Detection of the Coherent Pulse Signals with an Unknown Frequency against the Correlated Interferences

Oleg V. Chernoyarov[1,2,3], Vladimir A. Ivanov[3], Kirill A. Melnikov[1,3], and Artem A. Gulmanov[1]
[1] National Research Tomsk State University, Tomsk 634050, Russia
[2] Maikop State Technological University, Maikop 385000, Russia
[3] National Research University "Moscow Power Engineering Institute", Moscow 111250, Russia
Email: ChernoyarovOV@mpei.ru; IvanovVA@mpei.ru; o_v_ch@mail.ru; GulmanovAA@mpei.ru

Abstract —The algorithm for detecting the coherent-pulse signals against correlated interferences is considered. It is invariant to both the carrier frequency of the signal and the statistical characteristics of its fluctuations. Its optimization is implemented in terms of the signal-to-interference ratio. The structure of the optimized procedure for extracting the signals with the limited statistics is found under the arbitrary signal-to-interference ratio. The efficiency of the introduced procedure is estimated. A technique is presented for calculating the detection characteristics. The usefulness of the obtained results for designing the corresponding detection devices is confirmed by a number of examples of numerical calculations.

Index Terms—Signal detection, unknown frequency, interperiod processing, intraperiod processing, correlated interference, signal-to-interference ratio, false alarm probability, probability of correct detection

I. Introduction

The application of coherent-pulse radar systems provides the possibility of effectively protecting the radio channel from interference created by the reflections from the interfering objects by means of selecting targets by speed [1]. Implementation of these possibilities, in turn, requires the development of new signal processing algorithms.

The problem of joint processing of n coherent pulse group is considered assuming that the length of the interfering reflection zone does not exceed the interval between any pair of pulses. The processing should consist in the generation of an output signal to compare it with the detection threshold.

The problem of detecting the signals produced by moving targets under the influence of interfering reflections can be formulated as the problem of optimal radio reception against the correlated interferences. Under the specified conditions, it can be reduced to the generation of the separate samples for each of the pulses ("intraperiod processing") with subsequent joint processing of the received samples ("interperiod processing").

Manuscript received September 4, 2020; revised April 10, 2021.
This work was supported by the Ministry of Education and Science of the Russian Federation (research project No. FSWF-2020-0022).
Corresponding author email: chernoyarovov@mpei.ru.
doi:10.12720/jcm.16.5.185-190

It is well known [2], [3] that in most cases the procedure for interperiod processing of the complex samples $\dot{y}_k = R_k + iJ_k$, $k = \overline{1,n}$ of the additive mix of the signal $\dot{s}_k = x_k + iu_k$ and the correlated interference $\dot{N}_k$ is reduced to forming the quadratic form

$$z = \sum_{k=1}^{n}\sum_{l=1}^{n} Q_{kl}\,\dot{y}_k\,\dot{y}_l^* , \qquad (1)$$

where Q_{kl} is the elements of the processing matrix $\mathbf{Q}$, n is the number of samples generated at the output of the intraperiod processing system over the probe pulse period, and symbol "*" means complex conjugation.

In [4], [5], the solution is proposed to the problem of detecting a signal with an unknown frequency as the problem of simultaneous detection and measurement of the unknown components x_k, u_k of the input signal. Because a reliable description of the parameters of the signal with an unknown frequency is difficult, it is shown that, in this case, the elements of the matrix inverse to the interference correlation matrix $\mathbf{R} = \|R_{kl}\|$ can be used as the processing matrix elements in (1):

$$Q_{kl}^{\mathrm{I}} = R_{kl}^{-1} = \sum_{m=1}^{n} \frac{1}{P_{\mathrm{CN}}\lambda_m} \nu_{mk}\nu_{ml} \qquad (2)$$

where λ_m and ν_{mk} (ν_{ml}) are, respectively, the eigenvalues and the elements of the eigenvectors $\mathbf{v}_m$ of the normalized total interference correlation matrix $\mathbf{R} = \left(P_{\mathrm{C}}\mathbf{R}_{\mathrm{C}} + P_{\mathrm{N}}\mathbf{I}\right)/P_{\mathrm{CN}}$; $\mathbf{I}$ is the unit matrix; $\mathbf{R}_C$ is the correlation matrix of the correlated interference component; $P_{\mathrm{CN}} = P_{\mathrm{N}} + P_{\mathrm{C}}$ is the total interference power including the power of both the white noise P_{N} and the correlated interference component P_{C} .

Applying the coefficients (2) provides the invariance of the algorithm (1) with respect to both the frequency of the signal and the statistical properties of its fluctuations. In each specific case, the efficiency of the algorithm (1) depends on the real spectrum of signal fluctuations. It is obvious that when a priori or experimental characteristics of the fluctuations are taken into account, more effective procedures can be obtained.

One way to improve the procedure (1) using the processing matrix (2) is to make some assumptions regarding the signal characteristics. In this paper, the algorithm (1) is optimized in terms of the signal-to-(correlated interference + noise) ratio (SINR)

$$q^2 = P_{\mathrm{S}}/P_{\mathrm{CN}} \tag{3}$$

where P_{S} is the power of the received signal.

Evaluation of the procedure (1) efficiency can be obtained based on the study of the detection characteristic that is the dependence of the probability of correct detection D upon the ratio q^2 (3) under the fixed value of the false alarm probability F. In this case, calculations are usually performed for the extreme values of the target speed, that are the "optimal" speed (when the signal phase incursion is $\varphi = 2\pi fT = \pm(2k-1)\pi$, $k = 1, 2, \ldots$) and the "blind" speed (when $\varphi = \pm 2k\pi$) [1]. Here the notations are: T is the pulse repetition period, f is the Doppler signal frequency. However, the construction of the detection characteristic as the function $D = D(q^2)$ for the extreme values of the target speed does not show the detection efficiency in the range of target speeds (Doppler target signal frequencies). Therefore, in this paper, when analyzing the efficiency of the presented processing systems, the detection characteristics are calculated as the function $D = D(fT)$ for the different values of q^2.

II. Optimization of the Interperiod Processing Algorithm

One considers the sequence of the complex samples $\dot{\mathbf{y}} = \| \dot{y}_1, \ldots, \dot{y}_n \|$ of the additive mix of the useful signal $\dot{\mathbf{s}} = \| \dot{s}_1, \ldots, \dot{s}_n \|$ and the interference $\dot{\mathbf{N}} = \| \dot{N}_1, \ldots, \dot{N}_n \|$ generated at the output of the intraperiod processing unit at the sequential points of time $t_1, \ldots, t_n$:

$$\dot{y}_k = \dot{s}_k + \dot{N}_k, \qquad k = \overline{1, n} \tag{4}$$

The likelihood ratio for the vector $\dot{\mathbf{y}}$ (4) against alternative $\dot{\mathbf{y}} = \| \dot{N}_1, \ldots, \dot{N}_n \|$ is of the form

$$\begin{aligned} \Lambda(\dot{\mathbf{y}}) &= \exp\left[\mathrm{Re} \sum_{k=1}^{n} \sum_{l=1}^{n} R_{kl}^{-1} \left(\dot{y}_k \dot{s}_l^* - \frac{1}{2} \dot{s}_k \dot{s}_l^* \right) \right] = \\ &= \exp\left[\mathrm{Re} \sum_{m=1}^{n} \frac{1}{P_{\mathrm{CN}} \lambda_m} \left(\tilde{\dot{y}}_m \tilde{\dot{s}}_m - \frac{1}{2} \left| \tilde{\dot{s}}_m \right|^2 \right) \right], \end{aligned} \tag{5}$$

where

$$\tilde{\dot{y}}_m = \sum_{k=1}^{n} \nu_{mk} \dot{y}_k, \qquad \tilde{\dot{s}}_m = \sum_{k=1}^{n} \nu_{mk} \dot{s}_k. \tag{6}$$

According to the specified criteria of maximizing the ratio (3), the maximum likelihood estimates $\hat{\tilde{\dot{s}}}_m$ of the partial sums $\tilde{\dot{s}}_m$ can be found from the expression

$$L\left(\hat{\tilde{\dot{s}}}_1, \hat{\tilde{\dot{s}}}_2, \ldots, \hat{\tilde{\dot{s}}}_n \right) = \max_{\tilde{\dot{s}}_1, \tilde{\dot{s}}_2, \ldots, \tilde{\dot{s}}_n} L\left(\tilde{\dot{s}}_1, \tilde{\dot{s}}_2, \ldots, \tilde{\dot{s}}_n \right)$$

where

$$\begin{aligned} & L\left(\hat{\tilde{\dot{s}}}_1, \hat{\tilde{\dot{s}}}_2, \ldots, \hat{\tilde{\dot{s}}}_n \right) = \\ & = \sum_{m=1}^{n} \frac{1}{P_{\mathrm{CN}} \lambda_m} \left(\tilde{\dot{y}}_m \tilde{\dot{s}}_m - \frac{1}{2} \left| \tilde{\dot{s}}_m \right|^2 \right) - \frac{\chi}{2} \sum_{m=1}^{n} \left| \tilde{\dot{s}}_m \right|^2 \end{aligned} \tag{7}$$

and χ is the Lagrange multiplier that takes into account the set value (3).

Differentiating (7) by the variable $\tilde{\dot{s}}_m$ leads to the equation

$$\left(\tilde{\dot{y}}_m - \hat{\tilde{\dot{s}}}_m \right) \Big/ P_{\mathrm{CN}} \lambda_m - \chi \hat{\tilde{\dot{s}}}_m = 0$$

and its solution is

$$\hat{\tilde{\dot{s}}}_m = \tilde{\dot{y}}_m \big/ (1 + \chi P_{\mathrm{CN}} \lambda_m) \tag{8}$$

If the ensemble of signals with an arbitrary carrier frequency is considered, then it can be assumed that $\overline{\tilde{\dot{s}}_k \tilde{\dot{s}}_l} = 0$. Then, taking into account (6), the sum of the mathematical expectations of the squares of signal samples estimates is equal to

$$\sum_{k=1}^{n} \overline{\left| \tilde{\dot{s}}_k \right|^2} = n P_{\mathrm{S}} = n P_{\mathrm{CN}} q^2 \tag{9}$$

On the other hand, in view of (8), one can obtain

$$\begin{aligned} \sum_{m=1}^{n} \overline{\left| \tilde{\dot{s}}_m \right|^2} &= \sum_{m=1}^{n} \frac{1}{(1 + \chi P_{\mathrm{CN}} \lambda_m)^2} \left| \tilde{\dot{y}}_m \right|^2 = \\ &= (P_{\mathrm{S}} + P_{\mathrm{CN}}) \sum_{m=1}^{n} \frac{1}{(1 + \chi P_{\mathrm{CN}} \lambda_m)^2}. \end{aligned} \tag{10}$$

By equating the right-hand sides of the expressions (9) and (10), one can write the transcendental equation that allows determining the value of the multiplier χ:

$$\sum_{m=1}^{n} \frac{1}{(1 + \tilde{\chi} \lambda_m)^2} = n \frac{q^2}{1 + q^2} \tag{11}$$

where $\tilde{\chi} = P_{\mathrm{CN}} \chi$, and the likelihood ratio (5) can be represented in the following way:

$$\Lambda(\dot{\mathbf{y}}) = \exp\left[\sum_{m=1}^{n} \frac{1 + 2\tilde{\chi} \lambda_m}{2\lambda_m (1 + \tilde{\chi} \lambda_m)^2} \left| \tilde{\dot{y}}_m \right|^2 \right] \tag{12}$$

Thus, as it follows from the expression (12) and taking account the relation (6) for $\tilde{y}_m$, the processing matrix with the elements

$$Q_{kl}^{\mathrm{II}} = \sum_{m=1}^{n} \frac{1+2\tilde{\chi}\lambda_m}{2\lambda_m\left(1+\tilde{\chi}\lambda_m\right)^2} \nu_{mk}\nu_{ml} \tag{13}$$

should be used while implementing the algorithm (1) under the known SINR (3). The multiplier $\tilde{\chi}$ in (13) is found from (11) taking into account the desired SINR q^2 (3). Moreover, $q^2 \to \infty$, if $\tilde{\chi} \to 0$, and $q^2 \to 0$, if $\tilde{\chi} \to \infty$.

The analysis of the expression (13) shows that for the high SINR ($q^2 \to \infty$), the values of the coefficients of the processing matrix coincide with the values R_{kl}^{-1} in (2). However, if the SINR is low ($q^2 \to 0$), then the elements of the processing matrix are determined as

$$Q_{kl}^{\mathrm{III}} = \sum_{m=1}^{n} \frac{1}{P_{\mathrm{CN}}\lambda_m^2} \nu_{mk}\nu_{ml} = R_{kl}^{-2} \tag{14}$$

and that corresponds to the application of the squared processing matrix inverse to the interference correlation matrix $\mathbf{R}^{-2}$ [6] in (1). By other means, a similar result for the case $q^2 \to 0$ has been obtained in [6]-[9].

It should be noted that the expression (13) for the matrix processing elements Q_{kl} is a generalization of the result obtained in [4], [6], [7] under the arbitrary SINR. Thus its application should provide the highest efficiency of the algorithm (1) under the specified radio reception conditions.

III. Efficiency of the Optimized Algorithm

In order to determine the efficiency of the algorithm (1) while the weight coefficients (2), (13), (14) are applied, one calculates the detection characteristics using the procedure used in [2, 10] that is based on the calculation of the poles of the characteristic distribution function of the decision determining statistics (1). According to this approach, the probability of threshold z_0 being crossed by the value (1) is determined by the expression [10], [11]:

$$P = \sum_{k=1}^{M} \frac{1}{\left(\mu_k - 1\right)!} \times \frac{\mathrm{d}^{\mu_k - 1}}{\mathrm{d}\lambda_k^{\mu_k - 1}} \left[\lambda_k^{\mu_k - 1} \exp\left(-\frac{z_0}{\lambda_k}\right) \prod_{\substack{l=1 \\ l \neq k}}^{M} \left(1 - \frac{\lambda_l}{\lambda_k}\right)^{-\mu_l} \right] \tag{15}$$

where $M \le n$ is the number of different eigenvalues λ_i of the determining matrix $\mathbf{\Lambda}$ equal to the product of the processing matrix $\mathbf{Q}$ and the correlation matrix of the processed sequence:

$$\mathbf{\Lambda} = \begin{cases} \mathbf{QR} & \text{– in the absence of a signal ,} \\ \mathbf{Q}\left(\mathbf{R} + q^2\mathbf{R}^{\mathrm{S}}\right) & \text{– in the presence of a signal ,} \end{cases} \tag{16}$$

μ_k and μ_l are the multiplicities of eigenvalues λ_k and λ_l, respectively; q^2 is the SINR (3) that is determined based on the intraperiod processing; $\mathbf{R}^{\mathrm{S}}$ is the signal correlation matrix.

From (15), the formulas for calculating the probability of threshold crossing can be written for the cases when all the eigenvalues of the determining matrix that are not equal to zero are different ($\mu_k = \mu_l = 1$) [10, 11]:

$$P = \sum_{k=1}^{n} \exp\left(-\frac{z_0}{\lambda_k}\right) \prod_{\substack{l=1 \\ l \neq k}}^{n} \left(1 - \frac{\lambda_l}{\lambda_k}\right)^{-1} \tag{17}$$

or all the eigenvalues are multiple ($\mu_k = \mu_l = n$, $\lambda_k = \lambda_l = \lambda$):

$$P = \exp\left(-\frac{z_0}{\lambda}\right) \sum_{k=0}^{n-1} \frac{1}{k!} \frac{z_0}{\lambda} . \tag{18}$$

In [11], it is shown that when using the coefficients (2) in the processing matrix, the eigenvalues of the determining matrix $\mathbf{\Lambda}$ are equal to

$$\lambda_1 = \lambda_3 = \ldots = \lambda_n = 1 \quad \text{– in the absence of a signal,} \tag{19}$$

$$\left.\begin{aligned} &\lambda_1 = \lambda_3 = \ldots = \lambda_n = 1, \\ &\lambda_2 = 1 + q^2 \sum_{k=1}^{n}\sum_{l=1}^{n} W_{kl} \cos\left(\varphi_k - \varphi_l\right) \end{aligned}\right. \quad \text{– in the presence of a signal .} \tag{20}$$

In view of (15) and (18), one can obtain the formulas for calculating the false alarm probability F and the probability of correct detection D:

$$F = \exp\left(-z_0\right) \sum_{k=0}^{n-1} \frac{1}{k!} z_0^k , \tag{21}$$

$$D = \frac{1}{(n-2)!} \frac{\mathrm{d}^{n-2}}{\mathrm{d}\lambda_1^{n-2}} \left[\frac{\lambda_1^{n-1}}{\lambda_1 - \lambda_2} \exp\left(-\frac{z_0}{\lambda_1}\right) \right] + \left(\frac{\lambda_2}{\lambda_2 - \lambda_1}\right)^{n-1} \exp\left(-\frac{z_0}{\lambda_2}\right). \tag{22}$$

In (21), the relation (19) is taken into account while in (22) λ_1, λ_2 are substituted from (20). The formulas for calculating the probability of correct detection D obtained applying the expression (20) for the number of samples (pulses) $2 \le n \le 6$ are shown in Table I.

The direct calculations confirm that when using the coefficients (13) and (14) in the processing matrix, the eigenvalues of the determining matrix $\mathbf{\Lambda}$ in both the presence and absence of a signal are different positive numbers. It allows applying the formula (17) for calculating the F and D probabilities.

TABLE I: THE FORMULAS FOR CALCULATING THE PROBABILITY OF CORRECT DETECTION

n	The probability of correct detection D
2	$\exp(-z_0)/(1-\lambda_2)+\lambda_2\exp(-z_0/\lambda_2)/(\lambda_2-1)$
3	$\left[(2+z_0)/(1-\lambda_2)-1/(1-\lambda_2)^2\right]\exp(-z_0)+$ $+\lambda_2^2\exp(-z_0/\lambda_2)/(\lambda_2-1)^2$
4	$\left[\left(6+4z_0+z_0^2\right)/2(1-\lambda_2)-(3+z_0)/(1-\lambda_2)^2+1/(1-\lambda_2)^3\right]\times$ $\times\exp(-z_0)+\lambda_2^3\exp(-z_0/\lambda_2)/(\lambda_2-1)^3$
5	$\left[\frac{24+18z_0+6z_0^2+z_0^3}{6(1-\lambda_2)}-\frac{12+6z_0+z_0^2}{2(1-\lambda_2)^2}+\frac{4+z_0}{(1-\lambda_2)^3}-\frac{1}{(1-\lambda_2)^4}\right]\times$ $\times\exp(-z_0)+\lambda_2^4\exp(-z_0/\lambda_2)/(\lambda_2-1)^4$
6	$\left[\frac{120+96z_0+36z_0^2+8z_0^3+z_0^4}{6(1-\lambda_2)}-\frac{60+36z_0+9z_0^2+z_0^3}{6(1-\lambda_2)^2}+\right.$ $\left.+\frac{20+8z_0+z_0^2}{2(1-\lambda_2)^3}-\frac{5+z_0}{(1-\lambda_2)^4}+\frac{1}{(1-\lambda_2)^5}\right]\exp(-z_0)+$ $+\lambda_2^5\exp(-z_0/\lambda_2)/(\lambda_2-1)^5$

As an example, one presupposes that the reflected signal is the pulse packet, the correlation matrix components of which are of the form:

$$R_{kl}^{\mathrm{S}}=\exp\left[j(\varphi_k-\varphi_l)\right]$$

where $\varphi_j=2\pi fT_j$ is the phase incursion of the j-th pulse, T is the pulse repetition period while interferences are the mix of the white noise and the correlated interference with the Gaussian correlation function

$$r_{kl}=\exp\left[-\pi^2(\Delta fT(k-l))^2/2.8\right] \tag{23}$$

In (23), Δf is the interference bandwidth at the level of 0.5 while the normalized correlation coefficients of the total interference are $R_{kl}=\left(q_{\mathrm{C}}^2r_{kl}+\delta_{kl}\right)/\left(1+q_{\mathrm{C}}^2\right)$, where δ_{kl} is the Kronecker symbol [2] and $q_{\mathrm{C}}^2=P_{\mathrm{C}}/P_{\mathrm{N}}$ is the correlated interference-to-noise ratio.

In Figs. 1, 2, there are shown the results of calculating the detection characteristics for a periodic sequence of five pulses ($n=5$) while the false alarm probability F is fixed and equal to 10^{-3} (during the detection the Neyman-Pearson criterion is applied) and the normalized interference bandwidth is $\Delta fT=0.05$.

In Fig. 1, the characteristics are presented as the dependence of the probability of correct detection D upon the normalized signal frequency fT, if the signal-to-noise ratio is $q_{\mathrm{S}}^2=P_{\mathrm{S}}/P_{\mathrm{C}}=10$ and the correlated interference-to-noise ratio is $q_{\mathrm{C}}^2=10^2$ (Fig. 1a) or $q_{\mathrm{C}}^2=10^4$ (Fig. 1b). Curve 1 corresponds to the case when the coefficients (13) are used in the algorithm (1), curve 2 depicts that the coefficients (2) are used and curve 3 – that the coefficients (14) are used.

These characteristics allow tracing the change in the probability of correct detection D within the expected signal frequency range fT when using processing matrices with the coefficients (2), (13), (14).

The characteristics drawn in Fig. 2 represent the dependences of the probability of correct detection D upon the signal-to-noise ratio q_{S}^2 while the processing algorithm is used with the coefficients (2), (13) and (14) (curves 1, 2, and 3, respectively). It is assumed that the correlated interference-to-noise ratio is $q_{\mathrm{C}}^2=5$ (Fig. 2a) or $q_{\mathrm{C}}^2=10^4$ (Fig. 2b) and the normalized signal frequency is $fT=0.5$ while the SINR (3) varies within the ranges $q^2=0.8\ldots3.3$ (Fig. 2a) and $q^2=0.0004\ldots0.0025$ (Fig. 2b).

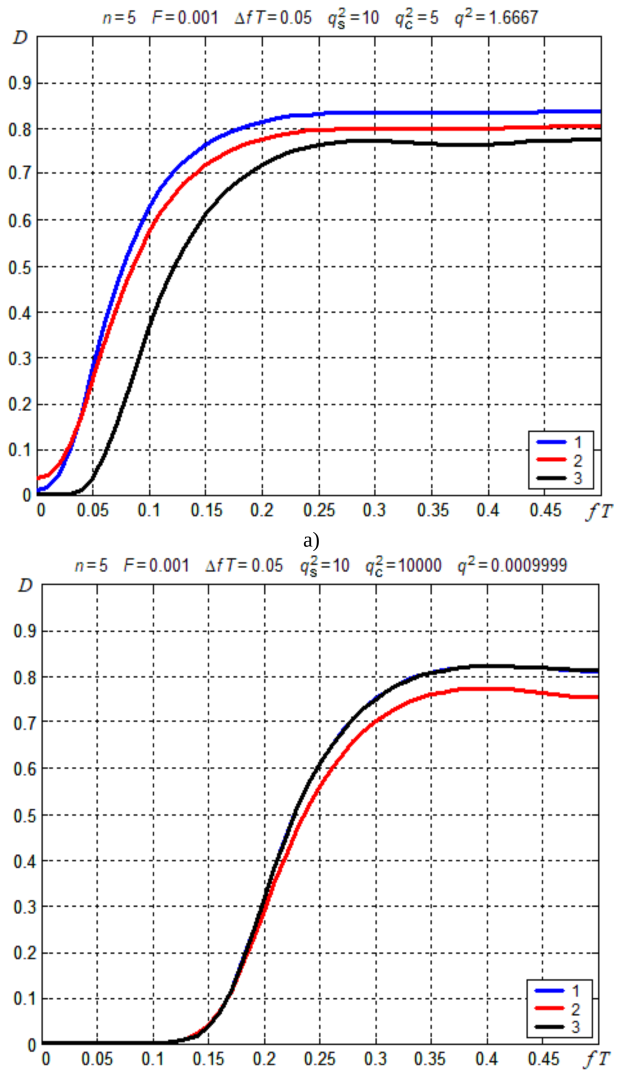

Fig. 1. The dependence of the probability of correct detection upon the normalized signal frequency.

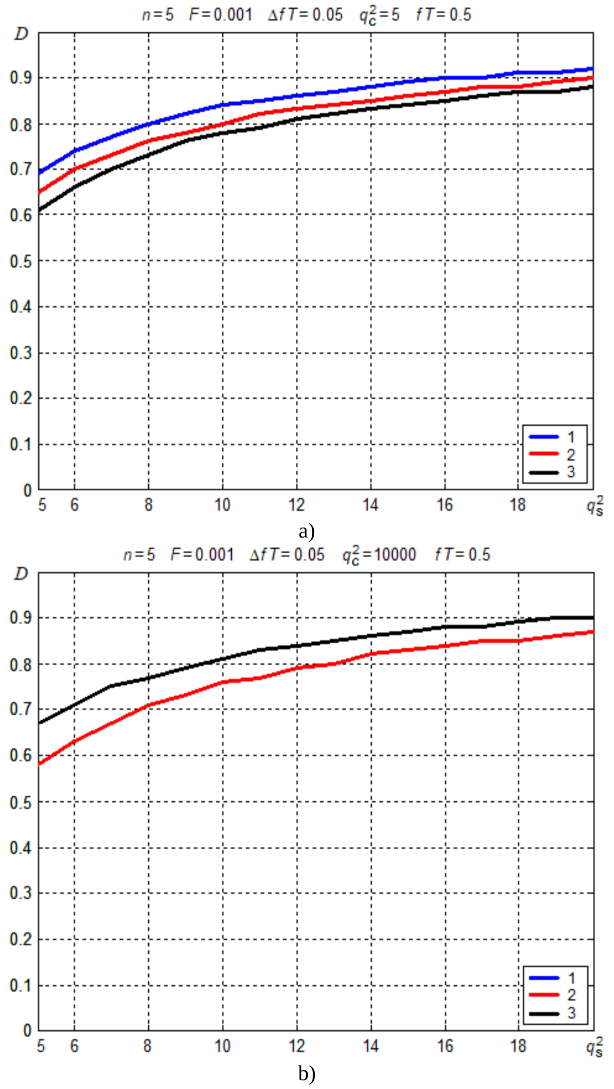

Fig. 2. The dependence of the probability of correct detection upon the signal-to-noise ratio.

From Fig. 1a, it follows that the probability of correct detection gets higher over the whole frequency range, if in the detection algorithm the optimized processing matrix $\mathbf{Q}^{\mathrm{II}}$ (curve 1) is used instead of the matrix $\mathbf{Q}^{\mathrm{I}}$ (curve 2), while the SINR (3) is high enough.

However, with the increasing signal power, the values of the probability of correct detection when using the matrices $\mathbf{Q}^{\mathrm{I}}$ and $\mathbf{Q}^{\mathrm{II}}$ get closer and closer together (Figs. 1a, 2a). It should also be noted that under the high SINRs (3) the application of the matrix $\mathbf{Q}^{\mathrm{III}}$ (curves 3 in Figs. 1a, 2a) during the signal detection turns to be impractical.

According to Fig. 1b, if the SINR (3) is high enough, then the values of the probability of correct detection obtained with the help of the matrices $\mathbf{Q}^{\mathrm{II}}$ (curve 1) and $\mathbf{Q}^{\mathrm{III}}$ (curve 3) coincide over the whole frequency range.

At the same time, when the correlated interference level is high, the application of the matrix $\mathbf{Q}^{\mathrm{I}}$ (curves 2 in Figs. 1a, 2a) leads to great losses and is thus impractical.

The analysis of the detection characteristics reveals that the availability of information about the SINR value allows obtaining a gain in the threshold signal z_0. Thus, for the specified example such gains are up to 3 dB.

IV. Conclusions

One has considered the algorithm (1) for processing the coherent-pulse signal against the correlated interferences, that is invariant to both the carrier frequency value and the statistical characteristics of fluctuations of the signal. This algorithm can provide higher efficiency during the detection of moving objects when a priori or experimental data on the signal-to-interference ratio value are available and the relation (13) is applied to calculate the processing matrix components.

As the conducted numerical calculations demonstrate, the obtained results can be effectively used for designing the corresponding detection devices. Under current conditions, when the computing facilities are widely used as part of the radar, the implementation of the introduced procedure (13) for forming the weight coefficients in the algorithm (1) does not appear difficult.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Our project research team jointly conducted the presented study, carried out numerical calculations and analyzed the results obtained both individually and cooperatively. All authors had approved the final version of the paper.

References

[1] *Radar Handbook*, 2nd ed., McGraw-Hill, New York, NY, 1990, ch. 15.

[2] D. Middleton, *An Introduction to Statistical Communication Theory*; New Jersey: Wiley-IEEE Press, 1996, ch. 17, 19.

[3] T. Murakami and R. S. Johnson, "Glutter suppression by use of weighted pulse trains," *RSA Review*, vol. 32, no. 3, pp. 402-428, Mar. 1971.

[4] G. A. Sokolov and V. A. Ivanov, "Detection of signals in the case of limited statistics against correlated interferences" (in Russian), in *Improving the Efficiency and the Reliability of Electronic Systems*, Leningrad: Leningrad Electric Institute, 1978, pp. 71-74.

[5] G. A. Sokolov, "Resolution of discrete random signals in the case of limited a priori statistics," *Telecommunications and Radio Engineering*, vol. 44, no. 5, pp. 94-97, Mar. 1989.

[6] I. V. Tsevukh and A. I. Maliuta, "Stabilization of the level of false alarms in a coherent/noncoherent radar processing system" (in Russian), in *Proc. 16th Int. Conf. Modern Information and Electronic Technologies*, Odessa, 2015, pp. 119-120.

[7] I. V. Tsevukh, "Algorithm for processing Gaussian signals under Gaussian disturbances," *Journal of the Russian Universities. Radioelectronics*, no. 12, pp. 53-54, Dec. 1988. (in Russian)

[8] V. V. Rodionov, "Adaptive algorithm for detecting the pinpoint targets against the clutters extended in range," *Applied Radio Electronics*, vol. 1, no. 2, pp. 205-209, Jun. 2002. (in Russian)

[9] V. V. Rodionov and A. Y. Svetlov, "Adaptive detection algorithms of the moving radar-tracking targets on the clutter background," *Radio Engineering*, no. 10, pp. 24-30, Oct. 2007. (in Russian)

[10] O. V. Chernoyarov, B. Dobrucky, V. A. Ivanov, and A. N. Faulgaber, "The object detection efficiency in synthetic aperture radar systems," *International Journal of Engineering Transactions B: Applications*, vol. 33, no. 2, pp. 337-343, Feb. 2020.

[11] G. A. Sokolov and V. A. Ivanov, "To calculating detection characteristics of signals against correlated interferences in the interperiod processing systems," in *Improving the Efficiency and the Reliability of Electronic Systems*. Leningrad: Leningrad Electric Institute, 1979, pp. 46-53. (in Russian)

Oleg V. Chernoyarov was born in 1973. He received his M.Sc. and Ph.D. degrees in radio physics from the Voronezh State University, Voronezh, Russia, and the D.Sc. degree in radio physics – from the Moscow Pedagogical State University, Moscow, Russia, in 1996, 2000 and 2011, respectively. Presently, he is working as a Professor at the Department of Electronics and Nanoelectronics of the National Research University "Moscow Power Engineering Institute" as well as a Leading Research Worker of the National Research Tomsk State University (International Laboratory of Statistics of Stochastic Processes and Quantitative Finance) and the Maikop State Technological University (Department of Mathematics, Physics and System Analysis). His main research interests include development of methods for transmission, reception and processing of information.

Vladimir A. Ivanov was born in 1944. He received his M.Sc. degree in radio engineering as well as Ph.D. degree in radiolocation and radio navigation from the Moscow Power Engineering Institute (that is National Research University currently), Moscow, Russia, in 1971 and 1986, respectively. Vladimir A. Ivanov is currently working as a Leading Researcher at the RD Department "Scientific Production Center "Design Engineering Bureau of Radio Engineering Devices and Systems" of the National Research University "Moscow Power Engineering Institute". His research interests include the development of the systems for radio navigation, radar and radio communications in space.

Kirill A. Melnikov was born in 1993. He received the B.Sc. degree in radio engineering from the National Research University "Moscow Power Engineering Institute" in 2019. Presently, Kirill A. Melnikov is a master's student in the Department of Electronics and Nanoelectronics at the National Research University "MPEI". His research interests include synthesis, analysis and simulation of the processing algorithms of stochastic processes and fields with unknown parameters.

Artem A. Gulmanov was born in 1988. He received the B.Sc. and the M.Sc. degrees from the Institute of Cryptography, Telecommunications and Computer Science in 2008 and 2010, respectively, both in information security of telecommunication systems. Presently, Artem A. Gulmanov is a PhD student in the Department of Electronics and Nanoelectronics at the National Research University "Moscow Power Engineering Institute". His research interests include synthesis, analysis and simulation of the processing algorithms of stochastic processes and fields with unknown parameters.