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InterCriteria Analysis approach in radar detection threshold analysis

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Abstract: In this paper, several types of conventional and Hough radar detectors with different structures of Constant False Alarm Rate (CFAR) signal processors are considered. In order to choose the most efficient for randomly arriving impulse interference environment structure a comparative analysis is carried out. The effectiveness of the Hough radar detectors are studied using InterCriteria Analysis (ICA) approach. The average detection thresholds of the conventional detector and the Hough detector with the CFAR processors are estimated. The experimental results are obtained by numerical analysis. The target echo signal fluctuates according to a Swerling II case model. It has a Poisson distribution of the probability for appearance and Rayleigh distribution of the amplitudes. The research work is performed in MATLAB computational environment. The obtained results can be used both in radar and communication receiver networks.

Keywords: InterCriteria Analysis, Signal processing, Hough radar detector, CFAR signal processor, Randomly arriving impulse interference, Average detection threshold.
AMS Classification: 03E72.

1 Introduction

In signal processing, the surveillance area of a modern radar is conventionally divided into resolution cells "range–azimuth–elevation". Usually the geometrical dimensions of small airborne target images do not exceed of the radar resolution cells. Consequently natural parallelism of signal processing can be used in design of a processor architecture for target detection, i.e., all resolution cells can be processed independently from each other. For these reasons an original parallel algorithm for small airborne target detection in a single resolution cell is described in [15]. The problem of small airborne target detection is formulated as detection of a single pulse train on the background of Gaussian noise and interference. The signal desired and noise are statistically described as a set of independent segments of random Gaussian processes with unknown parameters. It is assumed that signal processing is performed in the processor after preliminary amplitude (linear or square-law) detection and analog–to–digital conversion of the received signals. Signal processing in the processor includes non-coherent pulse–to–pulse integration and adaptive detection of the integrated signal as the value of the integrated signal is compared with preliminary determined adaptive threshold. Target detection is declared if the signal value exceeds the threshold. The threshold is formed by estimating of the noise level in the reference window. The estimate of the noise level proposed by Finn and Johnson [16] is often used.

Numerous papers consider the case when the detection is held in conditions of homogeneous interference with unknown intensity and randomly arriving impulse interference with known parameters [9–15]. In this paper, comparative analysis of the performance of conventional detectors and two types of CFAR processors used in the algorithm of Hough detector are carried out. In this paper is presented the detectors effectiveness using the ICA approach for the achieved results for adaptive detection threshold of different detector structures in conditions of non-homogeneous background, which are presented in papers [9–15].

2 Problem formulation

In a CFAR processor, the square - law detected received signal is sampled in range and in time. The sampled signal is stored in the input processor memory like a data matrix. Let us assume that L pulses hit the target which is modeled according to Swerling case II. The received signal is sampled in range by using $M + 1$ resolution cells resulting in a matrix with $M + 1$ rows and L columns. Each column of the data matrix consists of the values of the signal obtained for L pulse intervals in one range resolution cell. Let us also assume that the first $M/2$ and the last $M/2$ rows of the data matrix are used as reference cells in order to estimate the "noise–plus–interference" level in the test resolution cell of the radar. In this case the samples of the reference cells result in a matrix X of the size $M \times L$. The test cell or the radar target image includes the elements of the $M/2 + 1$ row of the data matrix and is a vector Z of the length L. In the presence of randomly arriving impulse interference, the elements of the reference window are drawn from two classes. One class represents the noise only with the probability $(1-\varepsilon_0)$. The other class represents the interference–plus–noise with the probability ε_0.

The elements of the reference window are independent random variables with the compound exponential distribution law:

$$f(x_i) = \frac{1-\varepsilon_o}{\lambda_o} \exp\left(\frac{-x_i}{\lambda_o}\right) + \frac{\varepsilon_o}{\lambda_o(1+r_j)} \exp\left(\frac{-x_i}{\lambda_0(1+r_j)}\right), \quad i = 1, N, \tag{1}$$

where $N = ML$ and λ_0 is the average power of the receiver noise, r_j / λ_o is the average per pulse value of the "interference-to-noise" ratio at the receiver input. In the presence of a desired signal from a target the elements of the test resolution cell are independent random variables with the following distribution law:

$$f\left(z_i\right) = \frac{1-\varepsilon_o}{\lambda_o\left(1+s\right)}\exp\left(\frac{-z_i}{\lambda_o\left(1+s\right)}\right) + \frac{\varepsilon_o}{\lambda_o\left(1+r_j+s\right)}\exp\left(\frac{-z_i}{\lambda_0\left(1+r_j+s\right)}\right), i = 1, L, \qquad (2)$$

where s is the average per pulse value of the "signal–to–noise" ratio at the receiver input. In a CFAR processor, the estimate of the noise level is formed as a sum of the samples from the reference window:

$$V = \sum_{m=1}^{M}\sum_{l=1}^{L} z_{ml}. \qquad (3)$$

Let q_o be the signal formed by summing the elements of the test resolution cell:

$$q_o = \sum_{l=1}^{L} z_l. \qquad (4)$$

Then the target is detected according to the following algorithm:

$$\begin{cases} H_{1:} : \Phi\left(q_o\right) = 1, q_o \geq T_\alpha V \\ H_o : \Phi\left(q_o\right) = 0, q_o < T_\alpha V \end{cases}, \qquad (5)$$

where H_1 is the hypothesis that the test resolution cell, i.e., $\vec{Z}$ contains the echoes from the target and H_0 is the hypothesis that the test resolution cell, i.e., $\vec{Z}$ contains the receiver noise only. The constant T_α is a scale coefficient, which is determined in order to maintain a given constant false alarm rate. The probability of target detection is determined as:

$$P_D = \int_0^\infty f_V(V)dV \int_{T_\alpha V}^\infty f_q(q_0 / H_1)dq_0, \qquad (6)$$

where $f_V(V)$ is the probability density function of the noise level estimate and $f_q(q_0 / H_1)$ is the conditional probability density function of the test summed signal under hypothesis H_1.

The probability of false alarm is determined by substituting $s = 0$, that is:

$$P_{FA} = \int_0^\infty f_V(V)dV \int_{T_\alpha V}^\infty f_q(q_0 / H_0)dq_0, \qquad (7)$$

where $f_q(q_0 / H_0)$ is the conditional probability density function of the test summed signal under hypothesis H_0.

For the radar detector efficient is used the ratio between two values of "signal–to–noise" ratio for different CFAR processors, measured in dB. This approach is considered in [18]:

$$\Delta[dB] = 10\log\frac{SNR\big|_{CFAR_1}}{SNR\big|_{CFAR_2}}, \text{ by } P_{FA} = const,\ P_D = P_D^{CFAR_1} = P_D^{CFAR_2} = 0.5. \quad (8)$$

The probability characteristics of the researched detectors are presented in the following papers [9–15].

3 Numerical results

The current estimation of the noise level in the reference window forms the detection threshold. To estimate the noise level for radar signal detection in clutter environment with unknown average power level often the technique is used. In the present paper several types of detector structures with CFAR signal processors are investigated in order to choose the most efficient one in the randomly arriving impulse interference. The presence of strong pulse interference in the test resolution cells and in the reference cells can cause drastic degradation in the processor performance. This interference is non-stationary and non-homogenous and is often caused by adjacent operating radar or other radio-electronic devices. In this paper is considered the limit case when increasing the probability of appearance (ε_0) changes the distribution law from Poisson to binomial [8]. It is assumed that the noise amplitude is Rayleigh distributed and the noise power is exponentially distributed.

Using the results obtained from the threshold analysis for the different radar structures, in this paper is applied intercriteria analysis approach to determine the effect of various parameters on the detection process. The impact of the average power of the receiver noise, the adaptive detection threshold, the number of resolution cells and the average interference–to–noise ratio is considered.

The achieved results for CFAR detector threshold analysis with three values of the probability of false alarm (P_{FA}=10-4, 10-6, 10-8), for two values of number of observations in the reference window (*N* = 16, 32), for two values of number of observations in the reference window (*L* = 16, 32), for two values of average interference–to–noise ratio (*INR* = 10, 30 dB) and for five deferent values for a probability of appearance of impulse interference (ε_0 = 0, 0.01, 0.033, 0.066, 0.1) with average length in the range cells are presented in Table 1.

A detailed performance analysis of a Hough detector with Excision Binary Integration CFAR processor is presented in paper [13]. Its behavior has been studied for different values of the threshold constant and for different values of the probability for the appearance of impulse interference in Hough parameter space. The experimental results are obtained for the following input parameters: average power of the receiver noise λ_0 = 1; average interference–to–noise ratio (*INR* = 30dB); probability for the appearance of impulse interference with average length in the range cells from 0.1 to 0.9; number of reference cells *N* = 16; number of test cells *L* = 16; probability of false alarm $P_{FA} = 10^{-4}$, excision threshold B_E = 2, number of scans N_s = 20, optimal values of Hough detection threshold T_M=7, T_M=13 and binary rules *M*–out–of–*L* = 10/16, *M*–out–of–*L* = 16/16.

	$N=16$ $INR=10[dB]$	$N=32$ $INR=30[dB]$	$N=16$ $INR=10[dB]$	$N=32$ $INR=30[dB]$	$L=16$ $INR=10[dB]$ $INR=30[dB]$	$L=32$ $INR=10[dB]$ $INR=30[dB]$
$N=16$ $INR=10[dB]$	1.00	0.98	0.94	0.91	0.87	0.86
$N=32$ $INR=30[dB]$	0.98	1.00	0.96	0.93	0.85	0.84
$N=16$ $INR=10[dB]$	0.94	0.96	1.00	0.97	0.81	0.80
$N=32$ $INR=30[dB]$	0.91	0.93	0.97	1.00	0.78	0.77
$L=16$ $INR=10[dB]$ $INR=30[dB]$	0.87	0.85	0.81	0.78	1.00	0.99
$L=32$ $INR=10[dB]$ $INR=30[dB]$	0.86	0.84	0.80	0.77	0.99	1.00

In Table 2 are presented results for threshold analysis for average detection threshold (ADT) of EXC Hough CFAR BI detector for two different values for optimal values of Hough detection threshold.

	T_{EXCBI} $T_{M_{opt}}=7/20$ *M/L*=10/16	ADT_1	T_{EXCBI} $T_{M_{opt}}=7/20$ *M/L*=16/16	ADT_2	T_{EXCBI} $T_{M_{opt}}=13/20$ *M/L*=10/16	ADT_3	T_{EXCBI} $T_{M_{opt}}=13/20$ *M/L*=16/16	ADT_4
$T_{EXCBI} T_{M_{opt}}=7/20$ *M/L*=10/16	1.0000	0.9722	0.9722	0.9722	1.0000	0.9722	0.9167	0.9722
ADT_1	0.9722	1.0000	0.9722	1.0000	0.9722	1.0000	0.9167	1.0000
$T_{EXCBI} T_{M_{opt}}=7/20$ *M/L*=16/16	0.9722	0.9722	1.0000	0.9722	0.9722	0.9722	0.9444	0.9722
ADT_2	0.9722	1.0000	0.9722	1.0000	0.9722	1.0000	0.9167	1.0000
T_{EXCBI} $T_{M_{opt}}=13/20$ *M/L*=10/16	1.0000	0.9722	0.9722	0.9722	1.0000	0.9722	0.9167	0.9722
ADT_3	0.9722	1.0000	0.9722	1.0000	0.9722	1.0000	0.9167	1.0000
T_{EXCBI} $T_{M_{opt}}=13/20$ *M/L*=16/16	0.9167	0.9167	0.9444	0.9167	0.9167	0.9167	1.0000	0.9167
ADT_4	0.9722	1.0000	0.9722	1.0000	0.9722	1.0000	0.9167	1.0000

4 Conclusions

The achieved results shown relation between the value of the test resolution cell, the average detection threshold and the probability for the appearance of impulse interference. It is approved that application of censoring techniques in the detection algorithm improves the radar detectors effectiveness. The research is held in conditions of randomly arriving impulse interference. In a variety of different architectures, the Hough detector proves to be robust in a randomly arriving impulse interference environment with very high probability for appearance of impulse interference.

The results of the ICA approach in the presented paper confirm one more time that radar detectors with CFAR processors are almost as effective as the Neyman–Pearson detector when the number of reference cells becomes very large.

The results obtained in this paper could be used in radar and communication networks.

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