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Comparative Analysis between a Hough Detector and an Averaging Detector under Conditions of Strong Pulse Jamming[1]

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Abstract: *In this paper a Hough detector is compared with a Cell Averaging Constant False Alarm Rate (CA CFAR) detector in the presence of pulse jamming. The detection probability and the average detection threshold of these two types of CFAR detectors are studied. The experimental results are obtained by numerical analysis in MATLAB computational environment. The analytical results obtained for the Hough detector can be used in both radar and communication receiver networks.*

Keywords: *Radar Detector, Hough detector, Cell Averaging Constant False Alarm Rate (CA CFAR), Pulse Jamming, Probability of detection, Probability of false alarm, Detectability profits (losses).*

1. Introduction

In a modern radar, the target detection is declared if the signal value exceeds a preliminary determined adaptive threshold. Current estimating of the noise level in the reference window forms the threshold. The estimate proposed by Finn and Johnson in [5] is quite often used as an estimate of the noise level. Averaging the outputs of the reference cells surrounding the test cell forms this estimate. Thus a constant false alarm rate is maintained in the process of detection. These Cell Averaging Constant False Alarm Rate (CA CFAR) processors are very efficient in case of stationary and homogeneous interference. The presence of strong Pulse Jamming (PJ) in both, the test resolution cells and the reference cells can cause drastic degradation in the performance of the CA CFAR processor. Such type of

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interference is non-stationary and non-homogenous and it is often caused by adjacent radar or other radio-electronic devices.

The detection performance of CA CFAR processors with post detection integrator is proposed by Hou in [4] for the case of homogeneous environment and chi-square family of fluctuating target models (Swerling I, II, III, IV).

During the last few years, mathematical methods for extraction of useful data about the behaviour of observed targets by mathematical transformation of received signals are widely used in the design of new highly efficient algorithms for processing of radar information. Such a mathematical approach is the Hough Transform (HT). The concept of using the HT for improving of target detection in white Gaussian noise is introduced by Carlson, Evans and Wilson in [1, 2, 3]. This approach is used by Carlson in [3], for a highly fluctuating target – Swerling II type target model and stationary homogeneous interference.

In our paper we study the situation for a highly fluctuating target – Swerling II type target model detection in conditions of strong pulse jamming. In [8, 9, 10, 14, 15, 16] the detectability losses are calculated when compared to detectors in condition of PJ and without PJ. In our paper we compare Hough detector with an optimal detector, using the approach from [7].

The choice of the best pattern supposes comparison with respect to a total model, for example the optimal detector [7, 11, 13] or one in relation to another. In this paper we research the efficency of HT CA CFAR processor in strong pulse jamming for P_D=0.5. We estimate the efficiency of HT CA CFAR with the method from [9], i.e. the sensibility towards pulse jamming, the efficiency towards optimal detector and towards CA CFAR detector. These estimates allow the comparison of HT CA CFAR with respect to CA CFAR and the comparison with some other patterns studied by other authors.

The losses (profits) of the Hough detectors are calculated for different values of the false alarm probability, different number of observations in the reference window, an average Interference-to-Noise Ratio (INR) and probability for appearance of pulse jamming with average length in the cells in range. Our results show that Hough transform is very efficient under conditions of decreased pulse jamming.

2. Statistical analysis of a Hough detector

Using Carlson's approach [1, 2, 3] we obtain a new result for detection performance in Hough space, for a target model of type Swerling II in pulse jamming described with the probability density function (pdf) in the test resolution cell [6]:

$$f(x_i) = \frac{1-e_0}{\lambda_0(1+s)}\exp\left(\frac{-x_i}{\lambda_0(1+s)}\right) + \frac{e_0}{\lambda_0(1+r_j+s)}\exp\left(\frac{-x_i}{\lambda_0(1+r_j+s)}\right), \qquad (1)$$

where s is the per pulse average signal-to-noise ratio, λ_0 is the average power of the receiver noise, r_j is the average interference-to-noise ratio, e_0 is the probability for the appearance of pulse jamming with average length in the range cells.

The probability of false alarm for a CA CFAR detector, without PJ is determined in [7], as:

(2) $$P_{\text{fa}} = \frac{1}{\left(1+T_{\text{CA}}\right)^{N}},$$

where T_{CA} is the threshold constant determined to maintain the given level of false alarm and N is the length of the reference window.

The probability of detection for an optimal detector is determined in [7] as

(3) $$P_{\text{d}_{\text{opt}}} = P_{\text{fa}}^{\frac{1}{1+s}}.$$

The probability of detection for CA CFAR detector for target of case Swerling II under conditions of pulse jamming [6], is

(4) $$P_{\text{d}_{\text{sw2}}} = \sum_{i=1}^{N} C_N^i e_0^i \left(1-e_0\right)^{N-i} \left\{ \begin{array}{l} \dfrac{e_0}{\left(1+\dfrac{\left(1+r_j\right)T_{\text{CA}}}{1+r_j+s}\right)^{i}\left(1+\dfrac{T_{\text{CA}}}{1+r_j+s}\right)^{N-i}} + \\ \dfrac{1-e_0}{\left(1+\dfrac{\left(1+r_j\right)T_{\text{CA}}}{1+s}\right)^{i}\left(1+\dfrac{T_{\text{CA}}}{1+s}\right)^{N-i}} \end{array} \right\},$$

where s is the signal-to-noise ratio, T_{CA} is the threshold constant and r_j is the average interference-to-noise ratio.

The probability of false alarm for a CA CFAR detector for case Swerling II in strong pulse jamming [6] is obtained for a value of signal-to-noise ratio $s=0$:

(5) $$P_{\text{fa}_{\text{sw2}}} = \sum_{i=1}^{N} C_N^i e_0^i \left(1-e_0\right)^{N-i} \left\{ \frac{e_0}{\left(1+T_{\text{CA}}\right)^{i}\left(1+\dfrac{T_{\text{CA}}}{1+r_j}\right)^{N-i}} + \frac{1-e_0}{\left(1+\left(1+r_j\right)T_{\text{CA}}\right)^{i}\left(1+T_{\text{CA}}\right)^{N-i}} \right\}.$$

All indications for signal detection obtained from N range resolution cells and N_s scans are arranged in a matrix Ω of size $N \times N_s$ in r–t space. In this space stationary or constant radar velocity target pears as a straight line which consists of nonzero elements of Ω. Let as assume that Ω_{ij}^{nm} is a set of such nonzero elements of Ω that constitute a straight line in r–t space that is $(i, j) \in \Omega_{ij}^{nm}$. This line may be represented in Hough parameter space as a point (n, m). Denoting N_{nm} as the maximal size of Ω_{ij}^{nm}, the cumulative false alarm probability for a cell (n, m) is written according to [3]:

(6) $$P_{\text{fa}}^{nm} = \sum_{l=T_{\text{M}}}^{N_{nm}} \binom{N_{nm}}{l} \left(P_{\text{fa}}\right)^{l} \left(1-P_{\text{fa}}\right)^{N_{nm}-l},$$

where T_{M} is a linear trajectory detection threshold.

The total false alarm probability in Hough parameter space is equal to one minus the probability that no false alarm occurred in any of the Hough cells. For independent Hough cells this probability is

$$P_{\mathrm{FA}} = 1 - \prod_{N_{nm}}^{\max(N_{nm})} \left[1 - P_{\mathrm{fa}}^{nm}\right]^{W(N_{nm})}, \tag{7}$$

where $\max(N_{nm})$ is the accessible Hough space maximum and $W(N_{nm})$ is the number of cells from Hough parameter space whose values are equal to N_{nm}.

The cumulative probability of target detection in Hough parameter space P_{D} cannot be written in the form of a simple Bernoulli sum. As the target moves with respect to the radar, the SNR of the received signal changes, depending on the distance to the target and the probability of a pulse $P_{\mathrm{D}}(j)$ changes as well. Then the probability P_{D} can by calculated by Brunner's method. By means of Brunner's method we obtain a matrix of size 20×20, the elements of which are the primitive probability of detection in the k-th time slice [3]. Using (4) we can get all the $P(i, j)$ needed to calculate P_{D}. For N_s scans of monopulse radar we have:

$$P_{\mathrm{D}} = \sum_{i=T_{\mathrm{M}}}^{N_{\mathrm{S}}} P_{\mathrm{d}}(i, N_{\mathrm{s}}). \tag{8}$$

There are not many cases in practice when a radar is equipped with a Hough detector working in strong pulse jamming. In such situations it would be desirable to know the Hough losses depending on the parameters of the pulse jamming, for rating the behavior of the radar. For the calculation of Hough detector losses, we use the ratio between the two SNR, for a Hough detector and an optimal detector, measured in dB, presented by the expression:

$$\Delta = 10\log\frac{\mathrm{SNR}\big|_{\mathrm{Hough}}}{\mathrm{SNR}\big|_{\mathrm{opt}}} \tag{9}$$

under P_{FA} = const, $P_{\mathrm{D}} = P_{\mathrm{D}}^{\mathrm{Hough}} = P_{\mathrm{D}}^{\mathrm{opt}} = 0.5$.

The comparisons are made also with respect to CA CFAR in PJ and for a Hough detector in strong PJ.

3. Numerical results

In order to analyze the quality of the Hough detector we consider a monopulse radar with the following parameters, similar to [3]: the search scan time is 6s; the range resolution is δR=3 nmi (1 nmi = 1852 m); the beam range – time space has 128 range cells and 20 time slices, and the Hough space is 260 ρ^- cells by 91 θ^- cells; the lengths of the references windows in the CA CFAR detector are 16 and 32. We consider a straight line, an incoming target with the speed of Mach 3 and 1 sq. m radar cross section. The results of calculating are obtained for the following variants of pulse jamming environment: INR 10 and 30 dB, e_0 = (0; 0.01; 0.033; 0.066; 0.1). In the analysis the SNR average value is calculated as $S = K/R^4$, where $K = 0.16\times10^{10}$ is the generalized energy parameter of the radar and R is the distance to the target measured in nautical miles.

The threshold constant is obtained for each value of the false alarm probability P_{FA} being 10^{-4}, 10^{-6}, 10^{-8}, using (5). In Table 1 the threshold constant values are shown for a CA CFAR detector under conditions of pulse jamming.

The losses (profits) of the Hough detector in strong PJ are determined in relation to the optimal detector, following the algorithm proposed in [11], for a value of probability of detection – 0.5. The dependence of the losses on the average interference-to-noise ratio and the number of reference cells for different values of the probability of the false alarm and probability of appearance of pulse jamming with an average length in the range cells, is shown in the next tables.

Table 1. Value of the threshold constant of detection for a CA CFAR detector

e_0	P_{FA}	N = 16		N = 32	
		r_j = 10, dB	r_j = 30, dB	r_j = 10, dB	r_j = 30, dB
0	10^{-4}	0.778	0.778	0.334	0.334
	10^{-6}	1.37	1.37	0.54	0.54
	10^{-8}	2.16	2.16	0.778	0.778
0.01	10^{-4}	3.56	320	1.63	143.5
	10^{-6}	8.4	761	3.56	321
	10^{-8}	16.2	1350	6.336	525.6
0.033	10^{-4}	4.82	390.4	2.1	160
	10^{-6}	10.4	855	4.21	339
	10^{-8}	17.8	1474	6.69	547
0.066	10^{-4}	5.12	403	2.1	145
	10^{-6}	10.7	871	4.17	322
	10^{-8}	18.21	1495	6.59	527
0.1	10^{-4}	4.67	386.9	1.85	118.1
	10^{-6}	9.72	850	3.64	291
	10^{-8}	16.54	1466	5.79	490

The probabilities of detection of a CA CFAR detector are shown in Fig. 1, for a value of probability of the false alarm – P_{FA}=10^{-4}, for the length of a reference window – N =16 and for different values of the probability of appearance – e_0.

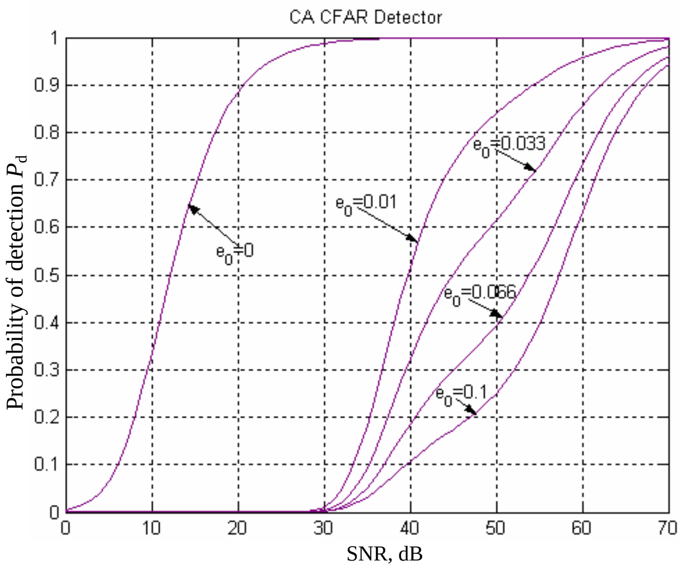

Fig. 1. Probability of detection of Cell Averaging Constant False Alarm Rate (CA CFAR) detector in the presence of pulse jamming, for P_{FA}=10^{-4} and N=16

Carlson's approach, using Brunner's method for calculating the probability of detection in Hough parameter space is further developed in order to maintain constant false alarm probability at the output of the Hough detector. The suitable scale factor is chosen iteratively. The influence of the threshold constant on the required signal-to-noise ratio is studied. The investigation is performed for probability of detection (P_D = 0.5) and different values of the probability for the appearance of pulse jamming with average length in the cells in range.

In order to achieve a constant value of the probability of false alarm (P_{FA}), the values of the threshold constants, which guarantee that, are determined for different numbers of observations in the reference window, an average interference-to-noise ratio and a probability for the appearance of pulse jamming with average length in the cells in range. The profits (losses) of the CA Hough detector in pulse jamming are determined in relation to the CA CFAR detector, following the algorithm proposed in [11], for probability of detection – 0.5.

In Table 2 the results are presented for average detection threshold for CA Hough CFAR detector with the probability of false alarm ($P_{FA} = 10^{-4}$), for a number of observations in the reference window (N = 16), an average interference-to-noise ratio (INR = 30 dB) and two different values of the probability for the appearance of pulse jamming with average length in the cells in range.

Table 2. Values of the threshold constant of detection for a Hough detector

T_M	T_{CA} for $e_0 = 0$	T_{CA} for $e_0 = 0.1$	ADT for $e_0 = 0$	ADT for $e_0 = 0.1$
2	1.14	672	7.3363	45.7179
3	0.57	225	5.1267	47.1774
4	0.401	93.5	4.3203	47.0781
5	0.315	28.9	3.9747	43.4509
6	0.2609	4.109	3.7442	34.8363
7	0.2225	1.186	***3.6290***	30.1511
8	0.193	0.472	***3.6290***	27.1285
9	0.1696	0.2195	3.7442	24.7103
10	0.150	0.1303	3.8594	23.5013
11	0.1334	0.0842	3.9747	22.7456
12	0.1188	0.0544	4.2051	22.1411
13	0.1059	0.0329	4.4355	20.6297
14	0.0942	0.0174	4.7811	18.6650
15	0.0836	0.00815	5.2419	15.9446
16	0.0737	0.00409	5.7028	13.6776
17	0.0645	0.00241	6.3940	12.3174
18	0.0557	0.001565	7.2005	***11.7128***
19	0.0470	0.001065	8.2373	11.8640
20	0.0384	0.000728	9.9654	12.7708

The authors in [3] use the approach proposed by Barton to determine the threshold in Hough parameter space. They assume T_M = 7 as an optimal threshold in the binary integration and apply it in Hough parameter space. In this paper after iterative analysis, the optimal threshold in Hough parameter space is also determined to be T_M = 7 for a value of probability of appearance of pulse jamming with average length in the range cells e_0 = 0.

Different values of the detection threshold in Hough parameter space – T_M are shown in Fig. 2. The optimal value for this threshold is $T_M = 7$ of 20 scans for values of probability for the appearance of pulse jamming with average length in the range cells $e_0 = 0$. For $e_0 = 0.1$, the optimal value for detection threshold in Hough parameter space is $T_M = 18$ of 20 scans.

The probabilities of detection of Hough detector with a CA CFAR processor are shown in Fig. 3 for a value of the detection threshold $T_M = 2$ and for optimal values of the detection threshold $T_M = 18$, for a value of probability of appearance – $e_0 = 0.1$ and Fig. 4 shows the results for $T_M = 2$, optimal values of the detection threshold $T_M = 7$, for a value of probability of appearance – $e_0 = 0$.

The profits of using a Hough detector with CA CFAR processor, calculated for the threshold value $T_M = 2$ and for optimal values of the detection threshold $T_M = 7$, for $e_0 = 0$ and $T_M = 18$, for $e_0 = 0.1$, compared to a CA CFAR processor, for the number of test resolution cells $N = 16$ and the value for probability of false alarm $P_{FA} = 10^{-4}$, are shown in Fig. 5.

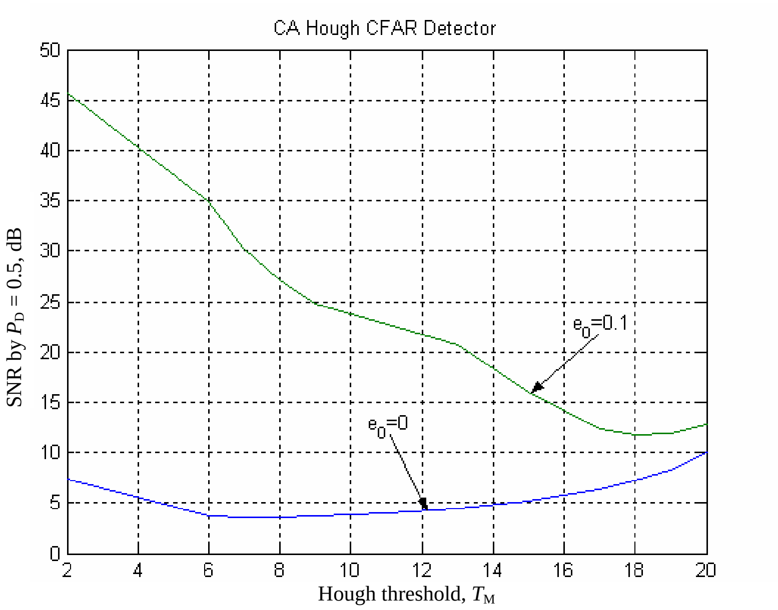

Fig. 2. Average detection threshold of a CA Hough CFAR detector

The CA Hough detector with the optimal Hough rule T_M-out-of-N equal to 7/20 is better in cases of lower values of the probability for appearance of impulse interference, up to 0.06. For higher values of the probability for appearance of impulse interference, above 0.06, the usage of the optimal Hough rule T_M-out-of-N_s=18/20 results in lower losses.

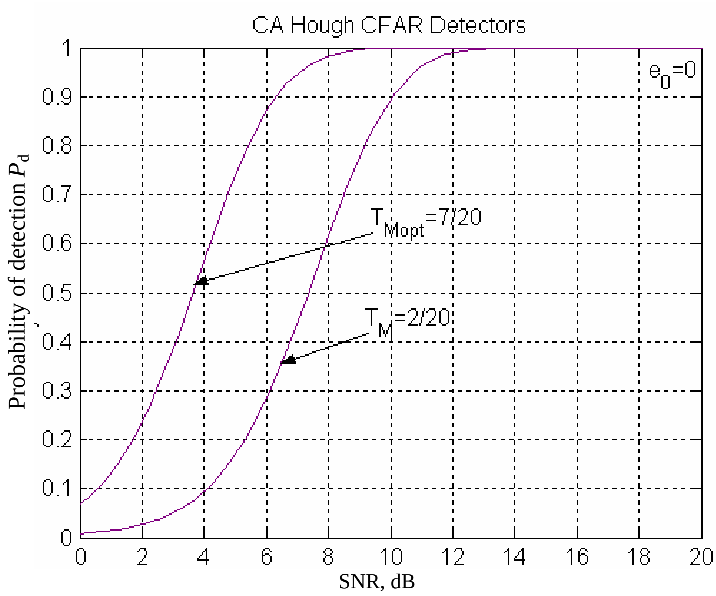

Fig. 3. Probability of detection of a Hough detector with CA CFAR processor in pulse jamming, for $T_M = 2$, $T_M = 7$ and $e_0 = 0$

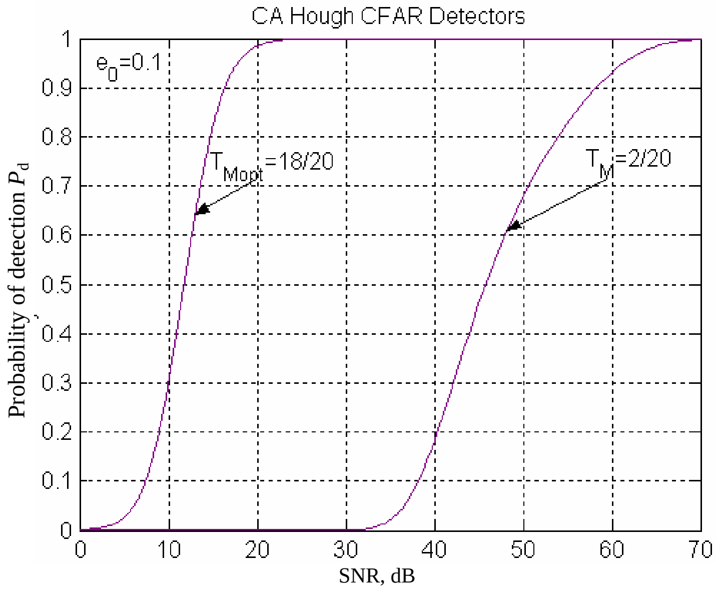

Fig. 4. Probability of detection of a Hough detector with CA CFAR processor in pulse jamming, for $T_M = 2$, $T_M = 18$ and $e_0 = 0.1$

Table 3 contains SNR losses of the Hough detector for target SW2, in dB, made in relation to the optimal detector as it is in [7]. INR is r_j = 10 and 30 dB, e_0=(0; 0.01; 0.033; 0.066; 0.1), the numbers of reference cells are N=16 and 32 and the probability of false alarm is P_{FA} being 10^{-4}, 10^{-6}, 10^{-8}.

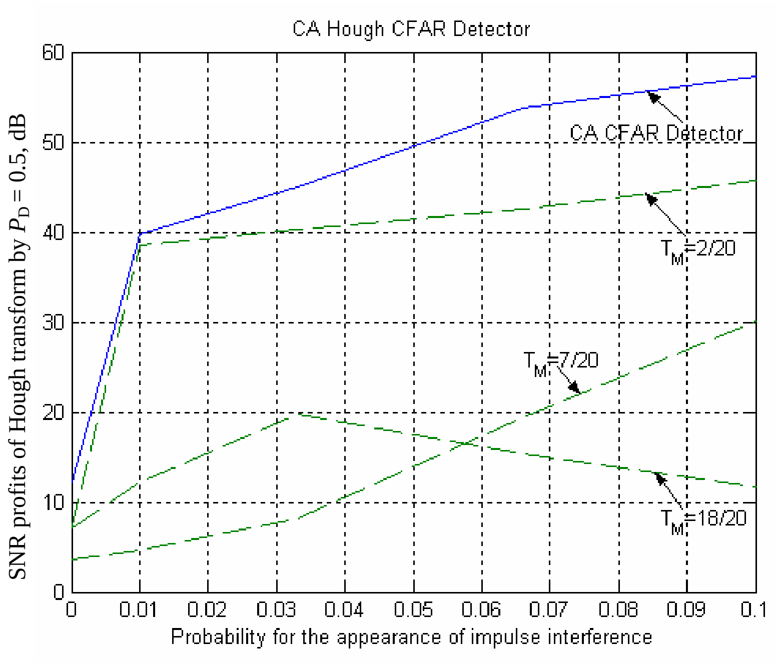

Fig. 5. Profits of a Hough detector (dashed line) with CA CFAR processor for 20 scans, $T_M = 2$ and two optimal values of the detection threshold, $T_M = 7$ for $e_0 = 0$ and $T_M = 18$ for $e_0 = 0.1$, compared to a CA CFAR detector (solid line) for $N = 16$

Table 3. SNR losses of the Hough detector, in relation to the optimal detector, in dB

e_0	P_{FA}	N=16		N=32	
		R_j=10, dB	R_j=30, dB	R_j=10, dB	R_j=30, dB
0	10^{-4}	1.2673	1.2673	0.4579	0.4579
	10^{-6}	2.0737	2.0737	0.9217	0.9217
	10^{-8}	2.8251	2.8251	1.2673	1.2673
0.01	10^{-4}	9.8402	31.7973	9.5623	31.9125
	10^{-6}	11.4055	33.1908	11.0599	33.1797
	10^{-8}	12.7880	34.3318	11.9816	33.7558
0.033	10^{-4}	11.8664	33.6406	11.5208	34.3318
	10^{-6}	13.0184	35.0231	12.3272	35.8295
	10^{-8}	13.7097	36.2903	12.9032	36.8664
0.066	10^{-4}	12.5576	35.3687	12.2120	37.9033
	10^{-6}	13.5945	36.8660	13.0184	39.8618
	10^{-8}	14.4009	38.3641	13.3641	40.7834
0.1	10^{-4}	12.4424	36.9864	12.3272	39.4010
	10^{-6}	13.4793	38.7097	12.7880	40.8203
	10^{-8}	14.2857	39.8618	13.3641	41.4912

Table 4 shows the profits of using the Hough detector compared to the CA CFAR detector in dB. INR is r_j=10 and 30 dB, e_0=(0; 0.01; 0.033; 0.066; 0.1), number of reference cells are N=16 and 32 and the probability of false alarm is P_{FA} being 10^{-4}, 10^{-6}, 10^{-8}.

Table 4. SNR profits of the Hough detector compared to the CA CFAR detector, in dB

e_0	P_{FA}	N=16		N=32	
		R_j=10, dB	R_j=30, dB	R_j=10, dB	R_j=30, dB
0	10^{-4}	7.1429	7.1429	7.2580	7.2580
	10^{-6}	6.2212	6.2212	6.5668	6.5668
	10^{-8}	5.9307	5.9307	5.9908	5.9908
0.01	10^{-4}	5.7128	4.1474	5.7603	4.9539
	10^{-6}	5.2996	3.4562	4.9539	4.6962
	10^{-8}	5.0692	3.2315	4.6518	4.4931
0.033	10^{-4}	5.6452	7.2581	5.6451	11.6360
	10^{-6}	5.1844	6.5668	5.1843	10.6567
	10^{-8}	5.0543	5.7028	4.8964	9.9654
0.066	10^{-4}	6.1060	13.9977	5.8180	12.8456
	10^{-6}	5.5299	12.8460	5.3572	11.4631
	10^{-8}	5.4724	11.9239	5.1267	10.8871
0.1	10^{-4}	6.5093	15.7258	5.9332	12.5000
	10^{-6}	5.8179	14.6889	5.5876	12.3479
	10^{-8}	5.7604	14.1129	5.4147	12.2531

4. Conclusions

The experimental results show the influence of the interference on the detection process, when having a constant false alarm rate in pulse jamming. A method for the losses estimation, which allows choosing of the optimal detector parameters, is developed. The estimates of the efficiency of the Hough detector with CA CFAR processor in pulse jamming are obtained, in order to allow making a comparison with other patterns studied by other authors.

The optimal threshold values for different input conditions are estimated. The value of the test resolution cell and the probability of false alarm over the average detection threshold are studied. Application of censoring techniques in the detection algorithm improves the Hough detectors efficiency.

Using Matlab, the probability functions of the Hough detector for a highly fluctuating target – Swerling II type target model detection under conditions of strong pulse jamming are calculated in accordance with the approach, represented in [11]. The losses (profits) of the Hough detector are shown for different values of the probability of a false alarm and different numbers of observations in the reference window and an average interference-to-noise ratio. Using this approach it is very easy to precisely determine the energy benefit when using a given detector. The results show that the Hough detector improve the detectability by approximately 4 to 10 dB compared to CA CFAR detector, which is presented in [12]. Our results show that Hough transform is efficient under conditions of decreased pulse jamming.

The results obtained in this paper could be practically used in the design of modern radar systems.

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Сравнительный анализ Хо-обнаружителя и обнаружителя с усреднением по выборке в условиях интенсивных импульсных помех

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В настоящей статье исследована эффективность Хо-обнаружителя и ПУЛТ обнаружителя с усреднением по выборке шума (CA CFAR) при наличии хаотично-импульсных помех на входе приемника. Выражения для расчета эффективности Хо-обнаружителя в терминах вероятностных характеристик обнаружения и среднего порога обнаружения были получены аналитическим путем. Результаты сравнительного анализа показывают, что использование Хо-обнаружителей особенно ефективно, когда отношение “сигнал/шум” на входе приемника сравнительно мало. Численные результаты получены в вычислительной среде МАТЛАБ. Полученные результаты могут быть использованы в радиолокациионных или коммуникационных сетях.