# Analysis of modified nonparametric algorithms for detecting radar signals

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**Abstract**

The paper is devoted to the actual problem of signal detection against the background of interference. The article considers the existing nonparametric algorithms for signal detection and provides an assessment of the effectiveness of the use of modified nonparametric algorithms for signs, Wilcoxon, and a digital quasi-nonparametric radar signal detection

**Keywords**

Nonparametric algorithms, detection of radar signals, detection efficiency

## 1. Introduction

The rapid development of business and banking services has led to the emergence of non-state security services that provide physical security and their protection from information leakage, that is, the protection of trade secrets. One of the possible channels of information leakage is various electronic devices for reading or recording audio information (radio microphones, telephone radio bookmarks, dictaphones, and other equipment), secretly installed in controlled premises. There are various methods for detecting radio microphones and telephone radio bookmarks. For this purpose, the radio broadcast is monitored with the help of various radio receivers, the transmitter is searched for with the help of broadband field indicators that register the presence of radio emissions, etc.

The ability to identify embedded devices (ED) that are active, and what is very important in the passive state, determines the role of nonlinear radars as an integral part of the complex technical means used in the search for embedded devices.

A common feature of signals and noises is the fact that in real systems, at the place of reception, they are random values, and their change in time is a random process. When designing communication systems, radar, and others, we often have to face a situation when the characteristics of signals are not known in advance or are subject to changes. Under these conditions, classical algorithms associated with the assumption that the noise is normal may turn out to be ineffective. When the law of noise distribution deviates from the normal, such algorithms lose their optimality. When the parameter of the normal noise changes, they do not provide the calculated indicators. In modern conditions, the development of automation and computer technology requires the creation of effective signal detection algorithms.

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## 2. Literature review and problem statement

The choice of a detection algorithm is the main design stage; therefore, any possible classifications must consider specific restrictions on the amount of initial information, the structure of the algorithm, and the possibility of technical implementation that occurs when solving practical problems. However, nonparametric algorithms are usually limited in cases of incomplete information on the statistical characteristics of interference. The classification of the structure of detectors synthesized on the basis of known and proposed algorithms [1-8, 10-13], is advisable to represent as:

- A class of detectors using engineering methods of stabilization;
- A class of "purely" nonparametric detectors;
- A class of parametric-nonparametric detectors;
- A class of adaptive-nonparametric detectors;
- A class of "quasi-nonparametric" detectors;
- A class of optimal rank detectors;
- A class of locally optimal rank detectors.

The first class includes detectors synthesized on the basis of transformations required in accordance with the selected "pure" ordinal criterion. Typical representatives of this class are detectors of signs, Wilcoxon, Smirnov, series, etc., based on well-known nonparametric criteria.

Modern radio engineering systems for various purposes are characterized by work in a complex interference environment when the statistical characteristics of signals and interference are not known in advance. In particular, the main negative factor that directly affects the efficiency of modern secondary radars, with an increased repetition rate of interrogation signals, is a high level of intrasystem interference [9-12]. Intra-system interference refers to such interference, the source of which is radio-technical devices directly included in the equipment of the secondary radar system and united by the general principle of operation of this system [14-18]. The result of the appearance of intra-system interference can be the formation of false target signals, misses of useful targets, and distortion of the received flight information with an unfavorable overlap in time of the code messages of the response signals.

The secondary radar system belongs to the class of asynchronous pulse radio systems operating on the principle of "request-response". The interrogator emits a periodic sequence of interrogation signals, and all transponders located in the zone of the interrogation antenna beam emit one response signal for each interrogation with a random delay determined by the current location of each responding aircraft transponder. Thus, after the emission of one interrogation signal, a random stream of response signals arrives at the interrogator's input, some of which may be lost or distorted due to their mutual overlap in time. Similarly, some interrogation signals may be lost, simultaneously arriving at the input of a single transponder, if the latter is in the range of several interrogators working independently of each other. In this case, the influence of intra-system interference on the quality of functioning of a separate "interrogator-responder" pair is manifested in the loss of useful information due to the interfering action of other interrogators and responders [21, 33-42].

For secondary radars, the principle of which is based on processing a packet of response signals, the resolution and azimuth accuracy are worse than those of primary radio locators. This leads to significant difficulties in separating signals and decoding response codes of aircraft transponders located at close distances to each other and at approximately the same bearings. To increase the azimuthal accuracy of such radars with the same width of the antenna directional pattern, it is necessary to increase the number of pulses in the packet, i.e. increase the frequency of requests, which automatically leads to a significant increase in intra-system interference. Attempts to reduce the frequency of inquiries lead to a decrease in the angular accuracy of the radio locator, which will inevitably cause additional difficulties in the trajectory processing of the received signals.

If the code positions of one response signal approximately coincide with the positions of the pulses of another transponder, then significant difficulties will arise in decoding the received information. Such intra-system interference has received the generally accepted designation "garble" ("distortion"). A more complex situation arises when two or more aircraft are for a long time at approximately the same slant range and approximately at the same bearing. In this case, there is a synchronous overlap of responses, commonly referred to as "synchronous garble". Another important type of intra-system interference, characteristic of secondary radar systems, is asynchronous interference that occurs when an interrogator receives signals from transponders requested at this time by other interrogators. This type of interference is called FRUIT (False Replies Unsynchronized In Time - false responses not synchronized in time). The probability of occurrence of such interference will be the greater, the higher the frequency of repetition of requests and the greater the number of interrogators simultaneously working in the controlled area.

When processing received signals, asynchronous interference is easier to suppress than synchronous interference. Therefore, to convert synchronous interference into asynchronous in some cases, special measures are taken, such as wobbling the repetition period of requests or spacing the repetition rates of requests of secondary radars located at a relatively close distance to each other. With a large number of simultaneously operating interrogators, a high frequency of interrogations and a high power of interrogation signals, a phenomenon may occur, which is called "over-interrogation", i.e. exceeding the intensity of requests of the maximum permissible level, which for modern respondents lies in the range of 1200 ... 2000 responses per second [3]. Exceeding this level causes an automatic decrease in the sensitivity of the transponder receiver. At the same time, responses to queries with weak signals will not be issued and, therefore, more remote interrogators will not interfere with the normal operation of the responder.

The disadvantages of traditional secondary radars discussed above significantly reduce the effectiveness of their use as a means of monitoring the air situation. A radical way to improve the efficiency of surveillance systems is to introduce a selective interrogation mode for responders, but the introduction of such systems requires large material costs and is justified only with a very high intensity of flights. A less radical, but economically more profitable way to increase the efficiency of existing surveillance systems is the introduction of a monopulse secondary radar method, which significantly improves the angular resolution and accuracy of determining the coordinates of targets at a low frequency of request signal.

Currently, nonparametric statistical methods are widely used, the use of which does not imply knowledge of the functional form of distributions. A detector is called nonparametric if, in the absence of a signal (there is only noise), the probability distribution of its decision statistics does not depend on the noise distribution [3]. This means that such a detector provides a constant probability of false alarms, regardless of the statistical characteristics of the noise.

Consider the work of a detector that separates the input data into two classes. Any decision rule can be described as a certain critical region in the space of vectors of input signals. When the input signal enters this area, a decision is made on the presence of the desired object. Otherwise, a decision is made on its absence. In case we have certain information about the dependence of events on their causes, we can use one of the most convenient ways, which is the method of testing statistical hypotheses. This method investigates a physical phenomenon, the mathematical model of which is a random process X(t) with incompletely known characteristics. Mutually incompatible hypotheses H0, H1,…, Hm are put forward regarding the unknown characteristics of the model. If a deterministic signal s(t) is detected in additive noise, the task will be to test the hypothesis H0. This hypothesis says that the implementation x(t) observed in a certain interval [0..T] is Gaussian noise, versus alternative H1, according to which this implementation is a mixture of a useful signal and noise.

With a finite value of the signal energy and the presence of random noise, the decision on the presence or absence of a signal is always accompanied by two errors [4]. An error of the first kind (false alarm) will occur if a decision is made that there is a signal with the correct null hypothesis H0, which assumes that there is no signal (the noise exceeds the threshold and the wrong decision is made). An error of the second kind (missing a signal) corresponds to the case of decision-making about the absence of a signal, while a signal is present, but not detected in the interference (a signal is present, but does not exceed a predetermined threshold). Here, an error arises due to the fact that the null hypothesis H0 is recognized as correct. Signal detection errors are random events that can be characterized by their probability: the probability of an error of the 1st kind α, and the 2-nd kind β [1]. The probability of missing a signal β is directly related to the probability of correct detection D:

$$D = 1 - \beta.$$

The probability of false alarm is calculated by the formula

$$\alpha = \int_{u_s}^{\infty} \omega_n(u)du,$$

where $\omega_n(u)$ – probability density of noises.

For the probability of missing a signal, you can write

$$\beta = 1 - \int_{u_s}^{\infty} \omega_n(u)du.$$

Probability of correct detection

$$D = 1 - \beta = \int_{u_s}^{\infty} \omega_{sn}(u)du,$$

where $\omega_{sn}(u)$ - signal-interference mixture probability density

Hence it follows that it is necessary to find such an algorithm for processing the received signal that would minimize the false detection error and maximize the probability of correct detection.

Signed algorithm. According to the signed algorithm, the alternative $H_1$ about the presence of a positive signal is recognized as valid if for an independent sample ($x = x_1, x_2, .. x_n$):

$$\sum_{i=1}^{n} sign\, x_i \leq C; \tag{1}$$

where $C$ is the chosen threshold, determined by the given value of the probability α, and the sign function is defined as follows ()

$$sign\, x_i = \frac{x_i}{|x_i|} = \{1, x_i \geq 0\ 0, x_i < 0.$$

In the case of the opposite inequality (1), alternative $H_1$ is rejected and the hypothesis $H_0$ about the absence of a signal is accepted [6]. For a given value of α, the threshold $C$ is determined as follows

$$C = \frac{x_\alpha \sqrt{n} + n}{2}$$

where $x_\alpha$ is the percentage point of the normal distribution corresponding to the probability of false detection [2, 6].

Sign-rank algorithm. Sign-rank detectors use information not only about the signs of the sample elements but also about the ranks of the absolute values of these observations. In this case, to obtain estimates of the parameters of the shift and the scale of the sample, rank tests are used to test hypotheses about the equality of these parameters in two samples: training - $x_1, ..., x_t$, working - $y_1, ..., y_t$, then such estimates are called $R$- estimates Accounting for signs allows improving the detection characteristics without violating the nonparametric properties of the detector [7-8].

Let ($x = x_1, x_2, .. x_n$) be the observed independent sample and be the rank of the sample element xi.

One of the possible sign-rank algorithms for detecting a positive signal against a background of interference is as follows:

The received signal is compared with the threshold of the sum of those components of the vector of positive ranks. In this case, the components of the vector must correspond to positive sample values xi≥0;

Then a decision is made on the presence of a signal, in the case when

$$\sum_{i=1}^{n} R_i^+ \leq C$$

For a given value of the probability of errors of the 1st kind α, the threshold C is determined as follows

$$C = \frac{n}{2}\left(x_\alpha \sqrt{\frac{n}{3}} + \frac{n}{2}\right)$$

where $x_\alpha$ is the percentage point of the normal distribution. This point corresponds to the probability of false detection.

## 3. Algorithms comparison

The use of classical nonparametric algorithms (signs, Wilcoxon, Kolmagorov-Smirnov, etc.), subject to accurate technical implementation, ensures the stability of the probability of false detections (PFD) in conditions of instability of the interference parameters.

However, the probability of correct detection for a number of important cases (in conditions of intense impulse interference, the presence of passive interference, etc.) is very low.

Therefore, of interest is a number of algorithms called quasi-nonparametric, which provide a high probability of correct detection and guarantee (PFD incomparably lower than that of parametric algorithms. The latter include the Markum algorithm [1, 13, 19-21] and its modifications.

Therefore, a number of algorithms called quasi-nonparametric is of interest which provide a high probability of correct detection and guarantee (PFD incomparably lower than that of parametric algorithms. The latter include the Markum algorithm [1] and its modifications.

Modification of nonparametric procedures [2, 3, 8] can also significantly increase their efficiency.

In this paper, the analysis of the effectiveness of the application of the quasi-nonparametric Markum detector and the detector using the modified Dillard-Anthonyan procedure [4] is carried out.

The algorithm for detecting signals in the *j*-th section of the range for a sign detector is written as follows:

$$z_j = \sum_{i=1}^{n} sign[\rho_i(j\Delta t) - \rho_i(j\Delta t - \tau_3)] \geq V, \tag{2}$$

$$j = 1,2 \dots l.$$

and involves comparing the difference in the counts of the envelopes with the zero threshold, counting the number of times the zero threshold is exceeded, and comparing the resulting sum over the interval with the detection threshold of the decision-making device.

In expression (2), the following designations are adopted:

$n$- the number of pulses in the packet of reflected radar signals; $T_n$ - sounding period; $V$ - detection threshold; $sign(y) = \{0, if\ y < 0\ 1, if\ y \geq 0$ - unit function; $\tau_3, \tau_k$ - delay time and correlation interval of the interference envelope (mixture of signal with interference), $\rho(t)$ respectively, $\tau_3 > \tau_k$; $l$ - the number of elementary range sections analyzed by the detector.

For a nonparametric signed detector, provided that the variance of the Gaussian noise is stable, the probability of false detection and correct detection will have the form:

$$F = 1 - \Phi\left(\frac{2V - n}{\sqrt{2}}\right), \tag{3}$$

$$D = 1 - \Phi\left(\frac{V - np}{\sqrt{np(1-p)}}\right), \tag{4}$$

where $\Phi()$ - integral of probability in Laplace form and

$$p = \frac{\psi + \psi_c}{2(\psi + \psi_c)}, \tag{5}$$

probability of exceeding the zero threshold of the analyzer by the difference between the samples of the noise envelope (mixture of signal with noise) $\rho(t), \psi, \psi_c$ - Gaussian noise variance and signal variance, respectively.

Obviously, in the absence of a signal ($\psi_c = 0$) $p = 1/2$.

Application of the procedure proposed in [4], which is, in fact, a modification of the algorithms of signs and Wilcoxon. It allows by insignificantly complicating the sequential detector circuit to use the statistics $K$ of noise range points without increasing the time for information processing, which significantly increases the detection efficiency. Consider the operation of a circuit that implements the modified sign algorithm (Fig. 1).

When using a delay line, it is assumed that the signal duration is equal to the delay time, and one signal falls into the so-called window. This task is typical for radar tasks when signals reflected from the target are received. In communication tasks, especially when intercepting signals, detection is complicated by the fact that signals are observed continuously, and the structure and a number of signal parameters are usually unknown.

The output voltage of the envelope detector $\rho(t)$ enters the delay line with an interval between taps that exceeds the correlation interval of the process. The output $\rho_{k+1}$ of the last tap is compared with the first comparison circuit (*S*) with the output $\rho_k$ of the penultimate tap, in the second comparison circuit with the output $\rho_{k-1}$ of the second from the end of the tap, etc. At the output of each of the comparison circuits, 1 is formed if $\rho_{k+1}$ greater than another input signal and, accordingly, 0 otherwise case.

The formation of ones and zeros at the output of the comparison circuit, of course, is carried out at the moment of applying the strobe pulses.

The outputs of all comparison circuits are connected to a coincidence circuit ("AND"), which generates 1 in case of receipt of units from all comparison circuits. The adder counts the number of triggering of the coincidence circuit for the interval *nT* with the decision threshold *V*, *n*, $T_n$, and the number of pulses in the "packet" of reflected radar signals and the sounding period, respectively.

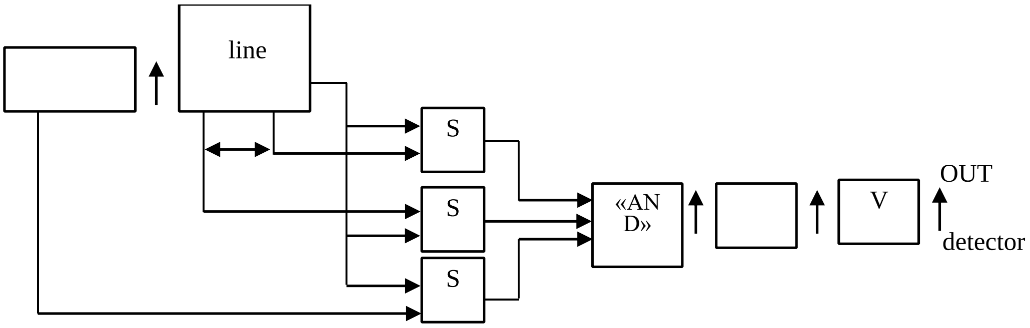

**Figure 1**: The scheme realizing of the algorithms of signs modification

where D- detector, S - circuit of subtraction, “AND” - coincidence circuit, Σ - adder, V - threshold device.

For n >> 1, the binomial distribution of the sum $z_i$ of the operations number of the coincidence circuit can be approximated by the normal law with the parameters

$$m_1\{z\} = np^k; \tag{6}$$

$$\mu_2\{z\} = np^k\left(1 - p^k\right). \tag{7}$$

The probability of a false and correct detection are determined by expressions (3, 4) when replacing $p$ to $0.5^k$ and $p\ to\ p^k$, respectively, - the probability of exceeding count $\rho_{k+1}$(signal) by each *K* independent (noise) counts.

Calculations show that the gain from the application of this procedure when detecting a Gaussian signal in a Gaussian noise by a threshold signal for a specific case: the volume of a packet of pulses of reflected radar signals *n* = 50; PFD $F = 10^{-4}$; the probability of correct detection *D* = 0.9; for *K* = 2 it is 2.47 dB; for *K* = 3 it is 3.34 dB in relation to *K* = 1 (Fig. 2). To determine, we used formula (5).

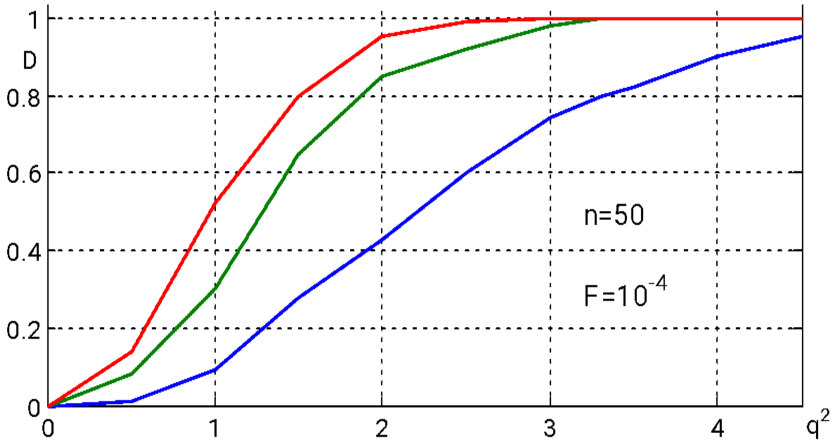

**Figure 2**: Plots of the dependence of the probability of correct detection on the number of independent samples

The number of taps of the delay line cannot be derived, since the distribution over the distance corresponding to the extreme taps. Should be approximately identical in the absence of a signal. At K≥5, the increase in the probability of correct detection is very small. The loss in the threshold signal with respect to the binary parametric procedure is 1 dB.

The considered procedure can be used to improve the efficiency of the Wilcoxon algorithm. Calculations show that the lower estimate of the power characteristic of the Wilcoxon algorithm at $K = 2$ practically coincides with the power characteristic of the sign algorithm for $K = 3$ when a Gaussian signal is detected in Gaussian noise ($n = 50$; $F = 10^{-4}$). Calculations of PFD and correct detection have made according to the formula:

$$D = 1 - \Phi\left(\frac{V - n^2 p}{n/2\sqrt{2n + 1/3}}\right) \tag{8}$$

when replacing as for the signed algorithm $p$ to $0.5^k$ and $p\ to\ p^k$, respectively.

Quasi-nonparametric algorithms, in particular, refer to an analogue automatic gain control (AGC) system, studied in many works, for transient and steady-state modes, and also a digital quasi-nonparametric detection system.

The analysis of digital signal detection against the background of noise is carried out. The case of detecting a Gaussian signal against a background of Gaussian noise is considered. Expressions are obtained for the power characteristics of the Wilcoxon detector with three-threshold quantization of the envelopes for the cases of optimal and uniform arrangement of the sampling thresholds. Optimization of the placement of thresholds gives a negligible gain in detection efficiency. Detection characteristics of parametric binary algorithm, analog Wilcoxon algorithm, discrete Wilcoxon algorithm, signed algorithm (respectively curves 1, 2, 3, 4) for the case of detection a Gaussian signal in Gaussian noise are presented on Fig. 3.

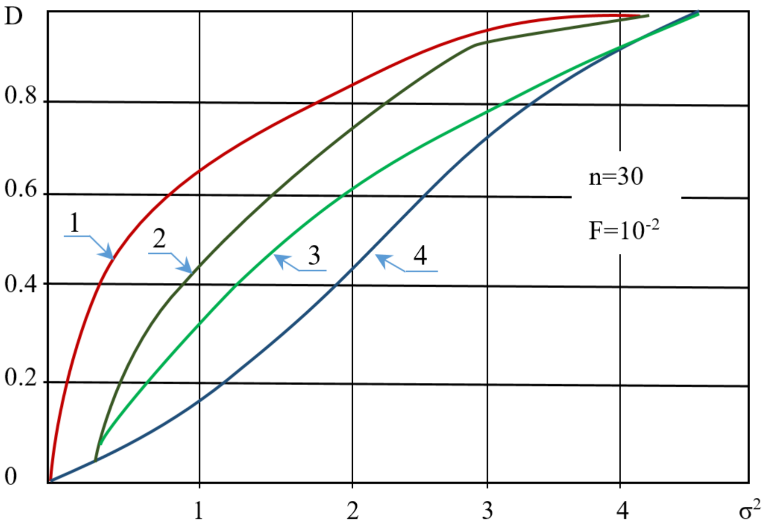

**Figure 3:** Detection characteristics of parametric binary algorithm (curve 1), analog Wilcoxon algorithm (curve 2), discrete Wilcoxon algorithm (curve 3), signed algorithm ( curve 4)

The detection characteristic of a binary parametric detector is built in accordance with the known expression:

$$D = 1 - \Phi\left(\frac{V - np}{np(1-p)}\right), \tag{9}$$

$$D = 1 - \Phi\left(\frac{V - np}{np(1-p)}\right)$$

$$- \frac{U_1^2}{\left(2(\sigma^2 + \sigma_c^2)\right]}$$

where *V* – detection threshold; *U* – quantization threshold, found from the condition *P*=0.2, $\sigma_c^2$ $\sigma_c^2$ = 0 and for $\sigma_c^2 = 1$ respectively equal 1.79; $\sigma_c^2$ $\sigma^2$ – variance of Gaussian signal; $\sigma^2$ $\sigma^2$ – variance of Gaussian signal and noise; $a^2$ – ratio of Gaussian signal variance to noise variance.

Detection threshold *V* is determined for the indicated *n* and *F* from the condition:

$$F = 1 - \Phi\left(\frac{V - n * 0.2}{n * 0.5(1 - 0.2)}\right) \tag{10}$$

In accordance with the calculations, it turned out that the three-threshold Wilcoxon detector is more effective than the analog sign detector and provides a constant probability of false detections.

## 4. Digital quasi-nonparametric detection system

Consider a two-channel digital system for detection a packet of pulsed signals with an unknown initial phase. From the output of the detector, the envelope of the interference (signal with interference) $\rho(t)$ enters through two channels, into one of which a time delay link is introduced $\tau_3 > \tau_k$- the process correlation interval.

At the moments when the strobe pulses are fed, the envelope readings in the channels are fed to the amplitude samplers with quantization levels *v* and then to the digital summation circuit with memory. At the end of a packet of volume *n* in the subtraction circuit, the obtained sums are compared and the result is output to the threshold detection device. We assume that at the output of the sampler, numbers from 0 are fixed, if the envelope samples fall into the interval between the first and second thresholds (assuming the first threshold is zero) to *v*-1, if the *v*-th threshold of the sampler is exceeded.

Further, the detection algorithm is considered as one of the possible modifications of the Markum algorithm [2-4]. With binary quantization of envelope samples, the modified Markum algorithm can be represented by the following relationship:

$$z = \sum_{i=1}^{n} \quad Sign(p_{1i}) - \sum_{i=1}^{n} \quad Sign(p_{2i}) \geq V. \tag{11}$$

where $\sum_{i=1}^{n} \quad Sign(p_{1i}) = \{0,\ if\ p_{1i} < V_1\ 1, if\ p_{1i} \geq V_1;$ $\sum_{i=1}^{n} \quad Sign(p_{2i}) = \{0,\ if\ p_{2i} < V_1\ 1, if\ p_{2i} \geq V_1;$ $p_{1i}, p_{2i}$ - envelope counts at adjacent range points; $V_1$ - quantizer threshold value.

The simulation results confirm the high efficiency of the algorithm when exposed to Gaussian noise and an additive combination of Gaussian noise and chaotic impulse noise.

In particular, when a Gaussian signal is detected against a background of Gaussian noise with a 2-fold change in the noise variance, the PFA changes by a factor of 3.5. High probability of correct detection is provided. A parametric detector is not operational with such changes in noise variance.

The efficiency of the modified Markum's algorithm obviously increases with an increase in the number of thresholds of the amplitude analyzer.

## 5. Conclusions

The possibility of using modified nonparametric algorithms of signs and Wilcoxon for radar detection of impulse signals is considered.

Expressions for estimating the probabilities of false and correct detection for K independent samples where there is no signal are obtained.

The results of calculations of the efficiency of the proposed detection system for private signal detection in Gaussian noise are given.

The results of evaluating the efficiency of the application of a digital quasi-nonparametric detection system of the modified Markum algorithm for binary quantization of envelope samples are presented.

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