Robust algorithms for point target detection in different background situations

Hermann Rohling

AEG Aktiengesellschaft, Research Center
Sedanstrasse 10, D-7900 Ulm

Resume:

On utilise des principes de detection ("constant false alarm rate, en anglais CFAR) dans les applications radar, sonar et infrarouge. Le but de ce principe de détection est une adaptation en fonction du clutter pour la détection des objets dans des situations variées. Divers principes de détection "CFAR" sont très discutés dans la littérature spécialisée.
Une comparaison des différents principes de détection CFAR est très compliquée du fait de la grande diversitée des situations de clutter. C'est de ce fait que la question de la robustesse joue un rôle important dans cette discussion.

Abstract:

In radar, infrared (IR), and sonar applications, so-called constant false-alarm rate (CFAR) detection procedures are used. The aim of adaptive threshold systems is target detection inside different local clutter situations. Some CFAR systems with different behavior, for example in changing clutter and multiple target situations, are currently under discussion in the literature. The comparison of different CFAR systems is complicated because of the numerous unknown clutter situations possible in the reference window. Therefore, the term "robustness" plays an important role in the discussion of these algorithms.

1. Introduction

The task of primary radar systems used in air or vessel traffic control is to detect all objects within the observation area and estimate their coordinates. Radar target detection procedures involve comparing the received signal amplitude to a theshold.
In order to obtain a constant false alarm rate in regions with unknown clutter level, a spatially local adaptive threshold must be applied. In real radar applications the targets are observed in different situations where the background is filled with clutter of varying extension and average power. Usually the background reflectors are denoted by the term clutter and very often the assumption in detecion theory is made that this clutter can be described by independent and identically distributed random variables inside the analyzed environment. This assumption is not very often fullfilled in practice. Therefore, modern radar target detection units use more than a single threshold system in the automatic detection process to adapt to the local background clutter and in order to control their false alarm rate, viz.:

- constant amplitude threshold T1 in pure noise situations
- a clutter map controlled threshold in ground clutter areas
- range CFAR procedures in local weather clutter regions.

The case with pure noise in the background signal and known average power leads to an amplitude threshold depending only on the required false alarm probability (Pfa). But temporally and/or spatially changing clutter situations make adaptive threshold systems necessary.

This paper gives an overview and a comparison of different CFAR systems which are currently under discussion and which are implemented for point target detection in 1-D and 2-D applications. Some questions concerning the implementation and choice of the system parameters will also be discussed. For 2-D applications, clutter map controlled detection algorithms are of high interest, which are used for adaptation in spatially non-homogeneous clutter backgrounds.

There are connections of these CFAR procedures to general image processing problems where so called rank filters (or median filters) are implemented for image enhancement applications (e.g. noise reduction, edge sharpening and contrast enhancement).

2. Point target detection with clutter map controlled thresholds

In the case of ground based radars the ground clutter echos in a single range azimuth cell are in general homogeneous, but these echos are spatially nonhomogeneous. This clutter behavior motivates the implementation of clutter map controlled threshold devices. From a statistical point of view it is assumed that the values $X_1, \ldots, X_N$, which are measured in different antenna scans and inside a single range azimuth cell, are independent and identically exponentially distributed. The single distribution parameter (average clutter power) differs from radar cell to cell.

A high resolution ground clutter map, with full range-azimuth resolution of the radar-raster image, stores the mean clutter power (or an estimation thereof) in each range azimuth cell. This estimation value C_n is updated in each scan and each radar cell by a recursive algorithm

$$C_n = a \cdot C_{n-1} + (1-a) \cdot X_{n-1} \tag{1}$$

In eq.1 X_{n-1} denotes the measured value of the (n-1)st antenna scan and inside the range azimuth cell considered. The weighting factor a is a constant parameter between $0 < a < 1$.
The resulting threshold for each cell is calculated as a product of the estimate C_n and a constant factor T which adjusts the probability of false alarms (Pfa).

$$\text{Threshold} = T \cdot C_n \tag{2}$$

Using this clutter map controlled device, the threshold can be adapted very precisely to the local ground clutter situation which is advantageous in detecting

tangetially flying targets which have no radial velocity component. On the other hand the estimation procedure in eq. 1 with a fixed weighting parameter a allows an adaptation to temporally slowly changing ground clutter background situations.
Nitzberg /1/ gives an analysis of the recursive estimation procedure of eq. 1. Spatially non-homogeneous clutter situations, where the expectation values $\hat{C}$ are different form cell to cell, are often described in statistical models with a log-normal or Weibull distribution. The probability of detection in such background situations and with clutter map controlled thresholds are given in /2/.

Figure 1 shows an example of a range azimuth area with spatially log-normally distributed mean clutter power values.

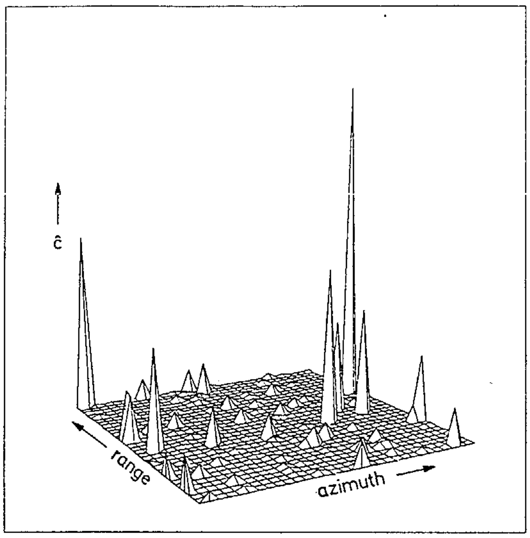

Figure 1: Spatial clutter behavior described by log-normally distributed mean clutter power $\hat{C}$.

3. Point target detection with sliding window range CFAR procedures

In the weather clutter case, the measured data inside a single range-azimuth cell and over several antenna scans can be used for estimation of the statistical parameters only with reservation since the weather clutter regions might move and change from scan to scan. Instead, the data from a single scan and local reference window enter into an algorithm for estimating statistical parameters used for target detection and clutter suppression. In existing range CFAR systems, target decision is commonly performed using the sliding window technique. Figure 2 illustrates the well known general structure of a 1-D CFAR system in a flowchart.

The data available in the reference window are used to calculate the decision theshold. This procedure is nearly the same in all range CFAR systems. The reference window in Fig. 2 is symmetrical to the test cell and split into two parts, the leading and lagging set of range cells.

Let $X_1, X_2, \ldots, X_N$ be the output values of a square law detector in N range cells and inside the reference window (see Fig. 2). In all examples we take the window length to be N=24 and a guard cell on each side of the test cell. The threshold in each CFAR system is optimized for homogeneous background situations and calculated for a fixed probability of false alarms, $Pfa=10^{-6}$

Conventional CFAR procedures suffer from the drawback that they are specifically based on the assumption of a homogeneous clutter background in the reference window with independent and identically distributed random variables. Improved CFAR procedures should be robust with respect to interfering signals generated by target returns in multiple target situations or by transition areas of different clutter sources.

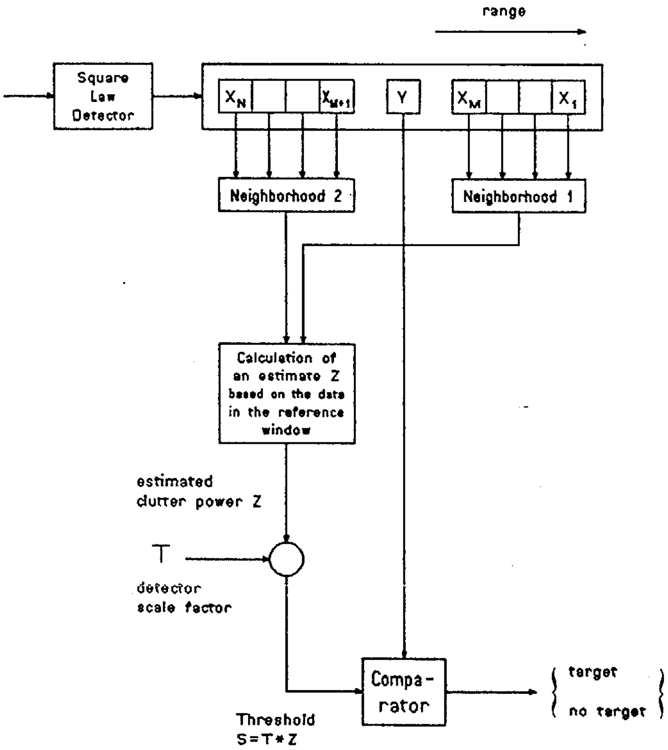

Figure 2:
General CFAR procedure for 1-D applications. The most important operation is the estimation of the clutter power level Z.

In the following, various CFAR procedures are described. A problem of adaptive target detection inside an unknown clutter background arises, for example, when a second target return is present inside the reference window and interferes the calculation of the average clutter level in the background area.

The well known cell-averaging CFAR calculates the arithmetic mean of the values inside the reference cells.

$$Z_{CA} = 1/N \sum_{i=1}^{N} X_i \tag{3}$$

In order to cope with local clutter phenomena, like weather clutter areas of small extend, the greatest-of (GO) CFAR /3/ takes the maximum of the two arithmetic means in the leading and lagging side of the reference window.

$$Z_{GO} = \mathrm{MAX}\left(2/N\left(\sum_{i=1}^{M} X_i,\ \sum_{i=M+1}^{N} X_i \right)\right) \tag{4}$$

In this paper we describe the behavior of all CFAR systems considered in four deterministic but characteristic target and clutter situations.

- small clutter areas with spatial extent of 10 or 15 range cells. The clutter power values are assumed to be independent and exponentially distributed.
- target situations where two targets come close in range (each target is observed in three adjacent range cells but with different amplitudes)

Figures 3 and 4 show the behavior of the CA and GO CFAR in these four situations and the poor target resolution of these two procedures. It can even happen with these devices that both adjacent targets are not detected since the threshold is raised drastically due to the interfering target signal power inside the reference window.

In radar literature different procedures are discussed and analyzed which have better behavior in multiple target and robust behavior in different clutter situations.

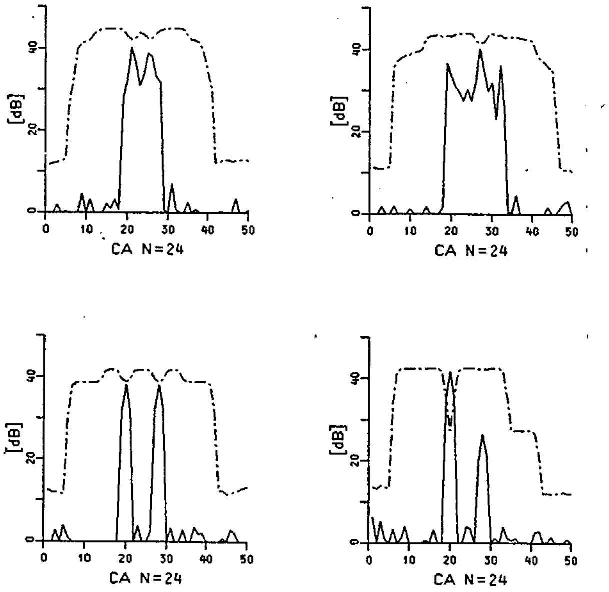

Figure 3:
Threshold response (dotted line) for CA CFAR in different target and clutter situations. The solide line shows the echo signal amplitudes in 50 range cells.

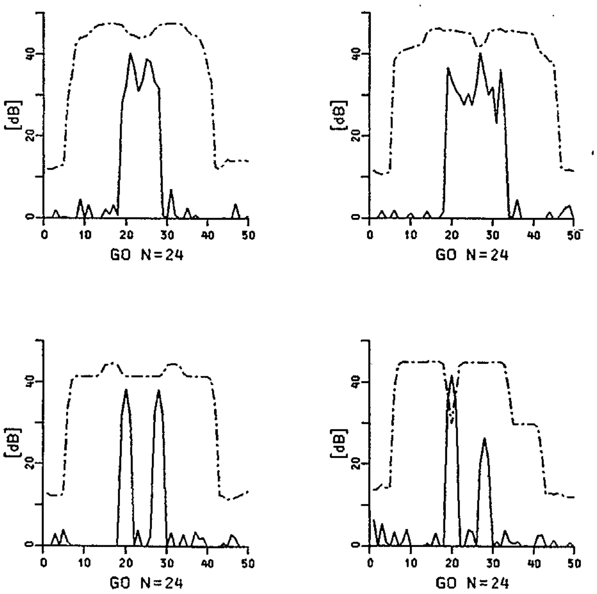

Figure 4:
Threshold response for GO CFAR in different target and clutter situatios

a) Censored algorithm /4,9/

Rickard and Dillard defined in /4/ a censored algorithm where the k largest values inside the reference window are censored (i.e. discarded from the sum Z in eq. 3). In /4/, simulation results are presented for the cases k=1 and k=2 which means the largest or two largest values are discarded from the sum Z.
Rictley /9/ described a generalized version of the censored mean level Detector. The implementation expense for this procedure is large since the sum and a part of the ordered amplitude sequence must be calculated for each reference window position. Fig 5 shows the behavior of this censored CFAR algorithm (for k=2) in the four signal situations considered in this paper. Since the assumed target extent covers three range cells but the CFAR algorithm descards only the two largest values of the reference window, the target resolution behavior is only fair, especially when small targets are in the neighborhood of large ones. But in general the target extent is unknown and sometimes it is necessary to discard more than the k=2 largest values.

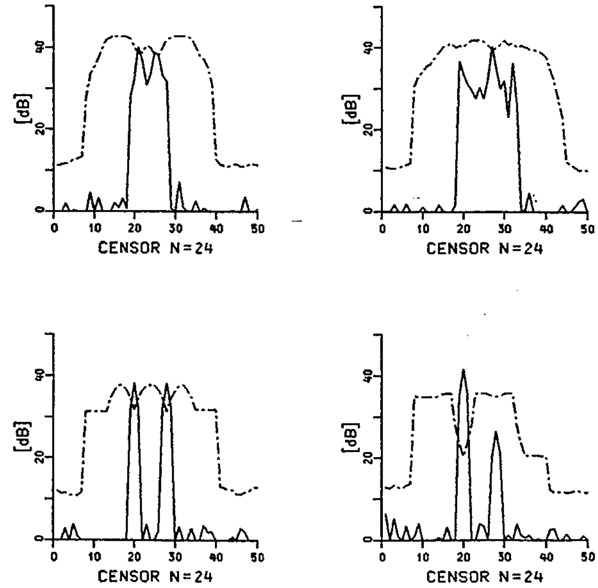

Figure 5:
Threshold response in different target and clutter situatios for the censored CFAR algorithm, which discards the two largest values (k=2) from the sum Z in eq. (3)

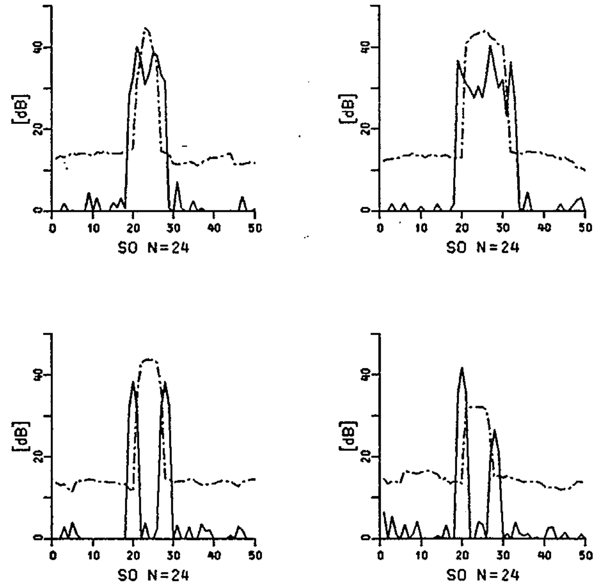

Figure 6:
Threshold response in different target and clutter situatios for SO-CFAR algorithm.

b) Smallest-of (SO) detector /5,6,10/

Trunk described in /5/ a so-called smallest-of (SO) CFAR procedure which calculates in eq. 4 the minimum of the two arithmetic means of the leading and lagging part of the reference window.

$$Z_{SO} = \mathrm{MIN}\left(2/N\left(\sum_{i=1}^{M} X_i,\ \sum_{i=M+1}^{N} X_i\right)\right) \qquad (5)$$

Weiss has given in /6/ a statistical analysis of this procedure. The additional CFAR losses occuring with SO-CFAR in homogeneous background situations are large (for N=32 reference window length and Pfa of 10-6 the additional loss is 1.76 dB in signal-to-noise ratio). But a real false alarm problem arises with this method in clutter edge situations. Fig. 6 shows the behavior of this SO-CFAR in the four signal situations and the poor adaptation to clutter edges.

c) Ordered statistic (OS) detector /7/

An ordered statistic of the amplitude values inside the reference window is analyzed in /7/. The amplitude of the test cell is compared with a theshold which is a constant multiple of the k-th largest amplitude out of the reference window. The additional CFAR-losses in homogeneous noise or clutter situations are small with OS-CFAR. The implementation expense is also small since only the ordered amplitude sequence must be calculated. In /11/ a CFAR procedure is described for two-parameter distributions (i.e. log-normal, Weibull, Gamma) and an ordered statistic method for parameter estimation. Fig. 7 shows the behavior of the OS-CFAR technique in the considered four signal situations.

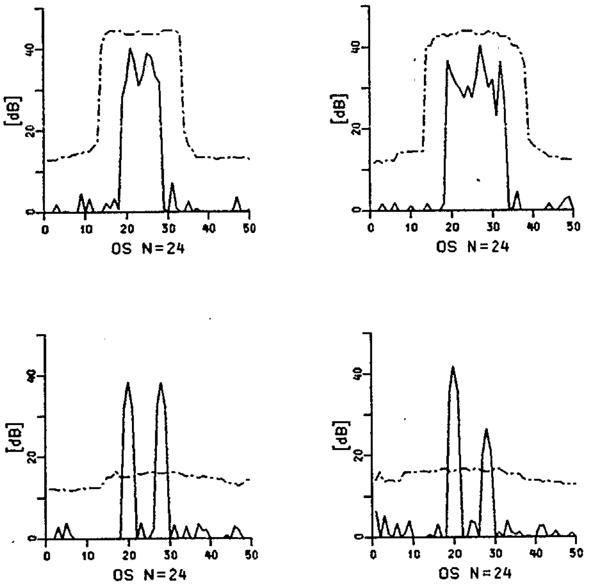

Figure 7:
Threshold response in different target and clutter situations for OS-CFAR algorithm where the k=17th largest amplitude inside the reference window is selected for the threshold calculation.

d) Adaptive censoring scheme /8/

Barboy et. al. /8/ proposed an iterative censoring scheme whereby the samples exceeding a first adaptive threshold are excluded from the reference window. This device works in more as one step. In the first step a theshold

$$Th1 = T_{CA} \cdot Z_{CA} \qquad (6)$$

is defined according to the cell averaging CFAR and the arithmetic mean of eq. 3.
Amplitudes which exceed this threshold Th1 are discarded from the sum. In the second step a new sum will be calculated. The procedure is continued until no amplitudes exceed the calculated threshold. Compared to the censored algorithm discussed by Rickard /4/ this adaptive censoring scheme does not always discard the largest amplitudes of the reference window, but only if these amplitudes exceed the calculated threshold.

4. Comparison

Point target detection devices in ground based radars use two adaptive threshold systems, a clutter map controlled threshold and a sliding window range CFAR with good target resolution behavior.

The censored algorithm /4,9/ behaves well in multiple target situations, but leads to high false alarm rates in the transistion area of small clutter regions. The smallest-of (SO) algorithm leads to very large false alarm rates at clutter edges. This procedure has good performance only in double target situations and is therfore not very robust against changing clutter background situations.
The ordered statistic CFAR procedure has good performance in all signal situations considered in this paper (clutter edges and double target situations).
The adaptive censoring scheme /8/ is an interesting device because it permits the detection of smaller targets in the neighborhood of larger ones. But the rare cases with two adjacent targets and the mutual cancellation effect, as shown in Figures 3 and 4, cannot be solved with this procedure.

References

/1/ Nitzberg, R., Clutter Map CFAR Analysis, IEEE Trans. Vol. AES-22, No 4, July 1986, pp 419-321

/2/ Rohling, H., Radar target detection with MTD processor in exponentially and Log normally distributed clutter, in Signal Processing III: Theories and Applications, I.T. Young et. al. (editors) EURASIP, 1986, The Haag, pp 1177-1180

/3/ Hansen, V.G., Sawyers, J.H., Detectability loss due to "greatest of" selection in a cell-averaging CFAR, IEEE Trans., Vol. AES-16, No. 1 (1980), pp 115-118

/4/ Rickard, J.T., Dillard, G.M., Adaptive Detection Algorithms for multiple target situations, IEEE Trans., Vol. AES-13, July 1977, pp 338-343

/5/ Trunk, G.V., Range Resolution of Targets Using Automatic Detectors, IEEE Trans., Vol. AES-14, No.5 (1978) pp 750-755.

/6/ Weiss, M., Analysis of some modified cell averaging CFAR processors in multiple target situations, IEEE Trans., Vol. AES-18, (1982), pp. 102-114

/7/ Rohling, H.: Radar CFAR Thresholding in Clutter and Multiple Target Situations. IEEE Trans., AES-19, (1983) 4, pp. 608-621

/8/ Barboy, B., Lomes, A., Perkalski, E., Cell-averaging CFAR for multiple-target situations, IEE Proc., Vol. 133, Pt. F, No.2 April 1986, pp 176- 186

/9/ Ritcey, J.A., Performance Analysis of the Censored Mean-level Detector, IEEE Trans., Vol. AES-22, No. 4 (1986), pp 443-454

/10/ Al-Hussaini, E.K., Ibrahim, B.M., Comparison of adaptive cell-averaging detectors for multiple-target situations, IEE Proc., Vol. 133, Pt. F, No. 3, (1986), pp 217-223

/11/ Weber, P., Haykin, S., Ordered Statistic CFAR Processing for Two-Parameter Distributions with Variable Skewness, IEEE Trans., Vol. AES-21, No. 6 (1985), pp 819-821