CONVENTIONAL ORDER STATISTIC-CFAR ANALYSIS IN WEIBULL CLUTTER

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Abstract

The performance of Cell Averaging-Constant False Alarm Rate (CA-CFAR) degrades rapidly in nonideal conditions caused by the presence of a strong target signal in one of the reference cells. The Order Statistic-CFAR (OS-CFAR) is used to eliminate the reference cells with a strong input. The performance of the Conventional-Order Statistic (Conventional-OS) detector is evaluated to determine the signal-to-clutter ratio required achieving a particular probability of detection in clutter environments whose amplitude statistics are modelled by the Weibull distribution, and where the clutter dominates receiver noise. The performance is evaluated in both homogeneous and nonhomogeneous clutter. The analysis shows that the Conventional-OS detector is quite robust against the clutter edge effect.

1. INTRODUCTION

A target is detected when the output of the radar receiver crosses a predetermined fixed threshold level set to achieve a specified probability of false alarm. In many situations, however, the clutter echoes and or hostile noise can be much greater than receiver internal noise, when this happens, the receiver threshold can be exceeded and many false alarms can occur. In many applications where the noise can changes due to interference or varying clutter. The solution is an *Adaptive Threshold* adjustment, designed to keep the false-alarm probability constant despite changes in the background noise or interference. Many techniques can yield **C**onstant **F**alse **A**larm

Rate (**CFAR**), under specific restrictions. CFAR usually reduces the probability of detection compared to similar case at known and stable noise level. In a Cell-Averaging (CA-CFAR) system the threshold adjustment for a specified resolution cell is based on the average detected input from the neighbouring cells during the same pulse or scans. This method is works well when the background interference is statistically homogeneous over the range. This assumption is violated in two major situations [1]:

a) When the reference cells cross an edge in the clutter background.

b) When one or more reference cells include returns from other targets.

When the cell under test is in the clear side of the edge, in the original CA-CFAR, the reference cells in the clutter will unnecessarily increase the threshold, causing a decrease in the probability of detection. The Greatest Of-CFAR (GO-CFAR) strategy will worsen the problem. One solution here is to use the opposite strategy by selecting the lower of the two levels. This type is known as the "Smallest Of-CFAR" or *SO-CFAR.* The presence of a strong target signal in one of the reference cells is similar to the problem of having stronger clutter in several adjacent reference cells.

Several solutions to the problem of maintaining CFAR in multiple-target situations have been proposed. They yield better Performance but require more complex implementation. Rohling [1] suggested a different approach to the elimination of reference cells with a strong input. This is called Order Statistic-Constant False Alarm Rate (OS-CFAR).

Several nonlinear estimation techniques have been proposed to reduce the above problems. The nonlinearity may involve taking the average of the reference cells, and variations on these recent interest has also concentrated on order statistic (***OS***) detectors that use the *K* th largest on *M* range cells

Order Statistics characterize amplitude information by ranking observations in which differently ranked outputs can estimate statistical properties of the distribution from which they stem. The order statistic corresponding to a rank *K* is found by taking the set of M observations X(k), k=1,2,….,M, and ordering them with respect to increasing magnitude.(i.e. $x_1 \le x_2 \le x_i \le x_k \le \cdots \le x_M$) [2, 3, 4], the *K* th largest sample is taken as an estimate for the unknown noise level.

Most papers are limited to Rayleigh distributed receiver noise. Real word clutter statistics are generally not Rayleigh distributed so, the performance of the above algorithms can be substantially degraded. The model uses a Weibull distribution to model the clutter. The approximation technique is applied here to study the performance of the conventional-OS detector under uniform and nonuniform background distribution. The block diagram of the processor is shown in fig. (1)

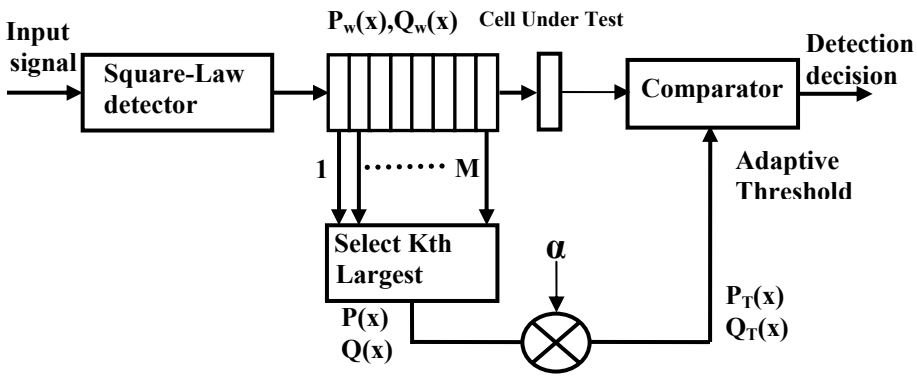


Fig. (1) Conventional-OS-CFAR Detector.

2. MATHEMATICAL MODEL

The processor is assumed to use an approximation of the magnitude, where **I** and **Q** are "*In-phase*" and "*Quadrature*" channels, respectively [5, 6] of the sampler that follows the matched filter to determine the threshold. A variety of probability density functions may be used to model this amplitude. The Cumulative Distribution Function (***CDF)*** of the Weibull distribution $Q_W(x)$ is given by [6, 7]:

$$Q_W(x) = 1 - \exp\left(-x^b/\gamma\right) \ , \ x \geq 0 \tag{1}$$

where b is the skewness parameter of the distribution and γ is the scale parameter, where both are greater than zero. At b=2 the distribution reduces to the Rayleigh distribution. Smaller values of b increase the skewness of the distribution, and allow the simulation of the *spiky* clutter. The probability density function of the Weibull distribution is the derivative of the CDF with respect to *x* [6, 7, 8]:

$$P_W(x) = \frac{d}{dx} Q_W(x) = \frac{b}{\gamma} x^{b-1} \exp\left(-\frac{x^b}{\gamma}\right), \quad x \geq 0 \tag{2}$$

The probability density functions in Fig. (1) $P(x)$ refers to the density function at the output of the order statistic calculator, similar notation for the cumulative distribution function $Q(x)$. The threshold multiplier α required guaranteeing a particular P_{fa} is determined as follows.

Since the threshold is modelled as a random variable, the P_{fa} is given by [1, 6, 8]:

$$P_{fa} = \int_0^\infty Q_T(x)\, P_T(x)\, dx \tag{3}$$

The cumulative distributions at the *OS* calculator output is given by [1, 6, 7]

$$Q(x) = \sum_{i=K}^{M} \binom{M}{i} \left[Q_W(x)\right]^i \left[1 - Q_W(x)\right]^{M-i} \tag{4}$$

The probability density function of the detector out of the order statistic calculator can be obtained by differentiating Eq. (4) with respect to x, which yields:

$$P_T(x) = P(x) = \frac{d}{dx} Q(x) = K \binom{M}{K} \left[1 - Q_W(x)\right]^{M-K} \left[Q_W(x)\right]^{K-1} P_W(x) \tag{5}$$

Since, one side of the reference cells is used in this detector, then, the CDF at the output of the multiplier is given by [6, 9]

$$Q_T(x) = Q\left(\frac{x}{\alpha}\right) \tag{6}$$

Eqs. (3) and (6) are used to calculate the values of the threshold multiplier α that gives a particular P_{fa}.

3. AVERAGE DETECTION THRESHOLD ALGORITHM

The ***A***verage ***D***etection ***T***hreshold (***ADT***) adopted here to evaluate the threshold algorithm, when square-law detection is used; is defined as [6, 8].

$$ADT = \frac{\alpha \overline{S^2}}{\mu}$$

where $\alpha \overline{S^2}$ represents the required signal energy to achieve a particular P_d, μ is the average noise power and *ADT* represents a required *SNR*.

The second moment of the output of the selection logic is used to obtain the ADT. The threshold multiplier α is squared when the squaring device is included [6, 7], the

ADT is then obtained from

$$ADT = \frac{1}{\mu}\alpha^{2}\overline{S^{2}} \tag{7}$$

Using the first derivative of $Q(x)$ for the specific detector, this is given by [6, 7]:

$$ADT = \frac{\alpha^{2}}{\mu}\int_{0}^{\infty} x^{2}\left[\frac{d}{dx}(Q(x))\right]dx \tag{8}$$

The mean noise energy is given by [6]:

$$\mu = \int_{0}^{\infty}\frac{b}{\gamma}x^{b+1}\exp\left(\frac{-x^{b}}{\gamma}\right)dx \tag{9}$$

Eqs. (4) and (9) are substituted into Eq. (8) to calculate the value of ADT for a particular value of α, which was previously calculated at different values of the skewness parameter b, and the result formula is:

$$ADT=\frac{\alpha^{2}}{\int_{0}^{\infty}\frac{b}{\gamma}x^{b+1}\exp\left(\frac{-x^{b}}{\gamma}\right)dx}\int_{0}^{\infty}x^{2}*\left[K\binom{M}{K}\left[1-Q_{W}(x)\right]^{M-K}\left[Q_{W}(x)\right]^{K-1}P_{W}(x)\right]dx \tag{10}$$

4. INTERFERENCE IN AN ESTIMATION CELLS

Extended analysis can be done when the interference exists within the estimation cells. If the interference is large, one or more of the cells used for background clutter estimation cells is well above the average value of the remaining cells. This interference could be caused by multiple aircraft flying information, or by jamming. If the interference is assumed to generate a constant return, then the density function describes a constant signal in Weibull- distributed background noise, else the cells are represented by different density function.

To avoid evaluating the weibull-plus-signal distribution functions, it is convenient to assume that the mean interference is much greater than the clutter in the remaining estimation cells. This approximation becomes more accurate as the returned energy from the interference increases relative to the energy in the remaining estimation cells. If one of the cells contains interference, the calculation is modified as follows. The P_{fa} is still given by Eq. (3). That is, the threshold multiplier is set with no interference

present. As in the non-interference case, Eq. (3) is solved for α, given a desired P_{fa}. The ADT is obtained from Eq. (8), using Eqs. (4), and (5) with Q(x) and P(x) as a function of M-1 estimation cells. Note that the actual cell occupied by the interference is irrelevant to this analysis.

5. CLUTTER BOUNDARIES ANALYSIS

The real world clutter background is not identically distributed among the estimation cells. This nonhomogeneity in the background environment occurs when one or more of these cells contain additional energy either from multiple targets or from intentional jamming. The reference channel is always assumed to be homogeneous and representative of the primary target distribution under the null hypotheses

The clutter boundary is modelled as a step function discontinuity in noise power. The window of size *M*, it is assume that there are R cells coming from heavy clutter region each with power level $\mu_c(\mu_c = \mu(1+CNR))$ [9, 10], where *CNR* denotes the clutter-to-thermal noise ratio, and the remaining M-R cells having thermal noise only with power level $\mu_t(\mu_t = \mu)$ each. The observations in both cases are assumed to be statistically independent. Then, the *CDF* of the *K* th ranked cell has a form given by [8, 11];

$$Q(x) = \sum_{i=K}^{M} \sum_{J=\max(0,\, i-R)}^{\min(i,\, M-R)} \binom{M-R}{J} \times \left[Q_1(x)\right]^{J} \times \left[1-Q_1(x)\right]^{M-R-J} \binom{R}{i-J} \left[Q_2(x)\right]^{i-J} \left[1-Q_2(x)\right]^{R-i+J} \tag{11}$$

$Q_1(x)$ and $Q_2(x)$ denote the CDFs of the Rayleigh and Weibull distributed receiver noise of the reference cells respectively.

Equation (11) can now be substituted into Eq.(3) to obtain the P_{fa} at clutter boundaries. The threshold Multiplier α is adjusted using Eq. (3) to yield a particular P_{fa} in *Rayleigh- distributed* receiver noise for the selected *OS* cell. Next, a clutter is passed through the estimation cells before the test cell. These cells consist of *Weibull-distributed* clutter having a variance (20 dB for example) above that used to initially set the threshold. The front advances one estimation cell at a time until it covers all the cells. During this period, the target test cell remains in *Rayleigh-distributed* receiver noise. After that, the test cell is assumed to respond to *Weibull-distributed*

clutter. Thus, a substantial performance change occurs when the clutter crosses the M the estimation cell.

The background energy μ in Eq. (9) has one of two values, depending on whether or not the test cell responds to clutter.

6. SIMULATION RESULTS

6.1 Threshold multiplier amplitude

To determine the threshold multiplier amplitude (α), it is convenient to normalize W so that it has unity mean, then γ in Eq. (1) can be set to unity [6]. The threshold multiplier α is determined under the hypothesis that the noise alone is present in the reference channel. The value of α for detector is numerically computed by solving Eq. (3). In all numerical results, the window size M is 24 cells and two values of P_{fa} are assumed: 10^{-4} and 10^{-6}.

It can be seen that from Fig.(2), the threshold multiplier α decreases as the order statistic cell K increases. As the skewness of the Weibull distribution increases (i.e. as b decreases), the threshold multiplier values (α) increases, raising the threshold to account for noise spikes.

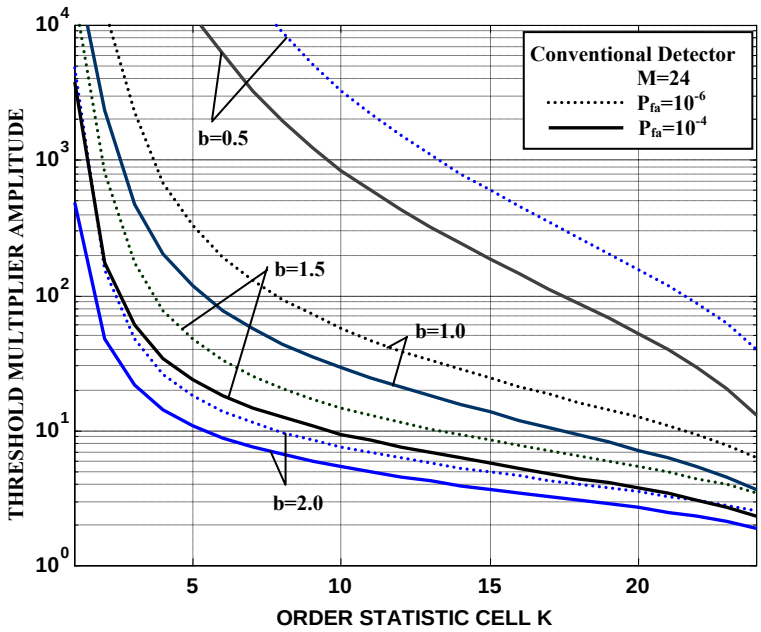


Fig (2) Threshold Multiplier Amplitude for the conventional-OS-CFAR, with various values of b and P_{fa}.

6.2 Average detection threshold calculation (ADT)

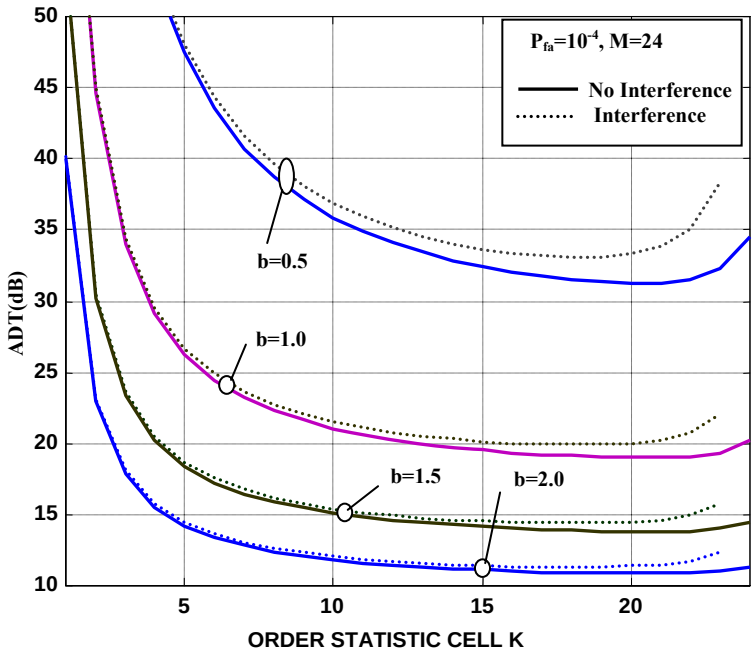
The ADT is now calculated for the detector. Eq. (8) is used to calculate the ADT for the detector. The ADT is obtained from this equation with $Q(x)$ and $P(x)$ as a function of (M-1) estimation cells for single interference case. The threshold multiplier is set with no interference present in the reference cells, and its values are obtained by solving Eq. (3), which was previously calculated for the design values of P_{fa} (10^{-4} and 10^{-6}), and different skewness parameter b. Fig. (3a) is plotted at $P_{fa}=10^{-4}$.

In the four pairs (b) that end at M=23 represents the single interference case, with interference case the best performance (i.e. smallest ADT) occurs near K=18. With no interference case, the best performance occurs also near K= 20. The same results are obtained in Ref.[6] for GO-OS detector. A relatively wide performance plateau exists for K between 17 and 22 for the Rayleigh amplitude (b=2) case within which the ADT varies less than 0.2 dB and K between 14-22 for GO-OS [6], the width of this plateau decreases for more spiky clutter. The detector introduces a higher loss in case of single interference compared with GO-OS detector; this is due to using single side of the reference window. The higher loss occurs at higher values of K for this detector, so, the smaller values of K can accommodate many interference-dominated clutter estimation cells in *Rayleigh* clutter, and this option becomes less attractive as the clutter becomes spikier.

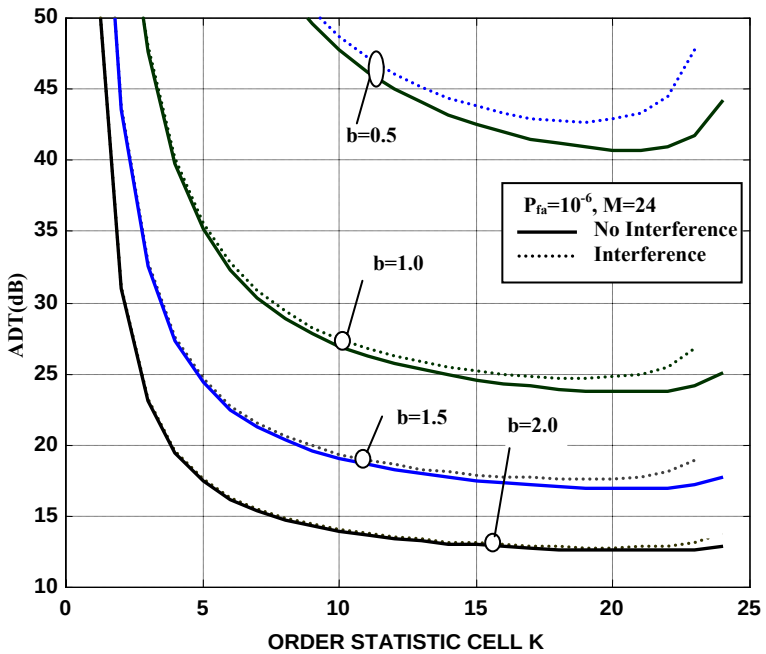
The interference causes a performance loss of only 2 dB or less for $b \geq 1$ and K=20, 1 dB for GO-OS detector under the same conditions. The performance is degraded by about 21 dB as b varies from Rayleigh to Weibull with b=0.5 and 19 dB for GO-OS detector. Fig. (3b) is plotted for $P_{fa}=10^{-6}$, the same results approximately are obtained. The ADTs are all higher and more degradation is caused by the interference (additional CFAR loss).

6.3 Order statistic cell (K)

The threshold multiplier α is calculated to guarantee $P_{fa}=10^{-4}$ at a value of b=1.5**.** The representative rank K, which makes P_{fa} insensitive to uncertainty in the clutter distribution model, is taken as an even number (for example). Then Eq. (3) is used to calculate the P_{fa} at different values of *b*. Fig. (4) Shows this result for the detector.



(a) $P_{fa}=10^{-4}$.



(b) $P_{fa}=10^{-6}$

Fig (3) ADT versus Conventional-OS cell K. (a) $P_{fa}=10^{-4}$, (b) $P_{fa}=10^{-6}$

From this figure, K=24 (i.e., the maximum value of M) shows the least sensitivity to changes in b. Similar results are obtained when the threshold is adjusted with $0.5 \le b \le 2$, Also, the same results are obtained when the design value of b=1.0. Thus, the higher values of K (K=24) is capable of maintaining a particular P_{fa} in

uncertain clutter background. The best performance (least sensitivity to change in b) occurs at $K \geq 18$ for this processor.

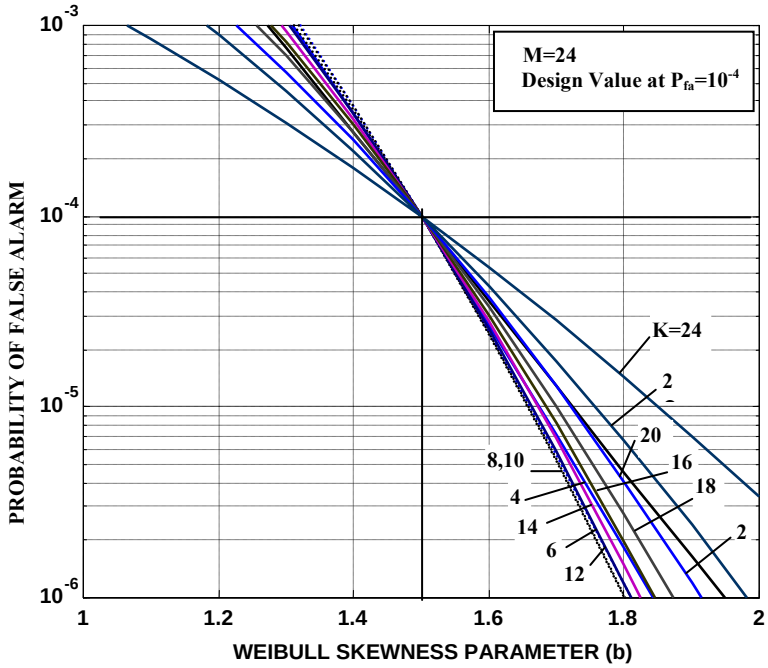


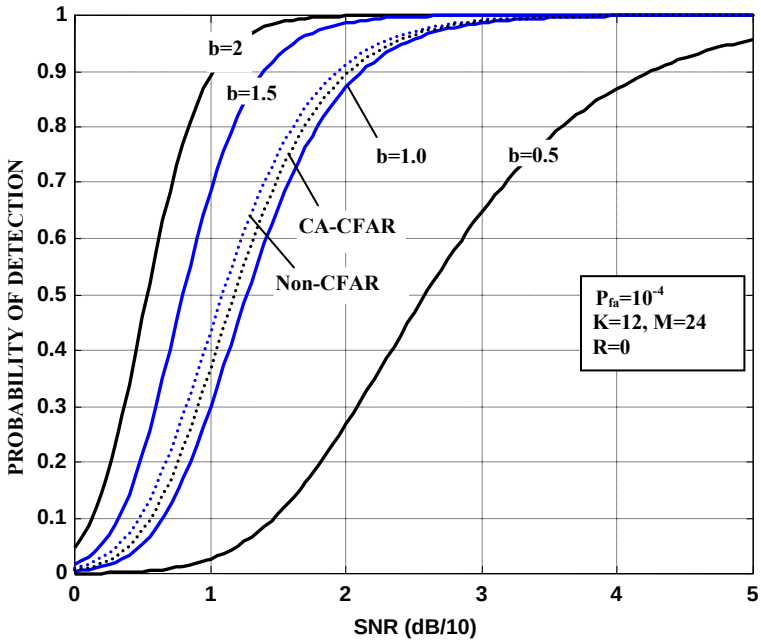
Fig (4) Sensitivity of P_{fa} to b for $P_{fa}=10^{-4}$, b=1.5

6.4 The detection performance of the detector

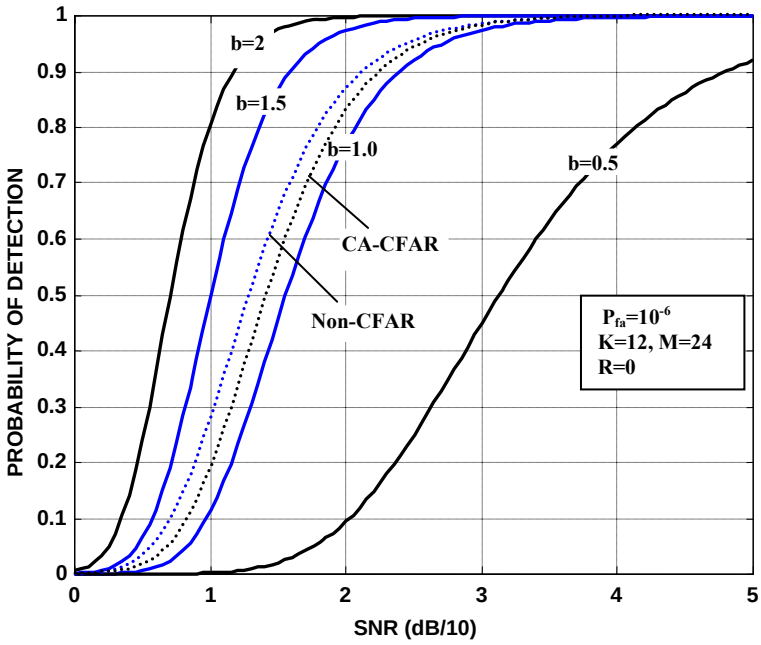
Fig.(5a) represents the detection performance in homogeneous background of the processor as a function of the primary target (SNR in dB), $P_{fa}=10^{-4}$ for window size M=24, K=12 and the skewness parameter b is variable. Also in the same figures the CA-CFAR and Non-CFAR processor detection performance curves are plotted, the equations of CA-CFAR processor are not mentioned and it is exist in many different papers [1, 7, 8, and 13]. Eq. (3) is used to calculate the P_d of this Processor with the assumption that the noise power has Rayleigh distribution (i.e. $\mu = 1$) and $\alpha_d = \alpha / \mu \left(1 + \overline{SNR}\right)$. From the displayed results, the detection probability increases by increasing SNR values, and it decreases for more skewed Weibull clutter (b). So, the SNR loss increases as b decreases. For the same parameters and K=18 as expected, the SNR loss decreased for this processor as in fig. (6). Finally, the detection Performance decreases as P_{fa} increases, figs. (5b) to (6b) are plotted at $P_{fa}=10^{-6}$.

Now it is suitable to assume that the noise power (μ) in the reference cells has the same shape of the noise in the test cell. From fig. (7), it can be seen that the required SNR values for achieving P_d=0.5 decreases as b decreases. This means that it

can be chosen this detector for more skewed Weibull distribution at K=12. For K=18, fig. (8), the SNR increases for more skewed Weibull distribution. Smaller values of SNR required achieving a specific P_d at higher values of b. The loss increases for more skewed Weibull distribution.



(a) $P_{fa}=10^{-4}$.



(b) $P_{fa}=10^{-6}$.

Fig (5) Probability of Detection against SNR with various Weibull skewness parameter b and Non-CFAR Processor, (a) $P_{fa}=10^{-4}$, (b) $P_{fa}=10^{-6}$ (M=24, K=12, R=0).

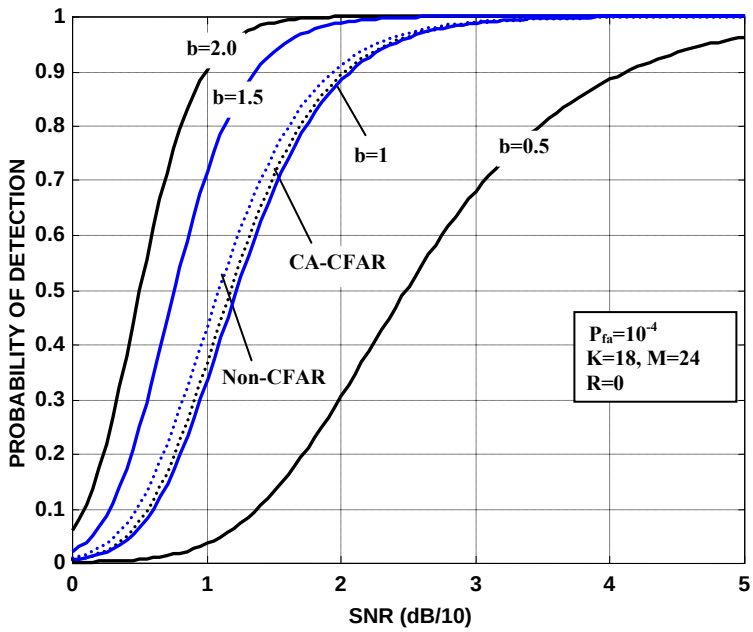
By comparing the two cases at K=12, b=1 the required SNR to achieves Pd=0.5 is 5.25 dB and 7 dB at K=18, the SNR required to achieve P_d=0.5, K=18 increased for more skewed Weibull distribution. The reason of this case, is the ability of cancellation more spikes signals for K=12 than K=18.

From the last two curves, the loss increased for the detector as K increased from 12 to 18. At this case, it can be find a value of the order statistic cell K that make the detector less sensitive to the variation of the skewness parameter b, fig. (9) Shows that for K=13, the SNR increases by about 2.4 dB as b varies from 2 to 0.1. This means that the best performance of the detector is obtained by selecting the order statistic cell (K) near the 55% percentile out of the total cells M, where at this value, the detector is less sensitive to the shape of the clutter distribution.

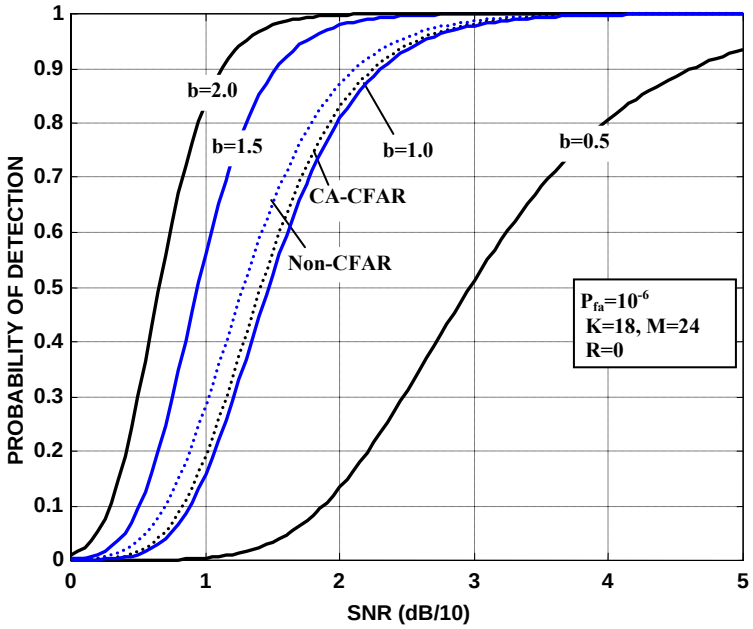
6.5 The performance at clutter boundaries

The P_{fa} is determined using Eq. (3) for the detector, with Q(x) as given in Eq. (11). The threshold multiplier values are calculated previously in section (6.1) for the selected order statistic cell (K=18) and CNR=20 dB. From fig. (10) the alarm probability is slowly decreases when fewer than (M-K+1) cells immersed in clutter. While in the same case the P_{fa} rapidly decreases in the simple CA-CFAR. So, the clutter power has less effect on the performance of the conventional OS-CFAR. The more skewed Weibull distribution has less decrease in the P_{fa}, and less required SNR to achieve the desired P_d.

For the same parameters the probability of detection can be calculated by solving Eq. (3) with $\alpha_d = \alpha / \mu \left(1 + \overline{SNR}\right)$ and the SNR=20 dB, these results are plotted in fig. (11). The P_d decreases when more than (M-K) cells immersed in clutter. With the most skewed Weibull clutter showing the greatest increase in the detection probability. Fig. (12) Shows the detection probability in the presence of clutter power transition (R) when the test cell responds to Weibull distributed (b=1) primary target at SNR=20 dB. The masking of the primary target occurs when there are less than (M-K+1) cells lying under clutter power transition's effect. Also, the more skewed Weibull clutter showing the more decrease in the detection probability.



(a) $P_{fa}=10^{-4}$.



(b) $P_{fa}=10^{-6}$.

Fig (6) Probability of Detection against SNR with various Weibull skewness parameter b and Non-CFAR Processor, (a) $P_{fa}=10^{-4}$, (b) $P_{fa}=10^{-6}$. (M=24, K=18, R=0).

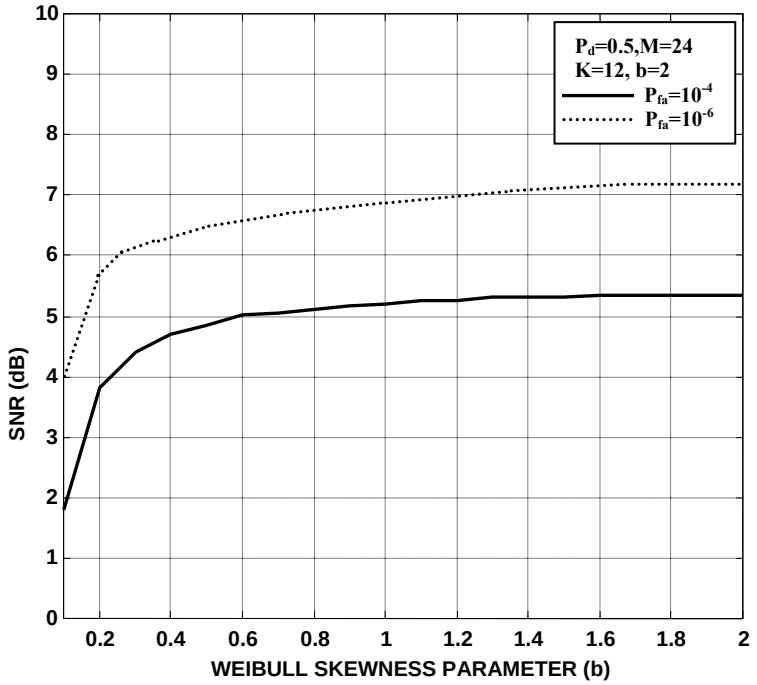


Fig. (7) SNR versus Weibull skewness Parameter b, (Design at b=2, M=24, K=12, P_d=0.5)

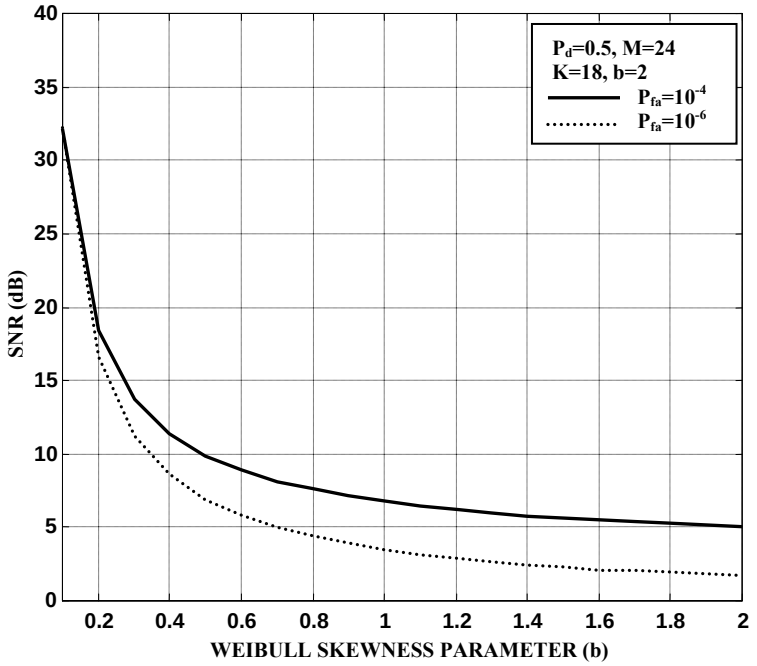


Fig. (8) SNR versus Weibull skewness Parameter b, (Design at b=2, M=24, K=18, P_d=0.5)

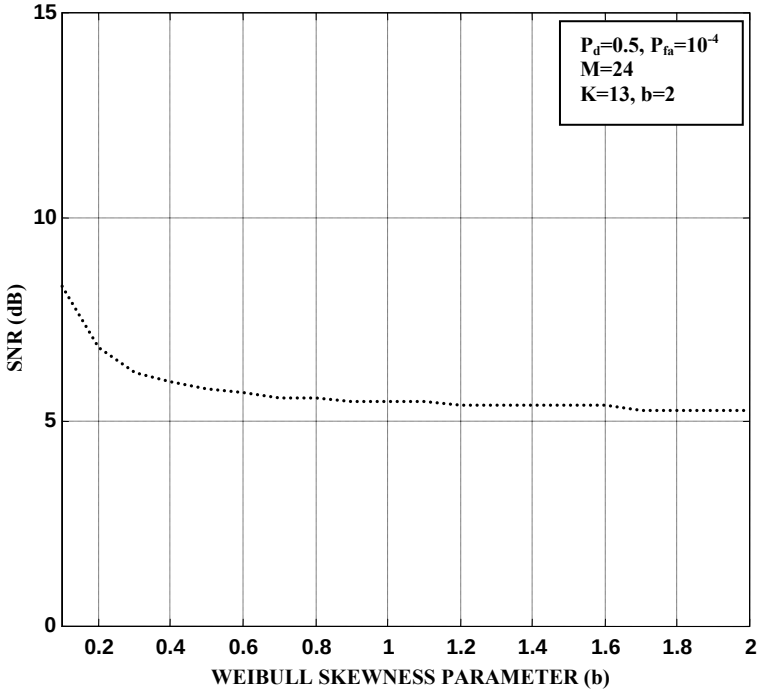


Fig. (9) SNR versus Weibull skewness parameter b, (Design values at b=2, M=24, K=13, P_d=0.5)

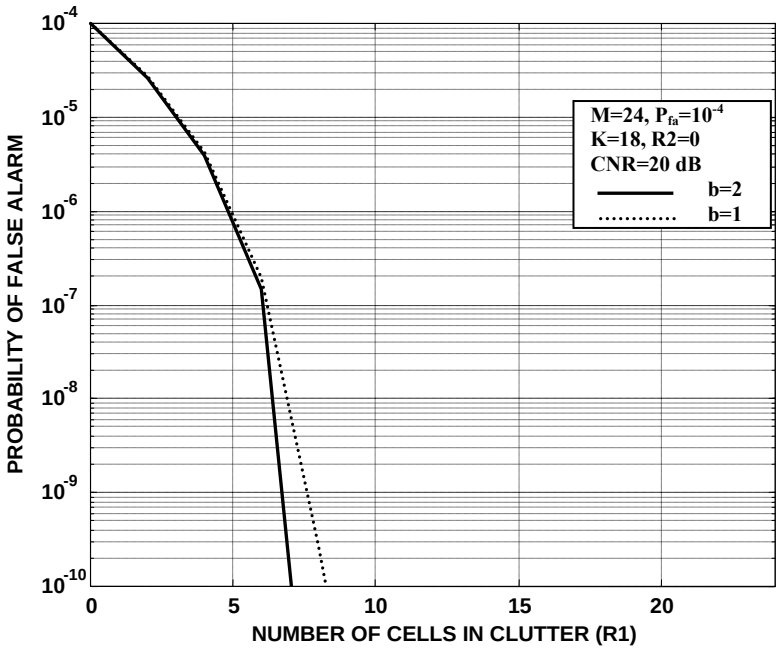


Fig. (10) P_{fa} versus the number of cells (R1) lying in clutter. (K=18, R2=0, $P_{fa}=10^{-4}$, CNR=20 dB)

In general, the P_{fa} achieved by the OS-CFAR family (GO-OS, SO-OS and the Conventional-OS) increases as the clutter increases, the GO-OS and the Conventional OS detectors has the best performance at clutter edges

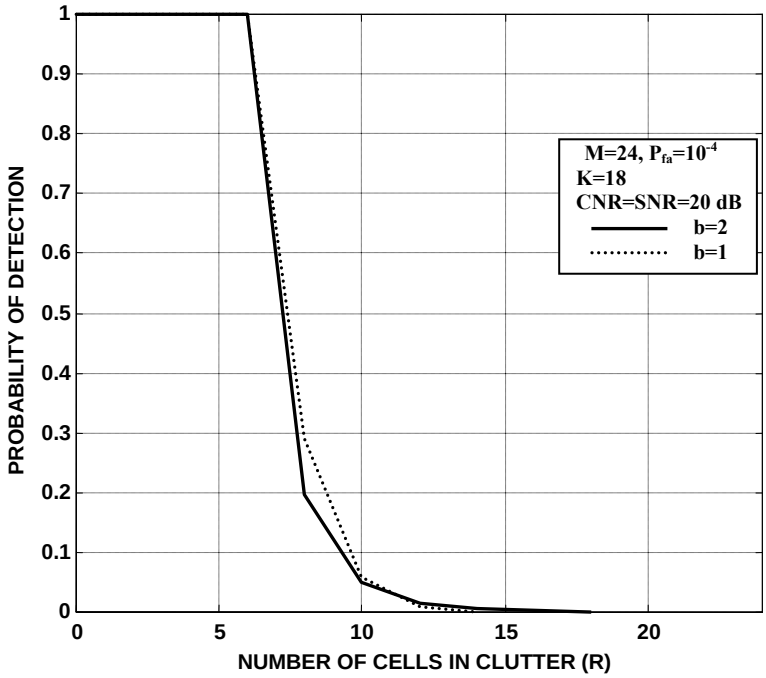


Fig. (11) P_d versus the number of cells (R) lying in clutter. (K=18, $P_{fa}=10^{-4}$ and CNR=SNR=20 dB)

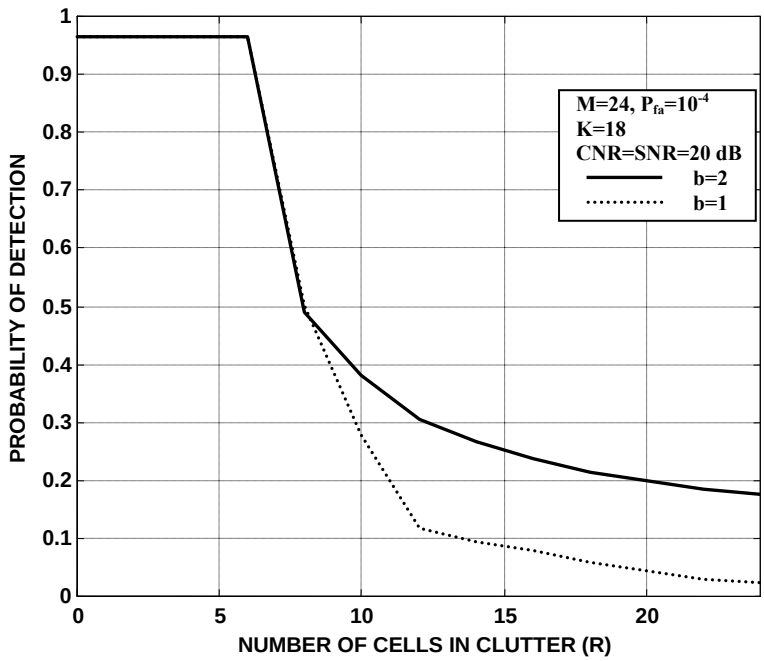


Fig. (12) P_d versus the number of cells (R) lying in clutter and the cell under test lying in Weibull distributed clutter (b=1). (K=18, $P_{fa}=10^{-4}$, CNR=SNR=20 dB)

6.6 Neyman pearson test of the detector

A simulation of Independent Identically Distributed *Rayleigh* and *Weibull* distributed data [12] is used to test the detector for a window size M=24, K=18, $P_{fa}=10^{-4}$ and the skewness parameter (b) is assumed known a priori.

Using 300 samples, multiple 16 dB point targets have been added at samples 70-105, isolated target at 150 and potentially masked target at 222 by the 15-dB edge at 240 onwards. With reference to fig. (13a):

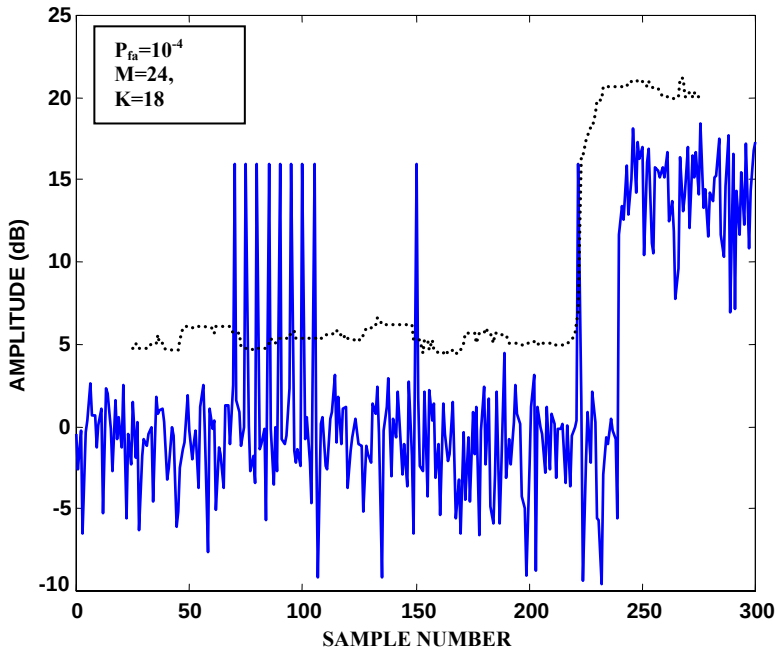
1. Multiple targets cause masking for this processor. The target near the clutter edge is also completely masked and very abrupt changes are seen in the threshold.
2. The conventional OS detector is extremely sensitive to clutter edge.

It can be seen that this detector are capable of overcoming the multiple target problems and is extremely sensitive to the clutter edge. With some going undetected for simple Cell Averaging-CFAR.

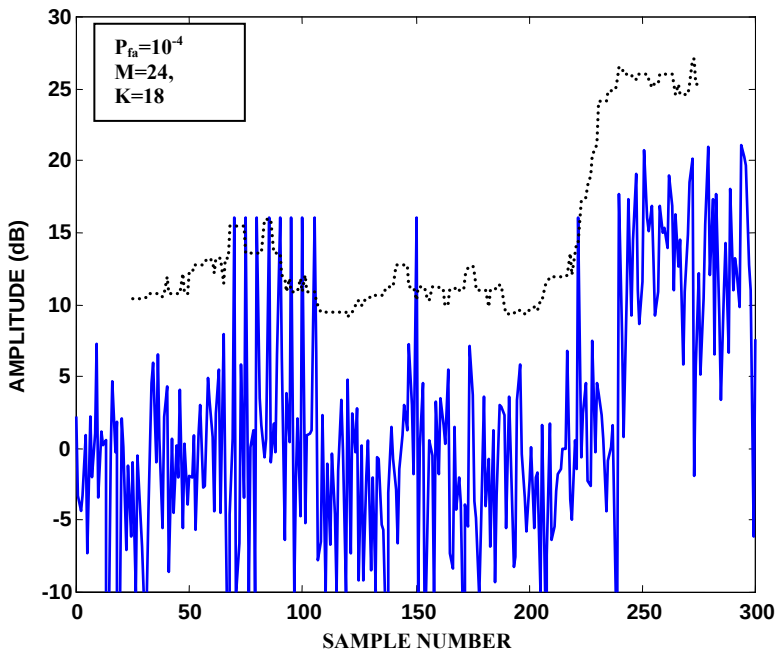
Fig. (13b) shows the effect of decreasing the value of the skewness parameter (b=1). The threshold level increases as b decreases; also, the fluctuation of the amplitude of the threshold is increases as b decreases for the same value of K, the detection probability decreases as b decreases. For more skewed *Weibull* distribution (b=0.5), (this curve is not shown) the required SNR for adjusting P_d at 0.5 should be increases as in fig. (5) and fig. (6) And the best detection performance can be obtained at this value (b=0.5).

For K=12, b=2, approximately, the same detection performance can be obtained as shown in fig. (14). More skewed *Weibull* distribution (b=1) has less effects on the performance of this processor and the processor becomes less sensitive to the uncertainty in the clutter distribution (i.e. lower adaptive threshold level than K=18) as shown in fig. (14b).

Fig. (15a) is plotted at K=20 and b=2, multiple targets would cause problems, some of these targets undetected. However, the value of K=M fig. (15b) cannot be used in practice due to suppression of targets this would give in the presence of multiple targets. In other words, for K=M the noise estimate x will be highest ordered sample which may contain in the interfering target echo with high probability.

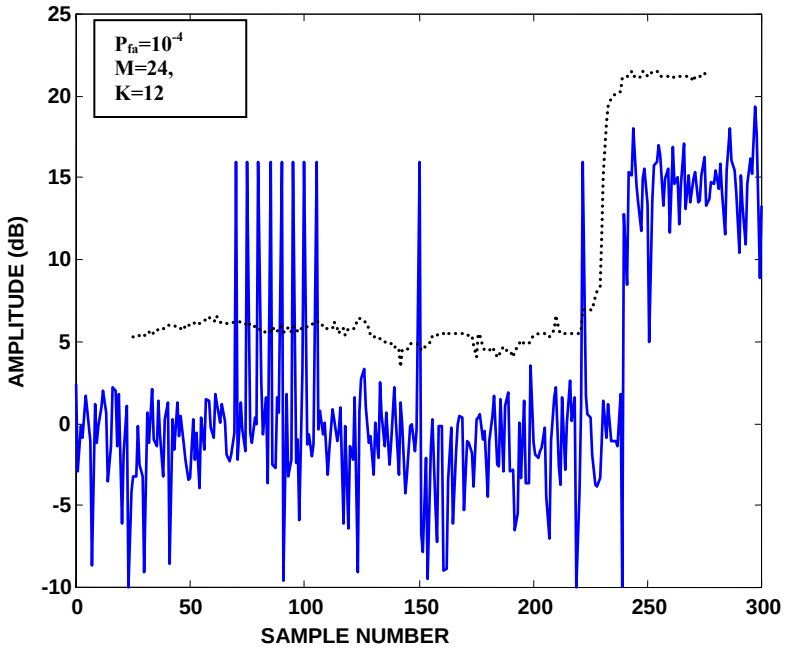


(a) Skewness parameter b=2

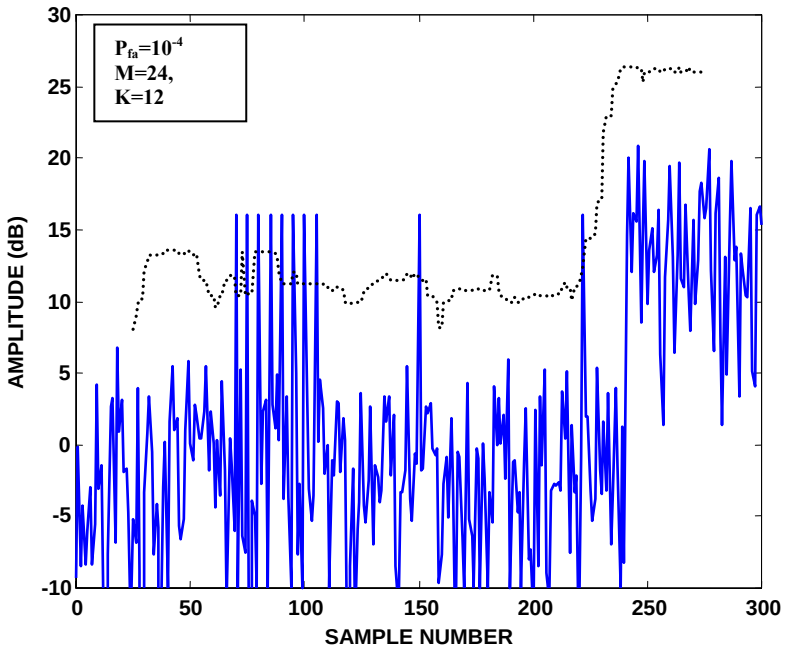


(b) Skewness parameter b=1

Fig. (13) NP test for the Conventional OS-CFAR. (a) b=2, (b) b=1. (M=24, K=18, $P_{fa}=10^{-4}$)

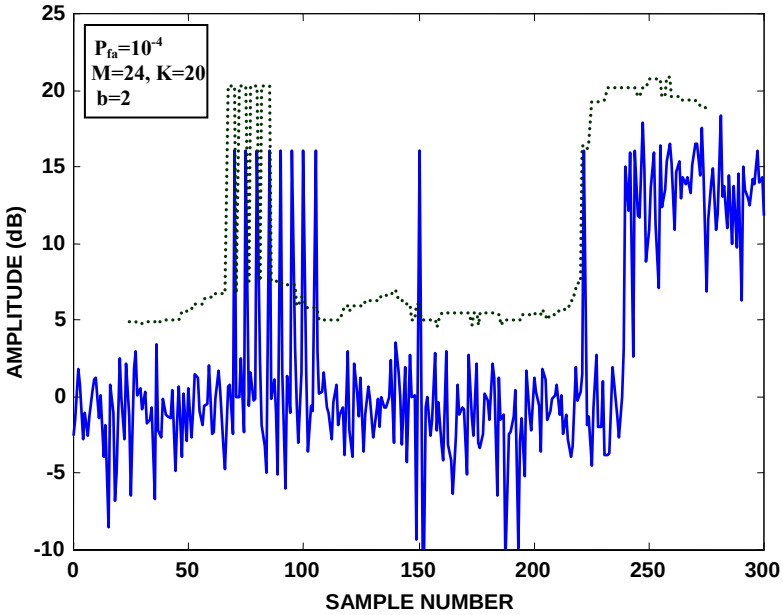


(a) Skewness Parameter b=2

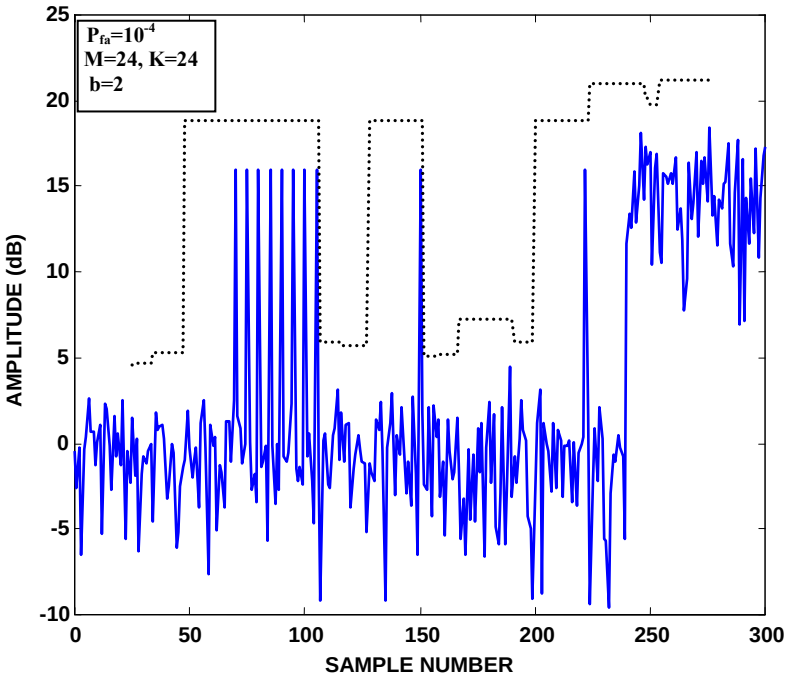


(b) Skewness Parameter b=1

Fig. (14) NP test for the Conventional OS-CFAR. (a) b=2, (b) b=1. (M=24, K=12, $P_{fa}=10^{-4}$)



(a) K=20



(b) K=24

Fig. (15) NP test for the conventional OS-CFAR. (a) K=20, (b) K=24. (M=24, b=2, $P_{fa}=10^{-4}$)

If a single extraneous target appears in the reference window, it occupies the highest ranked cell with high probability for the conventional OS detector; this will increase the overall threshold and may lead to the target miss. If, on the other hand, K is chosen to be less than the maximum value, the OS-CFAR processor will be influenced only slightly for up to M-K interfering targets, as in the past figures. The detector has the best detection performance under these conditions. For more results reference [6, 13] analyzed the performance of GO-OS under Weibull distributed clutter and reference [7] analyzed the performance of CA-CFAR by using FPGA Technology.

7. CONCLUSIONS

Limiting the number of false alarms that occur gives robustness to any detection scheme. At clutter edges, where both the power and type of statistics can vary abruptly, the CFAR detectors are lowered in performance. The Conventional-OS detector is used to reduce the effect of this problem, with reference to these results, most appealing conclusions are:

1) More skewed clutter distribution would require greater threshold increase, and greater concomitant increase in the required SNR.
2) The threshold multiplier values increases as the number of cells M, the order statistic cells K and the skewness parameter b decrease.
3) The best performance is obtained by selecting a cell near 75th percentile out of the order statistic calculator for this processor.
4) The Conventional OS-CFAR is found to be relatively insensitive to interference in one of the clutter estimation cells at different skewness parameter.
5) The best performance with single interference and with no-interference case occurs near K=18 for this detector.
6) The conventional OS detector provides good clutter boundary protection against abrupt changes in the unknown noise power level.
7) A selection of 55% out of the order statistic calculator makes the processor to be less sensitive to the variation in the skewness parameter.

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