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IMPROVING THE ACCURACY AND PERFORMANCE SPEED OF THE DIGITAL SPECTRAL-CORRELATION METHOD FOR MEASURING DELAY IN RADIO SIGNALS AND DIRECTION FINDING

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A promising direction for the development of passive radar monitoring stations is to improve their efficiency by increasing their speed of performance. For the digital spectral-correlation method for determining the delay of radio signals and direction finding, analytical expressions have been derived for a variance of the estimation of the delay in receiving a signal by radio channels and directions to the source of radio emission. A feature of the method reported in this study is the use of two-stage temporal and spatial spectral analysis of the mutual spectrum, a single-iteration correlation analysis.

The duration of estimating the direction finding has been evaluated through the total number of multiplication operations with accumulation. The proposed method, while providing for a gain of 27 times in terms of performance speed, demonstrated a slight decrease in accuracy compared to the optimal one due to energy signal loss.

The result of the simulation has established the dependences of the standard deviation in the direction finding and delay estimates on the signal-to-noise ratio, the type of spectral analysis window, and the size of the antenna base.

The standard deviation of the direction-finding estimate depends on the signal-to-noise ratio and varies over the range of values [0.08; 0.034]° with a change in the signal/noise ratio [–10; 40] dB. As the signal/noise ratio increases, the error decreases in line with a hyperbolic dependence. The standard deviation of the delay estimate depends on the signal-to-noise ratio and varies similarly to the error of the directional estimate, and is in the range of values [18.176; 1.56] ns, which corresponds to an error of [0.637; 0.055] %. The error of direction-finding estimation, depending on the size of the antenna base, decreases in the exponent within [1.6; 0.03]° with an increase in the antenna base in the range from 200 to 7,500 m.

The results reported here could be used for the parametric optimization of spectral-correlation radio direction finders at passive radar monitoring stations

Keywords: estimate variance, accuracy, speed of direction finding, spectral-correlation method, antenna base

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1. Introduction

The issue of improving the efficiency of the existing radio monitoring system is very relevant as it has not been solved in most applied tasks. Solving this problem is facilitated by the integrated use of various methods and means (signals of complex shape, optimal methods of their processing, phased antenna arrays, organizational measures). The rapid increase in the number of radio-electronic tools complicates the electromagnetic environment (EME) while electromagnetic compatibility issues are becoming important. These circumstances complicate the operation of radio monitoring equipment in operational detection systems, predetermine increased requirements for both the accuracy of signal parameter assessment and performance speed. Modern radio monitoring and radio navigation systems commonly employ digital correlation methods for determining the delay of radio signals and the direction of their arrival [1].

The most time-consuming processing is the calculation of the correlation function, which makes it possible to optimally determine the delay time of the signal. With the time digital algorithm for correlating the delay time, the sample rate of the signals depends significantly on the required measurement accuracy. Accordingly, the arrays of accumulated samples of signals become very large, which significantly reduces the speed of calculations in the classical multi-iteration correlation method of estimating the delay. The implementation of computations requires significant time or hardware costs, which reduces the efficiency of the system.

In practice, to improve the efficiency of radio monitoring systems using correlation methods for determining the delay and direction finding time, a high-speed digital spectral-correlation method has been proposed, which makes it possible to determine the delay in one iteration. At the same time, it is advisable to implement correlation processing by forming and analyzing a mutual complex spectrum of accepted implementations. In this case, the information parameter of the mutual spectrum is the difference phase spectrum and the dependence of its rate of change on the frequency. Spectral decomposition of the signal provides both high performance speed and minimal resource costs.

To further use the examined method in radio monitoring systems, it is necessary to perform an analytical assessment of its accuracy and performance speed. In addition, for its subsequent parametric optimization and effective use, it is necessary to derive the dependence of accuracy on the variable parameters of the signal processing algorithm.

Therefore, research on the development and analysis of high-speed digital methods for assessing signal delay and direction finding is relevant.

2. Literature review and problem statement

An urgent task is to assess the delay in receiving signals and the direction finding of broadband radio sources (BRS), in particular noise-like ones. In a complex EME, the use of fast correlational methods for estimating delay and direction finding is very promising [1]. Therefore, analytical studies into the accuracy and performance speed of the digital spectral-correlation method for determining the delay of signals and direction finding is a relevant task.

Paper [2] proposes a digital high-speed spectral-correlation method for estimating the delay in receiving a radio signal and direction finding and reports a preliminary analysis of its accuracy depending on the direction of signal arrival using modeling. Its peculiarity is the possibility of a single-iteration correlation algorithm for estimating signal delay and direction finding. The implementation of calculations does not require significant time or hardware costs, which could improve the efficiency of radio monitoring systems. A study of the principles for determining the delay of radio signals for the conditions of a large antenna base was carried out. However, no analytical studies of the error in estimating the signal delay and direction to BRS, as well as the speed of processing, were carried out. In addition, for the further use of a given method of estimating the delay and direction finding, it is necessary to derive the dependence of accuracy on the variable parameters of the signal processing algorithm by modeling. In addition, one needs to compare them with theoretical ones and carry out parametric optimization.

Paper [3] proposes a new method for estimating the direction to the radiation source and the coefficients of mutual influence depending on the direction. The method evaluates the initial directions of arrival using the MUSIC algorithm. Assessing the direction of arrival in the presence of mutual influence is an important problem in the tasks of determining the direction. The proposed method has a higher performance than conventional methods but, in general, has a high computational complexity and is not effective in practice for radio monitoring systems.

Paper [4] analyzes the features of the implementation and accuracy of the studied direction-finding method, as well as analytical optimization of the search-free digital method of correlation-interferometric direction finding with the reconstruction of the spatial analytical signal. The parameters included in the variance equation of the error of estimating the direction to the source of radio emission, which are subject to optimization, have been determined. Theoretical optimization of the parameters of the studied method was carried out, as well as a comparative analysis of analytical calculations and modeling results. That makes it possible to find the direction to radio emission sources under interference conditions using a linear antenna array (AA). This method does not allow the use of a large antenna base, which limits the possibility of increasing accuracy due to its adjustment. In addition, multi-channel AAs are costly. That necessitates the development and study of the accuracy of high-speed correlation direction finding methods using a large antenna base.

Paper [5] investigates the accuracy of the search-free digital method of correlation-interferometric direction finding with two-dimensional correlation processing of the spatial signal. Analytical expressions for the variance of the error in estimating signal delay and direction finding were derived. It is shown that in addition to the main classical adjustable parameters, such as the number of direction finding channels and the time of radiation analysis, the variance of the direction finding error is also affected by the magnitude of the spatial shift of correlation processing, the type of weight function of digital chart formation, and the value of its normalized autocorrelation function. The obtained expressions for variance of the error in estimating the delay of signal and direction finding cannot be directly used in correlational direction-finding methods that do not use linear AA. That necessitates an analysis for the method under study for assessing the delay in receiving the radio signal and direction finding.

Study [6] offers a broadband and reconfigurable vector antenna with radiation pattern for applications with dual polarization and the possibility of three-dimensional direction finding of radio emissions. Compared to the current state of the art, this antenna provides an accurate assessment of the direction of arrival of an incoming vertically or horizontally polarized electromagnetic field in a wider bandwidth. Issues related to the use of this antenna in correlation-interferometric radio direction finders remain unexplored.

Paper [7] reports the results of studying a method for determining the direction in the systems of phase interferometers.

The mean square deviation (RMS) is less than 0.1 degrees. Accuracy analysis was also performed in the frequency range of 6–18 GHz with a viewing sector of 120 degrees. However, the issues associated with the appearance of results with the maximum error of the phase difference remained unresolved. The reason for this may be the objective difficulties associated with the need to process large amounts of data. In practice, the disadvantage of such radio direction finders is the need for a high input signal-to-noise ratio exceeding 20 dB.

In work [8], an algorithm for determining the direction using a matrix with time modulation for binary phase shift keying signals is proposed. In the suggested scheme, only two antenna elements and one RF channel are required, and the switching period is not related to the period of the input signal symbol. It is advisable to conduct numerical modeling, and test the effectiveness by building two-element test platforms. The possibility of direction-finding of signals of other types has not been investigated. These results cannot be directly used for spectral-correlation direction finding methods.

Paper [9] proposes a method for detecting and directing vessels based on frequency-time analysis. The target ridges on the TF representation of the echo data are discovered first. Snapshots of the array are then formed by sampling the extracted ridges and used to estimate the direction of arrival. Such methods require a coherent integration time of a few minutes. The proposed method has an increased detection rate and reduced direction-finding errors, especially in scenarios with a relatively low signal-to-noise ratio. Thus, a given method is not implemented for short-duration radio signals and depends on the type of signal.

Paper [10] proposes a new method for determining the direction using a matrix with time modulation by analyzing the harmonic characteristic of the received signal, which requires only two antenna elements and one radio frequency channel. Signal processing by the proposed method is brief, and the scope of its calculations is focused on the two-point discrete Fourier transform. The cited paper does not carry out an analytical analysis of the accuracy and time spent on assessing the direction. This method requires further research to analyze the possibility of its application in radio monitoring systems.

An unsolved part of the general problem of improving the efficiency of radio monitoring equipment is the analytical study of the accuracy and performance speed (time spent on assessing the delay and direction of arrival of radio emission) of the digital spectral-correlation method for assessing the delay in receiving radio signals and direction finding.

3. The aim and objectives of the study

The aim of this work is to improve the accuracy and reduce the time spent on estimating the delay and direction of arrival of radio emission of the digital spectral-correlation method for assessing the delay of signals and direction finding. This would make it possible to improve the efficiency of radio monitoring equipment.

To accomplish the aim, the following tasks have been set:

– to conduct analytical studies into the accuracy of estimating the delay and direction of arrival of radio emission (direction finding);

– to conduct an analysis of performance speed (time spent on the assessment of delay and direction finding);

– to simulate the operation of a direction finder and investigate the dependences of the standard deviation of the direction finding and delay estimates on the signal-to-noise ratio, the type of the spectral analysis window, the size of the antenna base by modeling.

4. The study materials and methods

The object of this study is the algorithm of the digital spectral-correlation method for assessing the delay of radio signals and direction finding.

When addressing the first task, the methods of the theory of correlation analysis, digital spectral analysis, statistical radio engineering, comparative analytical analysis were used.

When tackling the second task, the method of digital spectral analysis, the correlation method for estimating the delay, was used.

When resolving the third task, the method of analytical program modeling, determining the adequacy of the radio direction finder model, and methods of statistical evaluation were used. A comparison of the dependence built on the basis of the obtained analytical assessment and the results of modeling has been carried out.

5. Results of studying the spectral-correlation method for estimating delay and direction finding

5. 1. Analytical study into the accuracy of the digital spectral-correlation method for estimating signal delay and direction finding

Let the a priori unknown radio signal $S(t)$ be received simultaneously by two identical radio channels spatially spaced by the amount of d of the antenna base. Radio channels have statistically independent Gaussian noises of their own $n_1(t)$ and $n_2(t)$ with known probabilistic characteristics and form implementations $S_1(t)$ and $S_2(t)$ of the $S(t)$ radio signal in additive mixtures $U_1(t)=S_2(t)+n_2(t)$ and $U_2(t)=S_2(t)+n_2(t)$, respectively. Implementations are formed during the time of analysis T_a, $t\in\{0; T_a\}$ within the frequency band $\{\omega_l, \omega_h\}$ of receiving. The $S_1(t)$ and $S_2(t)$ implementations of the radio signal are received with a relative random delay τ_S, which depends on the direction θ_S to the source of the radio signal $S(t)$ and has a uniform probability density distribution in the interval $\{0; \tau_{S\max}\}$, the value $\tau_{S\max}=d/c$, $\tau_{S\max}<T_a$.

For the specified conditions, it is necessary to determine with minimal time and hardware costs the assessment θ_S of the direction to BRS. In addition, an estimate of the relative delay τ_S, provided that the value d of the antenna base is greater than the order of magnitude of the wavelength λ_S of the radio signal $S(t)$: $d\gg\lambda_S$.

According to the high-speed spectral-correlation method proposed in work [2], a direct estimate of the relative delay τ_S is realized on the basis of two-stage temporal and spatial spectral analysis. To this end, first, by using the fast Fourier transform algorithm (FFT), the complex Fourier time spectra $U_1(j\omega_k)$ and $U_2(j\omega_k)$ of the received mixtures $U_1(t)$ and $U_2(t)$, respectively, and their mutual spectrum $U_{12}(j\omega_k)$ are determined:

$$U_{12}\left(j\omega_k\right)=U_1^*\left(j\omega_k\right)\cdot U_2\left(j\omega_k\right), \tag{1}$$

where ω_k is the k-th frequency count, $k=0,1, ..., (N_S-1)$; N_S is the number of time and spectral realization samples; $()^*$ is the complex pairing operation.

Next, based on the proposed quasi-harmonic model $U_{12}(j\omega_k)=A_\Omega\cdot\exp(j\Omega_S\omega_k)$ of the mutual spectrum, a Fourier-estimation of the spatial frequency Ω_S of the signal and filtering of the signal component $U_A(j\Omega_p)$ of the mutual spectrum is performed.

After that, the most plausible direct estimate τ_S of the relative delay of signal reception is determined:

$$\hat{\tau}_S=\frac{\Delta\psi_A(\Omega_p,z)}{(2\pi/T_a)\cdot(z_2-z_1)}, \tag{2}$$

where $\Delta\psi_A(\Omega_p,z)$ is the difference in the values of the complex analytical signal argument $U_A(j\Omega_p)$; z_1, z_2 are the numbers of spatial frequency samples selected to determine the difference $\Delta\psi_A(\Omega_p,z)$ of arguments; Ω_p is the p-th value of the spatial frequency, $p=0,1,\ldots,(z-1)$.

Using the estimate of the delay τ_S, obtained from (2), one determines the estimate θ_S of the direction to BRS [1, 2]:

$$\hat{\theta}_S=\arccos(c\cdot\hat{\tau}_S/d), \tag{3}$$

where c is the speed of propagation of electromagnetic radiation in free space.

Thus, the method proposed in [2] provides a combination of low computational costs and high accuracy of estimates τ_S of delay and θ_S direction to BRS when using a large antenna base, which could exceed several kilometers.

Let us perform an analytical assessment of the error in determining the estimates of delay τ_S and direction θ_S to BRS when using the method under study. Taking into consideration (3), the variance σ_θ^2 of the assessment of the direction to BRS θ_S is determined by the variance σ_τ^2 of the estimation of the relative delay in receiving the signal $S(t)$ by radio channels [1, 2]:

$$\sigma_\theta^2=c^2\cdot\sigma_\tau^2/d^2\cdot\sin^2\theta. \tag{4}$$

In turn, the variance σ_τ^2 of the delay estimate is determined, taking into consideration (2), as follows:

$$\sigma_\tau^2=\frac{\sigma_\psi^2(z_1)+\sigma_\psi^2(z_2)}{\left((2\pi/T_a)\cdot(z_2-z_1)\right)^2}, \tag{5}$$

where $\sigma_\psi^2(z_1)$, $\sigma_\psi^2(z_2)$ is the variance of the estimation of the complex analytical signal argument for z_1, z_2 frequency samples, respectively.

The variance $\sigma_\psi^2(z_2)$ of the evaluation of the complex analytical signal argument is determined by the signal-to-noise ratio when it is formed:

$$\sigma_\psi^2(z)=\frac{1}{\mu_A(z)}, \tag{6}$$

where $\mu_A(z)$ is the signal-to-noise ratio of the $U_A(j\Omega_p)$ implementation of the complex analytical signal.

Let us determine the dependence $\mu_A(z)$ on the value of the signal-to-noise ratio μ_1 at the inputs of radio channels. The ratio μ_1 is determined by the power P_S of the received radio signal $S(t)$ and the bandwidth of the frequency band $\{\omega_l,\omega_h\}$ of the reception:

$$\mu_1=\frac{P_S}{N_0(\omega_h-\omega_l)}=\frac{P_S}{P_n}, \tag{7}$$

where P_n, N_0 is the power and one-way spectral power density of the native noise of the radio channels.

After performing a time Fourier spectral analysis and determining the spectra $U_1(j\omega_k)$ and $U_2(j\omega_k)$, the value of the signal-to-noise ratio does not change and is equal to μ_1. This is determined by the uniform distribution of the signal power P_S and the natural noise P_n within the frequency band $\{\omega_l,\omega_h\}$ of the reception.

Let us determine the signal-to-noise ratio μ_2 after the implementation of the mutual spectrum $U_{12}(j\omega_k)$. To this end, taking into consideration (1), let us determine the spectral composition $U_{12}(j\omega_k)$:

$$\begin{aligned}&U_{12}(j\omega_k)=U_1^*(j\omega_k)\cdot U_2(j\omega_k)=\\&=S_1^*(j\omega_k)\cdot S_2(j\omega_k)+S_1^*(j\omega_k)\cdot n_2(j\omega_k)+\\&+S_2(j\omega_k)\cdot n_1^*(j\omega_k)+S_2(j\omega_k)\cdot n_2(j\omega_k)+\\&+n_1^*(j\omega_k)\cdot n_2(j\omega_k).\end{aligned} \tag{8}$$

Our analysis of (8) shows that the product of the spectra $U_{12}(j\omega_k)$ contains a signal component $S_1^*(j\omega_k)\cdot n_2(j\omega_k)$ and three noise components. Two of them $S_1^*(j\omega_k)\cdot n_2(j\omega_k)$ and $S_2^*(j\omega_k)\cdot n_2(j\omega_k)$ are the mutual spectrum of usable signal and random spectral realizations of natural noise, and the third $n_1^*(j\omega_k)\cdot n_2(j\omega_k)$ is the mutual spectrum of natural noise of radio channels. All three noise components are formed on the basis of linear transformations of Gaussian white noise, so they are also random functions with normal probability density, zero mathematical expectation, and the corresponding value of variance or power [1, 4].

With a large input ratio of $\mu_1\gg1$ the signal/noise ratio μ_2 the signal-to-noise is:

$$\mu_2\cong0.5\mu_1. \tag{9}$$

For the case $\mu_1<1$, the noise component $n_1^*(j\omega_k)\cdot n_2(j\omega_k)$ would prevail and the value of μ_2 in $U_{12}(j\omega_k)$ would equal:

$$\mu_2=\mu_1^2. \tag{10}$$

Further, after the operations of spatial spectral analysis, the nature of the power distribution of the usable signal $S_A(j\Omega_p)$ and the noise component $n_A(j\Omega_p)$ of the spatial spectrum $U_A(j\Omega_p)$ of the mixture has significant differences. Taking into consideration the quasi-harmonious model of the signal component $S_{12}(j\omega_k)$ of the mutual spectrum $U_{12}(j\omega_k)$, its spatial spectrum $S_A(j\Omega_p)$ is narrowband and concentrated in the band $(2\pi/T_a)\cdot m_S$. At the same time, the noise component $n_A(j\Omega_p)$ of the spatial spectrum $U_A(j\Omega_p)$ has a uniform power distribution within the band $(2\pi/T_a)\cdot z$ of the analysis.

Thus, as a result of spatial spectral analysis and signal selection, the signal-to-noise ratio μ_3 would increase significantly and would be equal to [4, 11]:

$$\mu_3=\frac{\mu_2\cdot Z}{m_S\cdot K_w}, \tag{11}$$

where Z is the number of samples of the mutual spectrum $U_{12}(j\omega_k)$ from which spatial spectral analysis is performed; m_S is the number of samples of the signal group of the spatial spectrum $S_A(j\Omega_p)$; K_w is the noise band of the weight function $W(z)$ of the spatial spectral analysis window.

At the stage of direct evaluation τ_S of the delay in receiving the signal, the difference $\Delta\psi_A(\Omega_p, z)$ of the values of the arg $(U_A(j\Omega_p, z))$ of the analytical signal with a shift (z_2-z_1) by the variable z [2] is determined. In this case, the variance

$\sigma^2_{\Delta\psi}$ of the difference $\Delta\psi_A(\Omega_p, z)$ of the argument taking into consideration (6) and (11) would be equal to:

$$\sigma^2_{\Delta\psi}=\frac{1}{\mu_3 W^2(z_1)}+\frac{1}{\mu_3 W^2(z_2)}=$$

$$=\frac{m_S\cdot K_w\left(W^2(z_1)+W^2(z_2)\right)}{\mu_1^2\cdot Z\cdot W^2(z_1)\cdot W^2(z_2)}, \tag{12}$$

where $\mu_3(z)=\mu_3 W^2(z)$.

Taking into consideration (5) and (12), the variance σ^2_τ of the estimate τ_S of the delay would be:

$$\sigma^2_\tau=\frac{m_S\cdot K_w\left(W^2(z_2)+W^2(z_1)\right)}{\mu_1^2\cdot Z\cdot W^2(z_1)\cdot W^2(z_2)\cdot\left((2\pi/T_a)\cdot(z_2-z_1)\right)^2}. \tag{13}$$

Taking into consideration the variance value σ^2_τ of the τ_S delay of the radio signal reception delay obtained in (13), the variance of the evaluation of the direction θ_S to BRS is determined using (4).

The potential accuracy of the proposed method is close to the optimal variant but, due to the energy losses during the spectral selection of the signal, it would be less.

The proposed model of the mutual spectrum is a quasi-harmonious process with constant power. All energy must be invested in the local extremes of the spectrum but, if parasitic modulation is taken into consideration in practice, then the energy would be distributed to other frequencies. In this case, the signal-to-noise ratio would become less, and the accuracy is correspondingly worse. As a result, in practice, accuracy losses compared to the optimal method could be up to 10 % due to energy signal loss [1, 11].

Thus, the errors of the estimates τ_S of the signal delay and direction to BRS θ_S have been determined.

5. 2. Analyzing the performance speed of the delay and direction-finding assessment

We analyzed the performance speed of the digital spectral-correlation method for assessing the delay of the radio signal and direction finding. For this purpose, the processing time T_1 of the radio signal $S(t)$ has been estimated.

The mixture of radio emissions at the intermediate frequency of the radio channels is converted to digital form with the sampling rate of the analog-to-digital conversion F_d during the analysis time T_a. At the same time, two arrays of samples $N_S=T_a\cdot F_d$ of the received mixtures $U_1(t)$ and $U_2(t)$ of radio emissions accumulate.

The main operation that is performed in correlation-interferometric direction finding is multiplication with accumulation [1, 4]. Therefore, it is advisable to estimate the duration of direction finding through the total number of multiplication operations with accumulation that must be performed to estimate the delay of the radio signal and direction finding. The speed of direction finding would be estimated by the signal processing time to estimate the direction finding.

The duration of FFT and correlation analysis should be determined through the number of complex multiplication operations [11]. The main time costs T_1 consist of time spectral analysis T_{SA} of the coherently received and digitized at an intermediate frequency of a mixture of radio emissions. In addition, spatial spectral analysis T_{SSA} for each time spectral component $\omega_{IF,k}$ of the received mixture, $k\in[0; 0.5\cdot N_S-1]$.

Other time costs could be neglected. Then the main time costs T_1 of the proposed method are determined from the formula:

$$T_1=T_{SA}+T_{SSA}. \tag{14}$$

To minimize the time costs of time spectral analysis, it is advisable to implement it based on fast algorithms, for example, the FFT algorithm. In this case, the number of temporal spectral analysis operations N_{SA} performed sequentially for $Z=2$ radio channels is [11]: $N_{SA}=2N_S\cdot\log_2\cdot N_S$.

Spatial spectral analysis T_{SSA} is performed for $0.5\cdot N_S$ temporal spectral components of the signal mixture with the number of operations $N_{SSA}=(N_S/2)\cdot\log_2\cdot(N_S/2)$. Then the total number of operations of multiplication N_1 with accumulation and T_1 is determined from the formulas:

$$N_1=2N_s\log_2 N_s+\frac{N_s}{2}\log_2\frac{N_s}{2},$$

$$T_1=\left[2N_s\log_2 N_s+\frac{N_s}{2}\log_2\frac{N_s}{2}\right]\cdot T_0, \tag{15}$$

where T_0 is the time to complete a single operation.

For the well-known correlation direction finding method, the correlation function is determined multiple times for an array of possible signal delay values using spectral processing [1]. Therefore, the total number of multiplication operations N_2 with accumulation would consist of the time spectral analysis operations N_{SA} and multi-iteration correlation processing:

$$N_2=2N_S\cdot\log_2\cdot N_S+m_\sigma\cdot(N_S/2),$$

where m_σ is the number of iterations of correlation processing, which depends on the specified accuracy of the signal delay estimate. The total time cost T_2 is, respectively, equal to $T_2=N_2\cdot T_0$.

The V gain in terms of the performance speed of the delay and direction-finding estimation could be determined from the following relation:

$$V=\frac{T_2}{T_1}=\frac{N_2\cdot T_0}{N_1\cdot T_0}=\frac{\left(2\log_2 N_s+\frac{m_\sigma}{2}\right)\cdot T_0}{\left(2\log_2 N_s+0.5\log_2\frac{N_s}{2}\right)\cdot T_0}, \tag{16}$$

where N_1, N_2 is the number of operations for the proposed and known correlation methods for estimating delay and direction finding, respectively; m_σ is the number of iterations of correlation processing.

For $N_s=32{,}000$, $m_\sigma=1{,}800$, $T_0=0.1$ ns considering (14) to (16), the V gain is:

$$V=\frac{T_2}{T_1}=\frac{\left(2\log_2 32{,}000+\frac{1{,}800}{2}\right)\cdot 10^{-10}}{\left(2\log_2 32{,}000+0.5\log_2\frac{32{,}000}{2}\right)\cdot 10^{-10}}\approx 27.$$

Thus, the gain is 27 times faster than the order and is significant.

The resulting reduction in total time costs is achieved by eliminating multi-iterative correlation processing. The most plausible direct estimate (2) of delay is used, at which $m_\sigma=1$.

5. 3. Simulation results

We have studied the characteristics of the temporal mutual and spatial spectra of radio signals, which are received by two radio channels spaced apart in space using the developed software model in the computer algebra environment PTC Mathcad, USA.

Conditions of research:

– type of signal modulation – linear frequency, $S(t)=A\cdot\sin(\omega_0 t+bt^2)$;

– the value of the carrier frequency of the signal $f_0=500$ MHz;

– the width of the signal spectrum $\Delta f_s=1$ MHz;

– the value of the antenna base $d=2{,}500$ m;

– the value of the direction to BRS is $\theta=70°$.

5. 3. 1. The dependence of the standard deviation of the direction finding and delay estimate on the signal-to-noise ratio

We have investigated the dependence of RMS estimation of the delay σ_τ and the direction finding σ_θ on the signal/noise ratio: Fig. 1. The specified value of the direction to BRS of $\theta=70°$ matches the signal delay value $\tau=2.852\cdot10^{-6}$ s. Type of window of spatial spectral analysis – Kaiser.

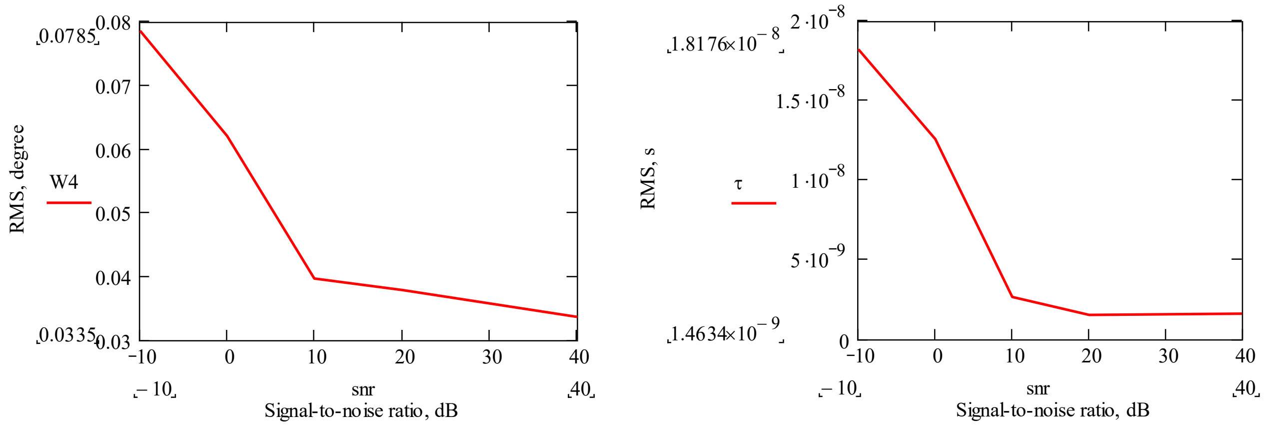
Our analysis of plots in Fig. 1 shows that the RMS of the estimation of direction finding σ_θ depends on the signal-to-noise ratio and varies over the range of values [0.08; 0.034]°. As the signal/noise ratio increases, the error σ_θ decreases in line with a hyperbolic dependence. In this case, a significant change in the RMS of the estimate of delay σ_τ and direction finding σ_θ is observed with the signal/noise ratio of [–10; 10] dB. According to the theory, the signal-to-noise ratio is inversely proportional to the RMS value, which coincides with the simulation results.

The RMS of the delay estimate also depends on the signal-to-noise ratio and changes similarly to the RMS of the direction estimate and is in the range of values [18,176; 1,559] ns, which corresponds to an error of [0.637; 0.055] %.

The method under study provides high accuracy of estimation of delay and direction finding in a wide range of signal-to-noise ratios [–10; 40] dB. The ability to process signals with a signal-to-noise ratio less than zero has been confirmed.

5. 3. 2. The dependence of the standard deviation of the direction finding estimate on the size of the antenna base

We studied the dependence of RMS of the assessment of direction finding σ_θ on the antenna base. Research conditions were: a signal-to-noise ratio, $S/N=10$ dB, Fig. 2.



a *b*

Fig. 1. The dependence of the rms deviation of the estimate of delay and direction to the source of radio emission on the signal-to-noise ratio: *a* — the dependence for direction finding; *b* — the dependence for delay

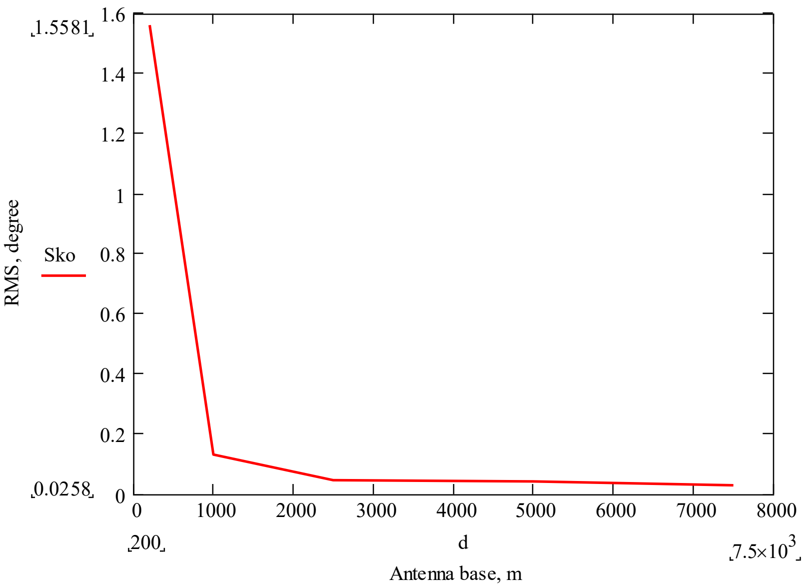


Fig. 2. The dependence of the standard deviation of the direction finding estimate on the antenna base

Our analysis of the plot in Fig. 2 shows that the RMS of the estimate of the direction finding σ_θ, depending on the size of the antenna base, decreases in the exponent within [1.6; 0.03]° with an increase in the antenna base in the range from 200 to 7,500 m. The maximum error is achieved with a base equal to 200 m, and its minimum value at 7.5 km is 0.03 degrees. This corresponds to theory (4) since the RMS is inversely proportional to the value of the antenna base.

5. 3. 3. The dependence of the standard deviation of the direction finding estimate on the type of the window of spectral analysis

We investigated the dependence of RMS of the assessment of direction finding σ_θ on the signal-to-noise ratio in various types of window of spectral analysis: Fig. 3.

Our analysis of plots in Fig. 3 shows that the RMS of the assessment of direction finding is significantly dependent on the type of «window». When the signal-to-noise ratio changes within [–10; 20] dB, depending on the type of window of the spectral analysis, the RMS of the assessment of direction finding changes in the following range of values. The theoretical dependence constructed using (4) and (13) for the Hamming window is [0.13; 0.011]°, Blackman [0.13; 0.03]°, Hannah [0.19; 0.03]°, Kaiser [0.08; 0.03]°, Hamming [0.13; 0.03]°.

Dependences for all window types are inversely proportional. Fig. 3 shows that for all dependences at signal/noise values starting from 20 dB and above, the RMS values vary slightly between windows. With a signal-to-noise ratio of –10 dB, the lowest value of RMS is for the Kaiser window (0.08°), the maximum value is for the Hannah window (0.2°).

The best of the studied is the Kaiser's «window» since it has the lowest RMS indicators. It is advisable to use the Blackman «window» for noise and interference since it has a side lobe level of –67 dB and strongly suppresses interference on neighboring frequency channels. The results of our simulation are consistent with the results of analytical studies.

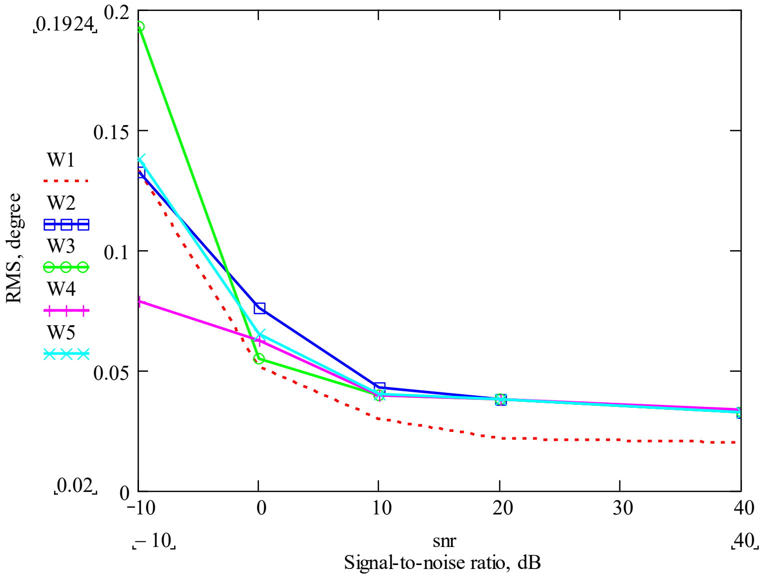


Fig. 3. The dependence of the standard deviation of the direction finding estimate on the signal-to-noise ratio for different types of «window»: W1 – a theoretical dependence for the Hamming window; W2 – Blackman window; W3 – Hannah window; W4 – Kaiser window; W5 – Hamming window

6. Discussion of results of studying the spectral-correlation method for assessing delay and direction finding

Our analytical studies into the accuracy of estimating the delay of radio signals and directions to BRS have shown that the features of the method under study are as follows. In contrast to the known methods of direction finding [1, 3, 6–10], parallel temporal (1) and spatial digital spectral analysis of radio signals is used, followed by a single-iteration assessment (2) of the difference in the values of the argument of the obtained complex analytical signal and the delay. This provides an assessment of the position of the extremum of the correlation function of the received radio signal with minimal computational and time costs, as well as high selectivity in frequency and direction.

The spatial spectrum of radio signals is narrowband, therefore, taking into consideration (11), the error in estimating the delay could be significantly reduced in proportion to the increase in the number Z of processed samples of the mutual spectrum with a signal-to-noise ratio of less than one. In addition, the accuracy of delay estimation is significantly affected by the type of «window» of spatial spectral analysis, the frequency shift (z_2–z_1), and the signal-to-noise ratio μ_1 at the inputs of radio channels. Taking into consideration the effect of noise, the impact of the window on the accuracy is estimated by the noise band K_w.

Unlike the well-known direction-finding methods [1, 3, 6–10], the combination of high accuracy and performance speed is provided by estimating the delay according to the difference in the values of the argument of the selected complex analytical signal. From (5), it could be seen that the variance of the delay estimate σ_τ^2 does not depend on the value d of the antenna base, the direction to BRS θ_S, and the value of the corresponding spatial frequency. This, in contrast to the methods reported in [4, 5], for which $d<\lambda_S/2$, provides for a large range of possible values τ_S for the conditions of a large antenna base d and a wide (0–180)° direction finding sector.

According to (4), similar to known correlation methods of direction finding, the variance σ_θ^2 of the estimation θ_S of direction to BRS is determined by the variance σ_τ^2 of the delay estimate and is inversely proportional to the size of the antenna base d. Increasing the accuracy of the direction finding method proposed in [2] is advisable to implement by increasing the antenna base d, and, unlike known direction finding methods, by the selectivity (11) of spatial spectral analysis.

The results of our performance analysis showed a significant, exceeding an order of magnitude, increase in performance speed by reducing computing costs. According to (16), in contrast to known methods of direction finding [1, 3, 8–10], high performance speed is provided by the use of digital parallel spectral analysis in time and space. In addition, according to its results, due to the direct one-iteration evaluation of (2) the difference in the values of the complex analytical signal argument and the delay.

The results of modeling the direction finder operation are well consistent with the results of theoretical analysis. Analysis of plots in Fig. 1 shows that the method under study provides an estimate of the delay and direction to BRS with a signal-to-noise ratio of less than one, which is characteristic of correlation methods. Both dependences in Fig. 1, *a*, *b* are hyperbolic in shape and correspond to (4) and (13). The efficiency of the proposed quasi-harmonic model of the mutual spectrum (1), the algorithm of its spatial filtering and high accuracy of estimation (2) of delay with minimal time costs were confirmed.

Fig. 2 shows that the size of the antenna base *d* could be changed by more than an order of magnitude, which corresponds to (4), and provides a proportional increase in accuracy with limited sensitivity of radio channels compared to the use of traditional antenna arrays [1, 3–5]. The possibility of estimating the direction at a large (more order of magnitude) range of delay change without applying additional costs to eliminate the ambiguity of measurement characteristic of phase systems [1, 7, 8] was confirmed.

It is relevant to choose a «window» of spectral analysis, which provides an increase in the accuracy of delay and direction-finding estimation [1, 2]. The results of studies in Fig. 3 correspond to the results of theoretical analysis (2), (11) to (13). With a signal-to-noise ratio greater than one, the accuracy characteristics of the «windows» differ insignificantly, which confirms the efficiency and invariance of the proposed algorithm (2) for rapid estimation of the delay when the shape of the spatial spectrum changes, which is consistent with (5) and (11). With a signal-to-noise ratio value of less than one, the Kaiser window with the best combination of the width of the noise band and the level of the side lobes provides the best accuracy (with an RMS in direction finding of 0.08°). This is consistent with known applications [1–3].

In general, our simulation results show that the studied spectral-correlation method for assessing the delay of radio signals and direction finding successfully solves the problem of increasing the efficiency (speed and accuracy) of radio monitoring equipment.

An increase in the accuracy of direction finding is provided by an increase in the antenna base, which may be limited by the complexity of ensuring the synchronization of radio channels and the identity of their characteristics.

An additional limitation of the application of a given method may be the movement of the source of radio emission, which could be ground or air, with the appearance of the Doppler shift in the frequency of the signal.

The number of direction-finding channels could be more than two, so there are tasks of mutual processing of the results of their reception, its optimization. The proposed method under study implements a quasi-plausible direct assessment of the position of the extremum of the correlation function of radiation. Therefore, it is advisable to carry out its parametric optimization by the amount of spread (z_2–z_1) to evaluate the argument of the complex analytical signal, the antenna base *d*, and the number of radio channels in accordance with the nature of the radiation and the type of BRS.

In the future, it is advisable to carry out studies into the methods of spatial selection of usable signals in the presence of noise and interference, as well as optimize the procedure for the synthesis of a multi-petaled radiation pattern.

7. Conclusions

1. We have analytically studied accuracy of the digital spectral-correlation method for estimating the delay of radio signals and direction finding for conditions of a large antenna base. Analytical expressions have been derived for the variance in the estimation of the delay in receiving the signal by radio channels and the direction to the source of radio emission. The potential accuracy of the proposed method is close to optimal but, due to energy losses in the selection of the spatial spectrum of the signal, it would be slightly less. Accuracy losses, compared to the optimal method, could be up to 10 % due to energy signal loss. The errors in the estimates of signal delay τ_S and direction to BRS θ_S have been determined.

2. An analysis of the time costs for assessing the delay and direction of arrival of radio emission has been carried out. The method provides a significant gain, by 27 times, in performance speed compared to the corresponding multi-iteration correlation methods for estimating signal delay. A feature of the proposed method is the use of two-stage temporal and spatial spectral analysis of the mutual spectrum, the most plausible direct assessment of the delay. The resulting reduction in total time costs is achieved by eliminating the multi-iteration correlation processing of the signal.

3. We have simulated the operation of a direction finder. The dependences of the standard deviation in the direction finding and delay estimates on the signal-to-noise ratio, the type of spectral analysis window, and the size of the antenna base have been investigated. The RMS in assessing the direction finding depends on the signal-to-noise ratio and varies in the range of values [0.08; 0.034]° with a change in the signal/noise ratio of [–10; 40] dB, the use of the Kaiser window, and the antenna base value of 2,500 m. In theory, the RMS value in assessing the direction finding is the ratio inversely proportional to the signal/noise value, which coincides with the results of the simulation. The RMS of the delay estimate also depends on the signal-to-noise ratio, changes similarly to the RMS in a direction estimate, and is in the range of values [18.176; 1.559] ns, which corresponds to an error of [0.637; 0.055] %.

The expediency of using the weight function of the Kaiser «window» in repeated spatial spectral analysis has been shown.

The expediency of using the largest possible antenna base has been demonstrated as it provides for an increase in accuracy. The error of direction-finding estimation, depending on the size of the antenna base, decreases in the exponent within [1.6; 0.03]° with an increase in the antenna base in the range from 200 to 7,500 m.

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