$

Since the variables α and β are Gaussian, uncorrelated and independent, we get the basic equation from the law of interference

$$f_{\alpha\beta} = E[(\alpha - \psi_x)(\beta - \psi_y)] = 0 \tag{4}$$

and their joint density function can be calculated as:

$$f(\alpha, \beta \mid \psi) = \frac{1}{2\pi\sigma^2{}_{\alpha\beta}} \exp\Big[-\frac{(\alpha-\psi_x)^2 + (\beta-\psi_y)^2}{2\sigma^2{}_{\alpha\beta}}\Big] \tag{5}$$

Considering polar coordinates on the envelope (r) we can replace by using $\alpha = r\cos\theta$ and $\beta = r\sin\theta$ in Eq.(5),

$$f(r \mid \psi) = \frac{r}{\sigma^2{}_{\alpha\beta}} \exp\Big[-\frac{r^2+\psi^2}{2\sigma^2{}_{\alpha\beta}}\Big] I_0\Big(\frac{r\psi}{\sigma^2{}_{\alpha\beta}}\Big) \tag{6}$$

where , $\psi^2 = \psi_x{}^2 + \psi_y{}^2 = 2P_{avg}P_s$

$$I_0\Big(\frac{r\psi}{\sigma^2{}_{\alpha\beta}}\Big) = \frac{1}{2\pi}\int_0^{2\pi} \exp\Big(\frac{r\psi}{\sigma^2{}_{\alpha\beta}}\Big)\cos\theta \tag{7}$$

The Eq.(7) is called Rician probability density function. If $\frac{\psi}{\sigma^2{}_{\alpha\beta}} = 0$, the Eq.(7) converts into Rayleigh probability density function as:

$$f(r \mid \psi) = \frac{r}{\sigma^2{}_{\alpha\beta}} \exp\Big[-\frac{r^2}{2\sigma^2{}_{\alpha\beta}}\Big] \tag{8}$$

when $\frac{\psi}{\sigma^2{}_{\alpha\beta}}$ is very large, Eq.(7) becomes a Gaussian probability density function as can be written

$$f(r \mid \psi) = \frac{r}{\sqrt{2\pi\sigma^2{}_{\alpha\beta}}} \exp\Big[-\frac{(r-\psi)^2}{2\sigma^2{}_{\alpha\beta}}\Big] \tag{9}$$

Probability density function of Gaussian and Rayleigh type signals is shown in Fig.1.

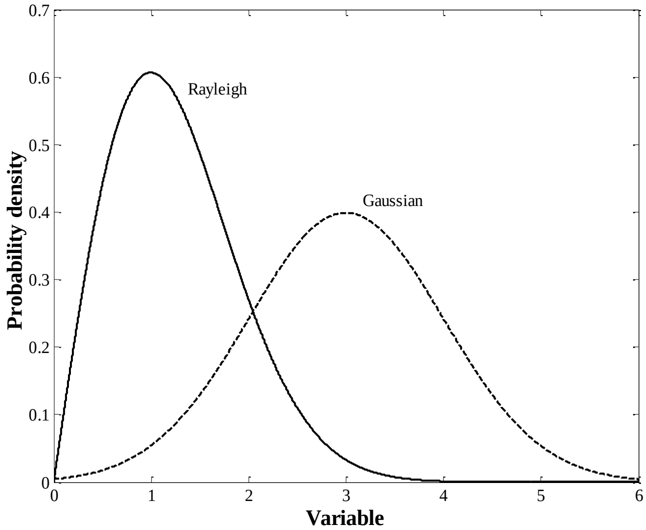

Fig.1. Probability density function of Gaussian and Rayleigh type signals

When false alarm probability of the system is P_{fa}, we can derive detection threshold V_T by putting $\psi = 0$ in Eq.(9) as:

$$V_T = 2\sigma^2{}_{\alpha\beta} \ln\Big(\frac{1}{P_{fa}}\Big) \tag{10}$$

The probability of detection (P_d) can be derived from Marcum's Q function in the following form:

$$P_d = Q\left(\Big[\frac{2P_s}{\sigma_n{}^2(1+\frac{F}{I.F})}\Big]^{1/2}, \Big[2\ln\Big(\frac{1}{P_{fa}}\Big)\Big] \right)^{1/2} \tag{11}$$

The above equation reveals that the probability of detection (P_d) increases with increase in improvement factor ($I.F$).

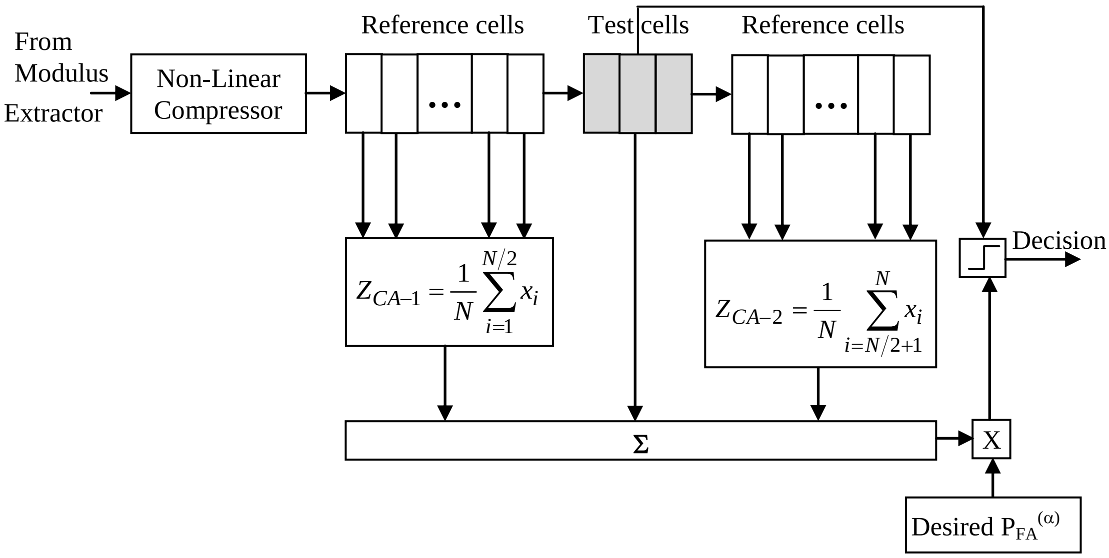

Fig.2. Modified CFAR system using non-linear compression method

3. NON-LINEAR COMPRESSION BASED CFAR DETECTOR

After detection of radar echo which accompanies with clutter and receiver noise at the receiver through coherent detection technique, a threshold is being produced at the receiver as we have seen earlier. Whenever target echo amplitude is greater than the established threshold, it is confirmed that target is present or otherwise it is declared as target absent. If the fixed threshold level is low enough, the noise alone will cross the threshold to represent itself on the scope. This situation is called false alarm. If the threshold level is too high, only target with sufficient amplitude will be detected and weak target echoes will not be detected. This condition is called missed detection.

In order to maintain the false alarm rate constant for a radar system, the established threshold has to be varied adaptively. CFAR is a technique that facilitates in automatic variation of the threshold to maintain false alarm of the radar constant. But false alarm remains constant in case of homogenous clutter. If clutter varies non-uniformly, it is likely that CFAR produces false alarm. When clutter distribution or interference increases, false alarm rate also increases alarmingly at the radar output. In such situation, appropriate CFAR algorithm is required to produce adaptive threshold to keep the false alarm rate constant. In most of the modern radar Cell Averaging CFAR (CA-CFAR) is being used in adaptive threshold processor when clutter distribution is homogeneous and Gaussian. But in practice, background clutter is never a homogeneous. The non-homogeneity is caused due to abrupt change in interfering noise or in extended clutter edge. To identify specific target amongst randomly varying clutter environment, a modified CA-CFAR algorithm based design has been proposed to operate in Pearson measurement using a non-linear compression method as shown in Fig.2. The output of the square law detector is compressed in order to reduce the effect of sudden variation of noise resulting in enhancement of performance of moving target detector.

The Pearson distributed probability density function (pdf) for signal $X_1, X_2,\ldots, X_N$ is given by,

$$P_{x_i}(x) = \begin{cases} \frac{\gamma}{\sqrt{2\pi}} \frac{1}{x^{3/2}} e^{\frac{-\gamma^2}{2x}}, & x \geq 0 \\ 0, & otherwise \end{cases} \tag{12}$$

where, γ is called dispersion parameter.

Let a noisy Pearson distributed signal passes through the compressor and its output is given by:

$$y = x^{\xi} \tag{13}$$

where, x is the output of modulus extractor and $0 < \xi \leq 1$ is a real coefficient which controls the degree of compression. The probability density function is given by:

$$p_{\gamma}(y) = \frac{f_X(x)}{|g'(x)|} \tag{14}$$

Now we get the pdf as:

$$p_{\gamma}(y) = \frac{\gamma}{\sqrt{2\pi\xi}} \frac{1}{y^{\frac{2\xi+1}{2\xi}}} \exp\left(-\frac{\gamma^2}{2y^{1/\xi}}\right) \tag{15}$$

The basics of CA-CFAR lie in estimation of an average value of atmospheric disturbances distribution and determination of the threshold to obtain the probability of desired false alarm. The estimation of this value is made for each range cell (CUT: Cell Under Test) that is being examined using number of samples amongst adjacent range cells as shown in Fig.2. The CA-CFAR can use up to 36 range cells from the CUT with a number of guard cells. These 36 range cells are divided into 6 sections each with 6 range cells. Inside each section, the highest value of clutter level is estimated which could ascertain the presence of interfering target. By sending the two values of input to the logic cell, the presence of target is extracted from the content of CUT. If P_{FA}^{CA} be the probability of detection of target echo in a random clutter C_0 is measured in a CUT, the following thresholding criteria can be given by:

$$P_{FA}^{CA} = P_r\{C_0 \geq T.Z\} \tag{16}$$

where, Z is an estimated average clutter power and T is the scaling factor. The decision regarding level of threshold is determined by the scaling factor. The average clutter strength within CUT is given by:

$$Z = Z_{CA-CFAR} = \frac{1}{N}\sum_{i=1}^{N} x_i \qquad (17)$$

The probability of detection of target echo amongst the clutter from CUT reference threshold can be given by:

$$P_{FA}^{CA} = \sqrt{\frac{2N}{\pi}}\int_0^{\infty} erf\left(\frac{y}{\sqrt{2\alpha}}\right).e^{-N\frac{y^2}{2}}\,dy \qquad (18)$$

where, $erf(y) = \frac{2}{\sqrt{\pi}}\int_0^{y} e^{-t^2}\,dt$

The first step for determination of the required level of P_{FA}^{CA} from the given environmental noise condition is to measure the RMS clutter power level Z. The next step is to multiply the Z with a scaling factor T to get a resulting product $T.Z$ for the decision thresholding.

To evaluate decision thresholding, a new method of non-linear compression method has been adopted to suppress spiky noise generated through sea clutter or rain. The detected clutter signal is passed through a non-linear compressor that compresses large amplitude of the spike by reducing the dynamic range of the clutter. Depending on the characteristics of the clutter that is being examined, the decision logic decides whether to consider for the threshold calculation either all six sections or only a part of them. By means of mutual calculation of all adjacent cells, number of cells to be used is determined.

4. PERFORMANCE ANALYSIS AND DISCUSSION

It is a fact that probability of detection lowers as per the variations of target cross section and therefore equivalently reduces the signal-to-noise ratio (SNR). We consider here Swerling I model for Rayleigh fluctuating target which is embedded with pearson distributed clutter. The Swerling I targets maintain constant amplitude over an antenna scan. However, the target amplitude does not remain constant from scan to scan. It varies independently as per Chi-square probability density function with two degrees of freedom. In our MATLAB simulation, one target has been considered along with non-homogenous clutters.

In Fig.3, we have simulated an input environment with a target which is embedded with non-homogeneous clutter within 1 ms time scale. When the input is passed through conventional CA-CFAR without any compression, the output signal we get as shown in Fig.4 with improvement in target detection level. The clutter around the target is significantly reduced. Let the same input signal is passed through non-linear compression based CA-CFAR with compression parameter $\xi = 0.5$. The result from the modified CFAR again gives more improved outcome as shown in Fig.5 as compared to Fig.4. Again, the compression parameter reduced further to $\xi = 0.1$. The corresponding outcome in Fig.6 shows that the clutter is suppressed significantly.

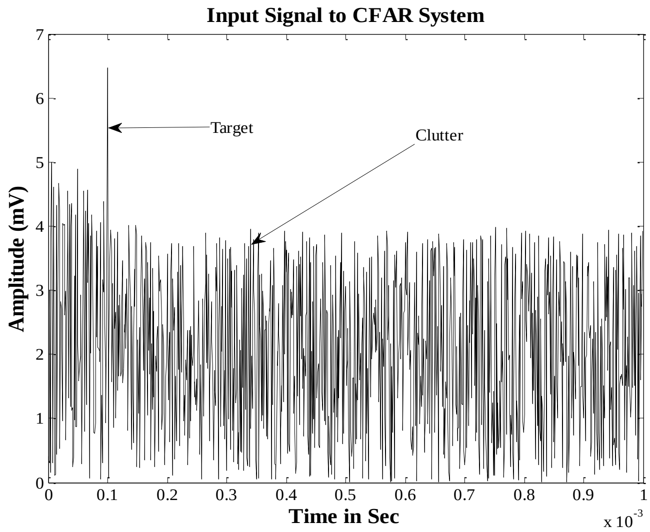

Fig.3. Input signal to CFAR system

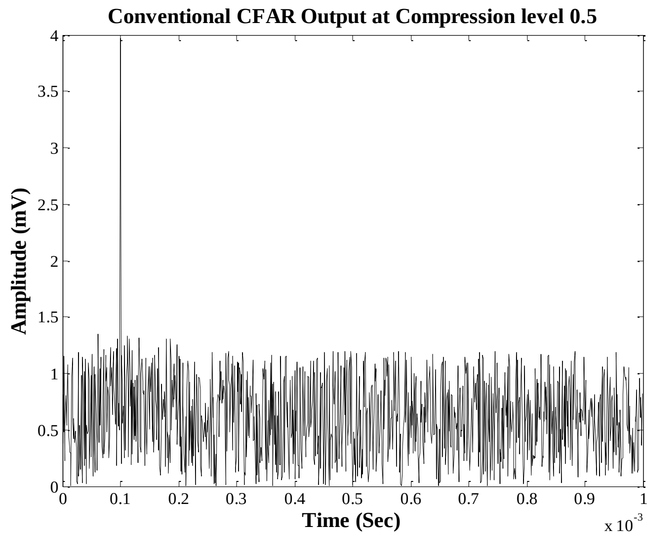

Fig.4. Conventional CA-CFAR output

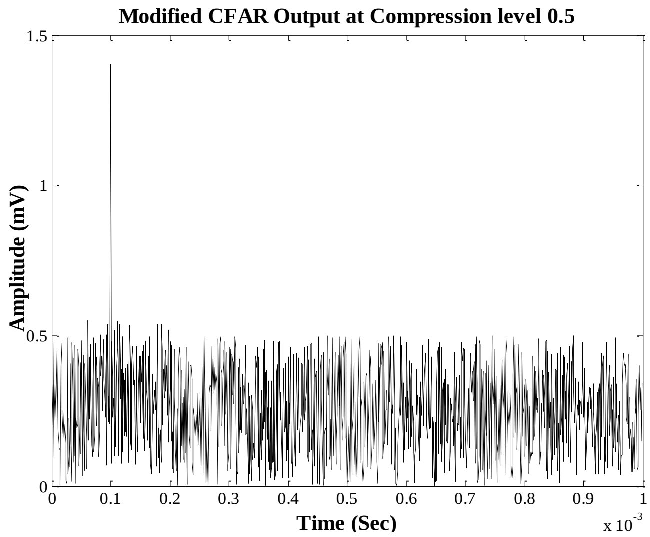

Fig.5. Modified CFAR output at $\xi = 0.5$

In the output of modified CFAR it is clear that compression technique not only suppresses noise, it improves Signal-to-clutter-ratio throughout the range. In the nearby region, clutter amplitude also has been mitigated significantly.

Considering Marcum Q -function [21, 22], the probability of detection (P_d) increases with increase in threshold voltage. A small change in threshold voltage generates big change in probability of false alarm as shown in Fig.7.

Again, we have simulated the performance of radar in terms of probability of detection with respect to SNR maintaining false alarm rate constant at 10^{-6} and 10^{-9} as shown in Fig.8 and Fig.9 respectively. It is evident from both the figures that the proposed architecture has better performance over the conventional CA-CFAR system. The outcome reflects that at lower SNR the proposed design achieves higher probability of detection (P_d). Therefore it gives better performance over the conventional CFAR technique.

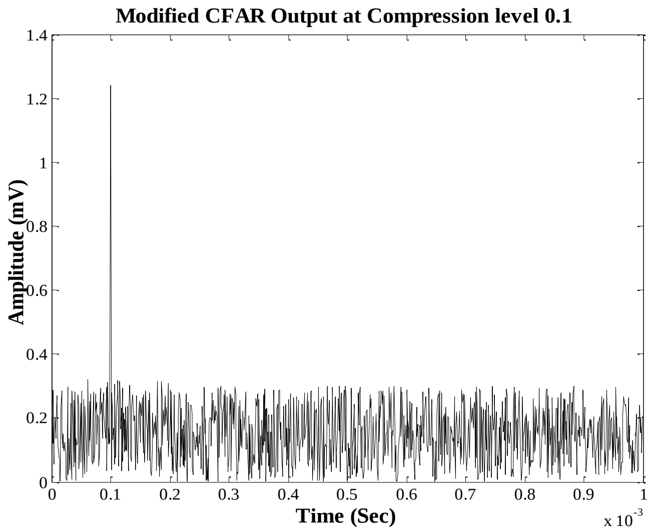

Fig.6. Modified CFAR output at ξ = 0.1

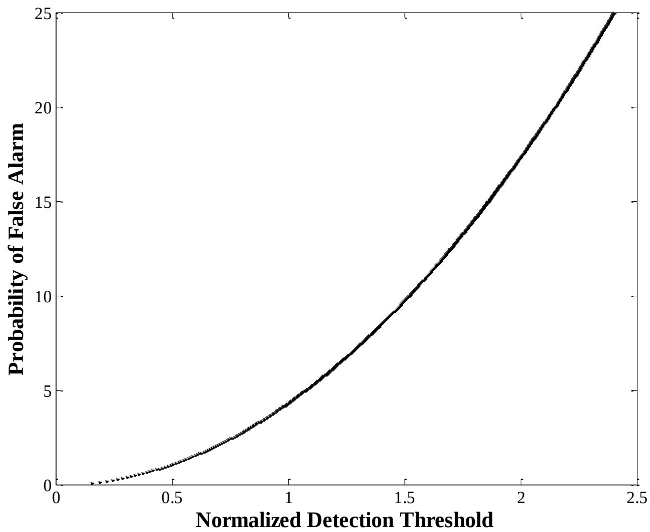

Fig.7. Normalized detection threshold Vs probability of false alarm

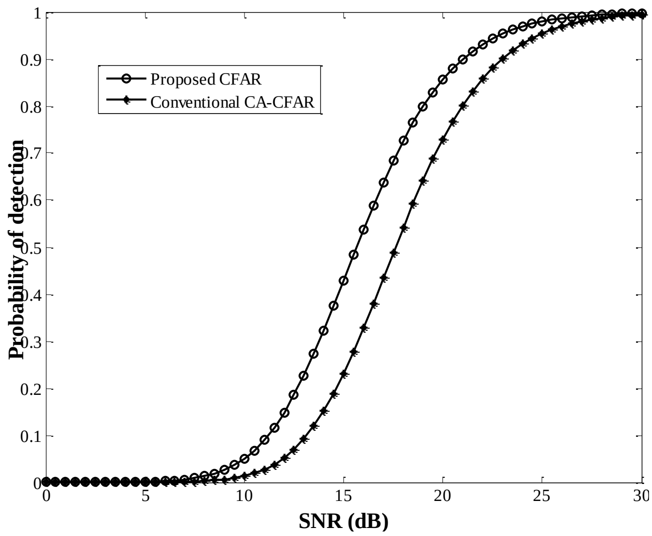

Fig.8. Probability of detection versus SNR for conventional CA-CFAR and proposed CFAR at false alarm rate 10^{-6}

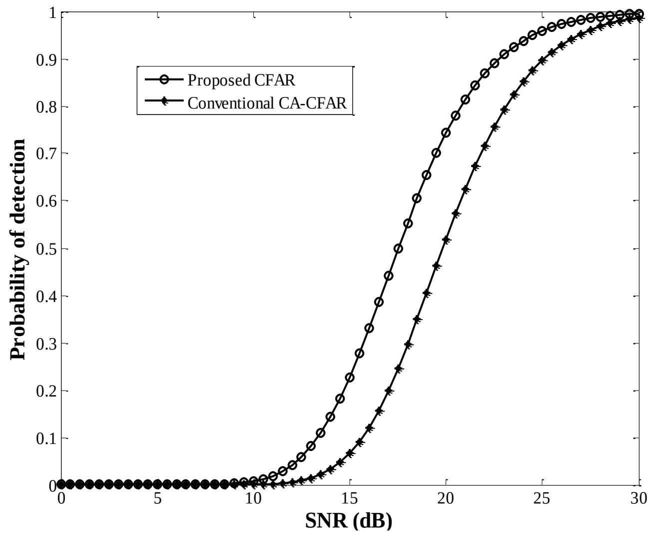

Fig.9. Probability of detection versus SNR for conventional CA-CFAR and proposed CFAR at false alarm rate10^{-9}

5. CONCLUSION

In this paper, we present a simple and efficient non-linear compression based CFAR detector for Pearson distributed non-homogeneous clutter. The implementation of modified CFAR which emanates from complete knowledge of clutters parameters along with the conventional CFAR algorithm used is highly effective even in very strong clutter conditions. The MATLAB simulation results for the target detection method shows that the proposed design works satisfactorily in various clutter environments. The analysis shows that the use of the proposed design not only improves the probability of detection for radar, it also improves SNR significantly.

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