Оцінено дисперсію похибки пеленгування, що складається з шумової та завадової складової. При моделюванні отримано залежність точності пеленгування від типу вікна спектрального аналізу, відношення сигнал/шум, рознесення за напрямком на джерела сигналу і завади при різних значеннях частоти сигналу. Отримано похибку 0,03 градуса, при вхідному відношенні сигнал/шум 0 дБ. Оцінено роздільну здатність пеленгатора

Ключові слова: аналіз завадостійкості, безпошуковий цифровий метод, кореляційно-інтерферометричне пеленгування, просторовий аналітичний сигнал

Оценена дисперсия погрешности пеленгования, состоящая из шумовой и помеховой составляющей. При моделировании получена зависимость точности пеленгования от типа окна спектрального анализа, отношения сигнал/шум, разнесения по направлению на источники сигнала и помехи при различных значениях частоты сигнала. Получена погрешность 0,03 градуса, при входном отношении сигнал/шум 0 дБ. Оценено разрешение пеленгатора

Ключевые слова: анализ помехоустойчивости, беспоисковый цифровой метод, корреляционно-интерферометрическое пеленгование, пространственный аналитический сигнал

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ANALYSIS OF INTERFERENCE IMMUNITY OF THE SEARCHLESS METHOD OF CORRELATION-INTERFEROMETRIC DIRECTION FINDING WITH RECOSTRUCTION OF THE SPATIAL ANALYTICAL SIGNAL

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1. Introduction

Presence of a complex electromagnetic situation (EMS) is typical condition of operation of the direction finding equipment in the systems of radiomonitoring radio emission sources (RES). It is characterized by a multipath propagation of radio emissions and frequency overlapping of the useful signal and noises. The main requirements to the present-day radio direction finding tools include ensurance of their high noise immunity as well as ability to work in real time at minimal hardware costs. The use of digital direction-finders with an antenna array (AA) which usually implement correlation-interferometric or spectral direction finding methods [1, 2] is a promising way of realization of radio direction finding under such conditions.

Correlation-interferometric methods of direction finding provide a wide frequency range, immunity to the interferences caused by multipath reception, high sensitivity and accuracy. However, the most plausible unbiased estimation of the directions to the RES is done based on the sequential correlation search analysis and the space survey. This significantly limits their speed or requires large hardware costs for the data processing system thus lowering effectiveness of their application for dynamic EMS conditions. One more disadvantage of such methods consists in a low accuracy of finding direction to the RES the spectra of which are completely frequency overlapped [2].

Therefore, development and investigation of high-speed digital methods of correlation-interferometric direction finding with spatial selection of signals for use in computer-aided radio monitoring systems is an urgent task.

2. Literature review and problem statement

The nonlinear spectral method of direction finding which provides an improved accuracy of spectral maxima estimation was studied in work [3]. However, it has a number of essential disadvantages for radio monitoring systems such as long time of signal processing.

The nonlinear spectral method of direction finding which ensures a high spatial resolution of the received emissions was investigated in work [4]. However it needs precise a priori information on the number of emissions received in a mixture. Its bias in the direction estimations worsens direction finding accuracy. If signal-to-noise ratios are low (about 10 dB), the direction finder becomes inoperative.

As a result, effectiveness of application of spectral methods of direction finding determined primarily by direction finding speed/accuracy ratio is insufficient in radio monitoring systems. This is confirmed by the fact of their disuse in the present-day digital direction finders for radio monitoring systems [1, 2].

The correlation method of direction finding which has an improved accuracy of direction finding was proposed in work [5]. The method is based on increasing the steepness of the mutual correlation characteristic of direction finding.

Accuracy and interference immunity of a correlation-interferometric direction finder with a double correlation-convolution processing was investigated in work [6].

The obtained results do not take into account the peculiarities of digital diagram formation with the reconstruction of the received emissions.

Analysis of accuracy of the bearing estimation using AA of various configurations was made in work [7]. An increase in accuracy of the potential direction finder using an AA with nondirectional noninteracting antenna elements was estimated.

Algorithms for finding noise-like radio emissions using a large antenna base were investigated in work [8].

However, only search correlation-interferometric methods of direction finding have been investigated. When using them to provide direction finding in real time, it is necessary to do multi-channel correlation data processing or increase the step of the delay estimation discreteness. This increases methodological error of direction finding.

In work [9], digital methods of diagram formation for improving noise immunity of direction finding were investigated. Formation of AA is done using the fast Fourier transform (FFT) algorithm. Application of the studied methods of digital diagram formation for improving noise immunity of direction finding was not considered.

A searchless digital method of correlation-interferometric direction finding with reconstruction of the spatial analytic signal was proposed in work [10]. This method features a high speed of direction finding due to a parallel spatial selection and searchless correlation estimation of directions to the RES. This method of direction finding is searchless since it makes a searchless correlation estimation of directions to RES in which one value of the argument of the correlation function corresponding to its maximum is calculated by a direct method. However, no study of noise immunity and accuracy of this method was done.

Thus, the known results of studies of accuracy and noise immunity of analog and digital correlation direction finders do not take into account features of the searchless algorithms with reconstruction of the received emissions. They can not be directly used for the method of direction finding under study.

Analysis of noise immunity of the searchless method of correlation-interferometric direction finding with reconstruction of the spatial analytical signal remains an unsolved part of the general problem of ensuring high noise immunity and accuracy of correlation-interferometric direction finding.

3. Objective and the tasks of the study

This work objective is analysis of noise immunity of the searchless digital method of correlation-interferometric direction finding with reconstruction of the spatial analytical signal.

To achieve this objective, the following tasks were accomplished:

– analytical evaluation of the noise and interference components of the direction finding error variance;

– study of accuracy and resolution of direction finding by means of modeling;

– comparative analysis of the obtained analytical estimates of the direction finding error variance and the formulas for the well-known direction finding method as well as comparison with the simulation results.

4. Analytical studies of the direction finding noise immunity

Perform analysis of the noise immunity of the searchless digital method of correlation-interferometric direction finding with reconstruction of the spatial analytical signal. Let an additive mixture of L random Gaussian quasicontinuous stationary material radio emissions Sl(t) of point RES with a uniform energy spectrum is received in a horizontal plane. Reception is carried out by a linear AA of the direction finder with a synthesized multilobe directional pattern (DP). In finding direction of the l-th RES, e. g. of the first radio emission S1(t), the rest of L-1 radio emissions Sl(t) are station interferences. The AA consists of Z identical direction-finding radio channels. There is a presence of own additive station normal noises nz(t) with a zero mathematical expectation and the same spectral density N of power constant within the bandwidth [ωL, ωH] of transmission of the direction finder radio channels. Assume that the intrinsic noises of the AA radio channels do not have inter-channel correlation and correlation with the received signals. Assume also that the RES the bearings of which are sought are in the far zone and there are no phase fluctuations in the signal propagation path. Consequently, the initial conditions of the study can be represented as follows:

$$U_z(t)=\sum_{l=1}^{L} S_{z.l}(t-\tau_z)+n_z(t), \tag{1}$$

where Uz(t) is the mixture of signals received by the z-th direction finding channel; Sz.l(t−τz) is the l-st signal received by the z-th direction finding channel; τz is signal delay in the z-th channel relative to the reference channel; nz(t) is the additive Gaussian noise of the z-th direction finding channel.

The number L of received radio emissions Sl(t) does not exceed the number Z of direction-finding radio channels of the AA: L <Z.

For the given initial conditions (1), investigate noise immunity of the searchless digital method of correlation-interferometric direction finding with reconstruction of the spatial analytical signal [10]. To estimate the noise immunity, use variance σθ.l^2 of the direction finding error. According to the studied method of direction finding, estimation of θl directions to the RES is made as follows:

$$\hat{\theta}_l=\arccos[\hat{\Omega}_l\cdot c/\omega_{S.L}], \tag{2}$$

where the dispersion-correlation estimate of the spatial frequency of the signal Sl(t):

$$\hat{\Omega}_l=\frac{1}{z_2-z_1}\operatorname{arctg}\left[\frac{\sum_{k=k_L}^{k_H} S_{12A.k}(\Omega_p,z_1,z_2)\cdot\sin\left(\Delta\hat{\Psi}_{A.k}(\Omega_p,\Delta z)\cdot K_\gamma(\omega_{S.k})\right)}{\sum_{k=k_L}^{k_H} S_{12A.k}(\Omega_p,z_1,z_2)\cdot\cos\left(\Delta\hat{\Psi}_{A.k}(\Omega_p,\Delta z)\cdot K_\gamma(\omega_{S.k})\right)}\right],$$

where z2−z1=Δz is the spatial shift within the AA aperture; z1, z2 are the numbers of the selected AA elements for which spatial analytical signal is reconstructed; S12A.k(Ωp,z1,z2) is the modulus of the complex common spatial analytical signal for the k-th radiation frequency $S_l(t)$ received by linear AA with a multilobe DP; Ωp=2π·p/d·Z is the spatial frequency value which determines direction of the p-th lobe of the multilobed DP, p=0.1,..., (Z–1); d is the distance between the AA elements; ΔΨA.k(Ωp,Δz)=ΨA.k(Ωp,z2)–ΨA.k(Ωp,z1) is the estimate of the phase shift of the spatial analytical signal at a distance Δz; Kγ(ωS.k)=ωS.L/ωS.k is coefficient of dispersion equalization; ωS.L, ωS.k are the lower and the k-th frequencies of the spectrum Uz(jωS.k) of the received mixture Uz(t) at the operating frequency, respectively; KL, kH are the numbers of the lower and upper frequencies of the spectrum Uz(jωS.k) of the accepted mixture Uz (t), respectively; c is the speed of propagation of electromagnetic emission in a free space.

Analysis of equation (2) shows that the estimates of θl directions to RES are obtained using a direct searchless correlation estimate of frequencies Ωl for each direction-sought l-th radio emission.

The variant of the structure scheme of the direction finder is shown in Fig. 1. Features of the direction finder (Fig. 1) are as follows. A mixture of radio emissions is received by the Z-channel linear AA. The AA channels are commuted to a Z-channel radio receiver with a common heterodyne. At an intermediate frequency, during the analysis time Ta, they are digitized and stored in the computer memory. The received arrays of counts of the received radio emissions are processed according to equation (2) of the direction finding method worked out in [10].

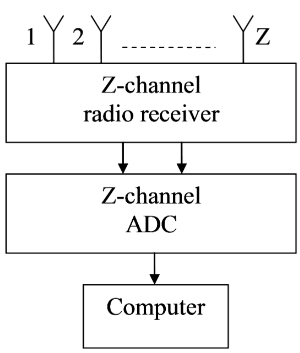

Fig. 1. Structure diagram of the studied direction finder

To investigate noise immunity of direction finding by the method under consideration, analyze its implementation features.

As it follows from equation (2) and the structure diagram given in Fig. 1, the radio direction finding algorithm is realized in four basic stages. They are frequency selection, spatial selection, reconstruction of the spatial analytical signal, and correlation searchless estimation of the bearing. This algorithm is equivalent to the parallel operation of Z/2 two-channel wideband correlation-interferometric direction finders using antenna systems with a narrow DP.

As a result, noise immunity of direction finding is advisable to estimate by the variance σθ.l^2 the error in estimating direction to the l-th RES which is determined by the variance στ.l^2 of estimating delay time for the corresponding signal Sl(t) reception by the space-separated direction finding radio channels. For the case of reading the direction to the RES from the antenna base line, the variance σθ.l^2 is determined as follows [11]:

$$\sigma^2_{\theta.l}=\frac{\sigma^2_{\tau.l}\cdot c^2}{(\Delta z\cdot d)^2\cdot\sin^2\theta}. \qquad (3)$$

In turn, the variance στ.l^2 in correlation-interferometric direction finding at a condition of absence of phase fluctuations in the emission propagation path is determined by the influence of intrinsic noises nz(t) of the direction-finding radio channels and external interferences as follows [11]:

$$\sigma^2_{\tau.l}=\frac{1}{\omega^2_{0.l}\cdot\mu_{rn.l}}=\frac{2\pi}{\omega^2_{0.l}\cdot T_a\cdot\mu_{n.l}\cdot\Delta\omega_{a.l}}+\frac{1}{\omega^2_{0.l}\cdot\mu_{r.l}}, \qquad (4)$$

where ω0.lε[ωL.l; ΩH.l] is the average frequency of the l-th band Δωa.l of the analysis frequencies; Ta=NS·Td is the time of the radio emission analysis; NS is the number of accumulated time counts of the mixture Uz(t) of radio emissions; Td is sampling period; μn.l=PSμ.l/PNμ.l, μr.l=PSμ.l/Prμ.l is the signal/noise and the signal/interference ratio at the correlator inlet for the extreme time spectral component (obtained by processing the temporal realization) of the l-th signal with a maximum power, respectively; Δωa.l=ωH.l–ωL.l is the frequency bandwidth of the analysis for the l-th signal; PSμ.l is the power of the extreme (with maximum power) time spectral component of the l-th signal; PNμ.l, Prμ.l are the powers of time spectral components of noise and interference for the extreme time spectral component of the lth signal, respectively; Mrn.l=PS0.l/PN0.l+Pr0.l is total signal/(interference+noise) ratio at the correlator output; PS0.l, PN0.l, Pr0.l is the power of the l-th signal, noise and interference at the correlator output.

Analysis of equation (4) shows that the variance στ.l^2 of the estimate of the signal reception delay time under other invariable conditions can be reduced by increasing the ratio μn.l signal/noise, ratio μr.l signal/interference and the analysis time Ta.

Determine the μn.l signal/noise ratio and the $\mu_{r.l}$ signal/interference ratio at the correlator input taking into account the values of the input ratios μnI.l signal/noise and μrI.l signal/interference for the l-th signal at Z inputs of the direction-finding radio channels. Considering location of the RES signals Sl(t) in the far zone and the identity of the direction-finding radio channels, the input ratio μnI.l signal/noise and μrI.l signal/interference ratio will be the same for all direction-finding radio channels.

Determine the μnI.l signal/noise ratio and the ratio μrI.l signal/interference ratio at the inputs of the direction-finding radio channels as follows:

$$\mu_{nI.l}=P_{S.l}/P_N=P_{S.l}/N\cdot\Delta f_k, \qquad (5)$$

$$\mu_{rI.l}=P_{S.l}/P_{r.l}, \qquad (6)$$

where PS.l, Pr.l, PN are power of the l-th signal, interference power relative to the l-th signal, and noise power at the inputs of the direction-finding radio channels of AA, respectively.

In turn, it is expedient to divide power Pr.l of interferences with respect to the l-th signal into three summands:

$$P_{r.l}=P_{r1.l}+P_{r2.l}+P_{r3.l},$$

where Pr1.l, Pr2.l, Pr3.l are the powers of the disjoint sets L1, L2, L3 of the interferences separated in the direction finder with the l-th signal Sl(t) in frequency ω, the arrival direction θ and the frequency ω and the arrival direction θ simultaneously while:

L1+L2+L3=L–1.

The main operations of the first stage of processing the received mixture Uz (t) which significantly affect the signal/(interference+noise) ratio are as follows: time spectral analysis (spectral analysis of Z time realizations of the received mixture of Uz(t) emissions) based on the FFT algorithm and subsequent frequency selection of the received emissions in each AA channel [10, 11]. In temporal digital spectral analysis and selection of time spectra Sl(jωS.k) taken within the Δfk band of emissions, the frequency resolution Δfp is determined by the Rayleigh criterion [12, 13] and is:

$$\Delta f_p = B_{Wt} / N_S \cdot T_d, \tag{7}$$

where Bwt is the passband width of the partial digital filter at a level of at least –6 dB.

After the time spectral analysis, frequency selection of the spectrum of mixture of the l-th signal, noise and interferences consistent with the frequency band Δωa.l is performed. As a result, the power of noise and interferences is reduced due to suppression of their spectral components that are outside the band Δωa.l of the l-th signal frequencies and an increase in the values of the μn1.l signal/noise and the μr1.l signal/interference ratios is ensured:

$$\mu_{n1.l} = P_{S.l} \cdot 2\pi / N \cdot \Delta\omega_{a.l} = \mu_{nI.l} \cdot 2\pi \cdot \Delta f_k / \Delta\omega_{a.l}, \tag{8}$$

$$\mu_{r1.l} = \frac{\mu_{rI.l} \cdot P_{r.l}}{K_{Bt}^2 \cdot P_{r1.l} + P_{r2.l} + K_{Bt}^2 \cdot P_{r3.l}}, \tag{9}$$

where KBt is the level of side lobes of the partial digital filters during the time spectral analysis.

The use of frequency-matched selection is determined by the random nature of taking the emission bearings and therefore the impossibility of using optimal (consistent) filtration.

At the second stage of the processing, the main operation significantly affecting the signal/noise and signal/interference ratios is synthesis of the complex multilobe DP Uk.l(jΩp) based on the FFT algorithm followed by a spatial selection of the signal groups $\left\{U_{k.l}(j\Omega_p)\right\}_{p\in[p_{L.l};p_{H.l}]}$ at its output. Synthesis of a complex multilobed DP is determined by equation [13]:

$$U_{k.l}(j\Omega_p) = \sum_{z=0}^{Z-1} \mathrm{Re}\left[U_z(j\omega_{S.k})\right] \cdot \exp(-j\Omega_p \cdot z) \cdot W_\theta(z), \tag{10}$$

where Uk.l(jΩp) is the complex spatial spectrum (obtained by processing the spatial realization) for the k-th component of the Uz.l(jωS.k) time spectra of the accepted Uz(t) realizations; Wθ(z) is the weighting function of the spatial digital diagram formation (the function of spatial spectral analysis "window").

As a result of formation of a multilobe DP, a Z/KWθ – fold gain in signal/noise ratio is ensured.

In this case, the isolated array $\left\{U_{k.l}(j\Omega_p)\right\}_{p\in[p_{L.l};p_{H.l}]}$ of the complex responses of AA with a multilobe DP (9) to the action of the k-th time spectral component Uz.l(jωS.k) is the k-th signal group. It has frequency ωS.k of emission of the l-th RES received by overlapping main lobes of the adjacent partial DPs Uk.l(jΩp), where pL.l, pH.l are the numbers of the lower and upper frequencies of the selected signal group, respectively.

As a result of combining Uk.l(jΩp) responses of a multilobe DP into signal groups, the μn1.l signal/noise and μr1.l signal/interference ratios will deteriorate mS times due to summation of the present partial additive noises and interferences. As a result, taking into account equations (5), (6) and (8), (9), the μn2.l signal/noise and μr2.l signal/interference ratios for the selected signal groups will be:

$$\mu_{n2.l} = \mu_{n1.l} \cdot \frac{Z}{K_{W\theta} \cdot m_S} = \mu_{nI.l} \cdot \frac{2\pi \cdot \Delta f_k \cdot Z}{\Delta\omega_{a.l} \cdot K_{W\theta} \cdot m_S}, \tag{11}$$

$$\mu_{r2.l} = \frac{P_{S.l}}{(K_{Bt}^2 \cdot P_{r1.l} + K_{B\theta}^2 \cdot P_{r2.l} + K_{Bt}^2 \cdot K_{B\theta}^2 \cdot P_{r3.l}) \cdot m_S}, \tag{12}$$

where KWθ is the coefficient of equivalent noise band of the weight function Wθ(z) of digital diagram formation; mS is the number of samples of the signal group; KBθ is the level of the side lobes of the partial DPs of the synthesized multilobe DP.

Analysis of equations (10) shows that it is possible to use matched spatially selective reception for point interference sources with their angular distances from the the useful signal source exceeding the Rayleigh resolution interval. This provides a significant increase in signal/noise and signal/interference ratios with an increase in number Z of direction-finding channels and a decrease in level KBθ of the partial DP side lobes.

At the third processing stage, the spatial analytical signal UAk.l(jz) is reconstructed for the two selected AA elements z1 and z2 for the selected signal groups $\left\{U_{k.l}(j\Omega_p)\right\}_{p\in[p_{L.l};p_{H.l}]}$. A common spatial analytical signal is formed:

$$S_{12A.k}(jz) = U_{Ak.l}(jz_1) \cdot U_{Ak.l}^*(jz_2), \tag{13}$$

where

$$U_{Ak.l}(jz) = \sum_{p=p_{L.l}}^{p_{H.l}} U_{k.l}(j\Omega_p) \cdot \exp(j\Omega_p \cdot z),$$

is the value of reconstructed spatial analytical signal at the AA point z=0.1, ..., Z–1.

Estimate the μn3.l signal/noise and the μr3.l signal/interference ratios after formation of the complex common spatial analytical signal S12A.k(jΩp,z1,z2). Taking into account multiplication of the counts UAk.l(jz) and U*Ak.l(jz) of the spatial analytical signal performed in formula (11), obtain [11]:

$$\mu_{n3.l} = \sqrt{\mu_{n2.l}(z_1) \cdot \mu_{n2.l}(z_2)}, \tag{14}$$

$$\mu_{r3.l} = \sqrt{\mu_{r2.l}(z_1) \cdot \mu_{r2.l}(z_2)}, \tag{15}$$

where μn2.l(z1), μn2.l(z2) are the signal/noise ratios for the selected AA elements z1 and z2, respectively; μr2.l(z1), μr2.l(z2) are the signal/interference ratios for the selected AA elements z1 and z2, respectively.

To determine the values of μn3.l and μr3.l, it is expedient to perform analysis of the features of distribution of the reconstructed spatial analytical signal UAk.l(jz) level within the AA aperture. It should be noted that the spatial analytical signal UAk.l(jz) contains additive components of signal SAk.l(jz), noise Nk.l(jz) and interference Sr.l(jz):

$$U_{Ak.l}(jz) = S_{Ak.l}(jz) + N_{k.l}(jz) + S_{r.l}(jz).$$

The noise component Nk.l(jz) is formed as a sum of the space-spectral quasiharmonic noise components Nk.l(jΩp) bounded with respect to the bandwidth {ΩpLs.l,ΩpHs.l} of spatial frequencies with a normal law of probability density distribution and a zero expectation:

$$N_{k.l}(jz) = \sum_{p=p_{L.l}}^{p_{H.l}} N_{k.l}(j\Omega_p)\cdot \exp(j\Omega_p \cdot z). \tag{16}$$

Each component of Nk.l(jΩp) is the response of identical partial DPs according to (16). As a result, it can be concluded that the noise component Nk.l(jz) of the spatial analytical signal UAk.l(jΩp,z) is a narrow-band normal spatial oscillation with a uniform power distribution within the signal group.

Similarly, the interference component Sr.l(jz) is a noise-like spatially narrowband normal process with a bandwidth {ΩpLr.l;ΩpHr.l} of frequencies with a zero mathematical expectation and a uniform power distribution within the signal group.

Make analysis of the features of distribution of power of the signal component SAk.l(jz) of the spatial analytical signal UAk.l(jz) within the AA aperture. The signal component SAk.l(jz) is formed by reconstruction, based on the Hilbert transform (inverse discrete Fourier transform for positive frequencies) of the signal component Sk.l(jΩp) of the signal group:

$$S_{Ak.l}(jz) = \sum_{p=p_{L.l}}^{p_{H.l}} S_{k.l}(j\Omega_p)\cdot \exp(j\Omega_p \cdot z). \tag{17}$$

In turn, the signal group is defined as the spatial spectrum of the k-th harmonic component Sz.l(jωS.k) of the time spectrum of the received l-th emission Sl(t) based on the FFT algorithm:

$$S_{k.l}(j\Omega_p) = \sum_{z=0}^{Z-1} \mathrm{Re}[S_{z.l}(j\omega_{S.k})]\cdot \exp(-j\Omega_p \cdot z)\cdot W_\theta(z). \tag{18}$$

Taking into account (18), equation (17) takes the form:

$$\begin{aligned} S_{Ak.l}(jz) &= \\ &= \sum_{p=p_{L.l}}^{p_{H.l}} \left(\sum_{z=0}^{Z-1} \mathrm{Re}[S_{z.l}(j\omega_{S.k})]\cdot \exp(-j\Omega_p \cdot z)\cdot W_\theta(z) \right) \times \\ &\times \exp(j\Omega_p \cdot z) = S_{Ak.l}\cdot W_\theta(z)\cdot \exp(j(\Omega_{A.k}\cdot z + \Psi_{A.k})), \end{aligned} \tag{19}$$

where ΩA.k=ωS.k·cosθl^2/c is the spatial frequency of the k-th spectral component of the l-th signal received by AA from direction θl; SAK.l, ΨA.k are the amplitude and the initial phase of the signal component SAK.l(jz) of the spatial analytical signal UAK.l (jz), respectively.

Analysis of equation (19) shows that the distribution of spatial counts of the signal component SAK.l(jz) of the spatial analytical signal UAK.l(jz) after its reconstruction within the AA aperture corresponds to the harmonic spatial process. It has an unknown constant frequency ΩA.k and amplitude SAK.l·Wθ (z) which varies in proportion to the value of the weighting function Wθ(z) of digital diagramming (of the window).

Thus, taking into account equations (8), (10), (12), (16) the signal/noise ratios μn2.l(z1), μn2.l(z2) as well as the signal/interference ratios μr2.l(z1), μr2.l(z2) for the selected AA elements z1 and z2 will be equal:

$$\mu_{n2.l}(z_1) = \mu_{n2.l}\cdot W_\theta^2(z_1);\quad \mu_{n2.l}(z_2) = \mu_{n2.l}\cdot W_\theta^2(z_2),$$

$$\mu_{r2.l}(z_1) = \mu_{r2.l}\cdot W_\theta^2(z_1);\ \mu_{r2.l}(z_2) = \mu_{r2.l}\cdot W_\theta^2(z_2). \tag{20}$$

Taking into account equations (14), (15) and (20), determine the signal/noise ratio μn3.l, as well as the signal/interference ratio μr3.l after spatial processing of the spatial analytical signal UAK.l(jz) and forming counts S12AK.l(jz):

$$\mu_{n3.l} = \sqrt{\mu_{n2.l}(z_1)\cdot \mu_{n2.l}(z_2)} = \mu_{n2.l}\cdot W_\theta(z_1)\cdot W_\theta(z_2), \tag{21}$$

$$\mu_{r3.l} = \sqrt{\mu_{r2.l}(z_1)\cdot \mu_{r2.l}(z_2)} = \mu_{r2.l}\cdot W_\theta(z_1)\cdot W_\theta(z_2). \tag{22}$$

Taking into account equations (11), (12) and (21), (22), the final signal/noise and signal/interference ratios after the searchless correlation processing of the spatial analytical signal UK.l(jz) will be as follows:

$$\mu_{n4.l} = \mu_{nI.l}\cdot \frac{2\pi \cdot \Delta f_k \cdot Z \cdot W_\theta(z_1)\cdot W_\theta(z_2)}{\Delta\omega_{a.l}\cdot K_{W\theta}\cdot m_S}, \tag{23}$$

$$\mu_{r4.l} = \mu_{rI.l}\cdot \frac{W_\theta(z_1)\cdot W_\theta(z_2)}{m_S \cdot K_{B\Sigma}^2}, \tag{24}$$

where

$$K_{B\Sigma}^2 = (K_{Bt}^2 \cdot P_{r1.l} + K_{B\grave{e}}^2 \cdot P_{r2.l} + K_{Bt}^2 \cdot K_{B\grave{e}}^2 \cdot P_{r3.l}) / P_{r.l}$$

is the effective level of the side lobes of the frequency-spatial path of the direction finder selective reception.

At the fourth stage of processing according to equation (2), a searchless dispersion-correlation estimation of direction to the l-th RES is realized. In this case, all k components of its common spatial spectrum S12AK.l(jz) are used within the entire allocated band Δωa.l of the analysed frequencies. In this case, the μn4.l signal/noise ratio and the μr4.l signal/interference ratio after dispersion-correlation processing are equal to the sought ratios μn.l signal/noise and μr.l signal/interference at the direction finder input, that is, μn4.l=μn.l and μr4.l=μr.l. As a result, taking into account equations (3) and (23), (24), the final value of variance σθ.l^2 of the error of estimation of direction to the l-th RES will be:

$$\begin{aligned} \sigma_{\theta.l}^2 &= \sigma_{\theta n.l}^2 + \sigma_{\theta r.l}^2 = \\ &= \frac{K_{W\theta}\cdot m_S \cdot c^2}{\omega_0^2 \cdot T_a \cdot \mu_{nI.l}\cdot \Delta f_k \cdot Z \cdot W_\theta(z_1)\cdot W_\theta(z_2)\cdot (z_2 - z_1)^2 \cdot d^2 \cdot \sin^2\theta} + \\ &+ \frac{K_{Bt\Sigma}^2 \cdot m_S \cdot c^2}{\omega_0^2 \cdot \mu_{r1.l}\cdot W_\theta(z_1)\cdot W_\theta(z_2)\cdot (z_2 - z_1)^2 \cdot d^2 \cdot \sin^2\theta} = \\ &= \frac{m_S \cdot c^2}{F_1[\mu_{rnI.l}]\cdot \omega_0^2 \cdot W_\theta(z_1)\cdot W_\theta(z_2)\cdot (z_2 - z_1)^2 \cdot d^2 \cdot \sin^2\theta}, \end{aligned} \tag{25}$$

where

$$F_1[\mu_{rnI.l}] = \left(\frac{K_{W\theta}}{T_a \cdot \mu_{nI.l}\cdot \Delta f_k \cdot Z} + \frac{K_{Bt\Sigma}^2}{\mu_{r1.l}} \right)^{-1},$$

is the functional of the input ratio signal/(interference+noise) for the direction finder in question.

Analysis of equation (25) shows that the variance σθ.l^2 of estimation of the direction to the l-th RES decreases significantly with increasing value of (z2–z1), the quality of frequency-spatial interference selection (the value of KBtΣ^2) and noises (the value of KWθ/Z). Application of reconstruction of the spatial analytical signal UAK.l(jz) makes it possible to control the value (z2–z1) of separation over a wide range, up to the AF aperture value, i. e., 0<z2–z1≤Z–1. This provides a significant reduction in the direction finding error since the value (z2–z1) of separation in equation (25) is taken into account in the second power. The interference component σθr.l^2 of the direction finding error, unlike the noise component σθn.l^2, does not depend on the analysis time Ta. It is determined by the quality of frequency-spatial selection (the value of coefficients KBt^2 and KBθ^2 as the components of KBtΣ^2 from equation (25)). In the future, the choice of the AA elements z1 and z2 for which reconstruction of the spatial analytical signal UAK.l(jz) is performed, will need optimization.

Now compare the obtained equation (25) of the variance σθ.l^2 of the error in estimating direction to the l-th RES with the analogous equation of the variance σθ^2 for the well-known search compensation method of correlation-interferometric direction finding. The known method is used with realization of spatial sequential search and selection by means of two narrowlobe DPs based on a linear AA [2, 11]:

$$\sigma_\theta^2 = \\ = \frac{2\pi \cdot K_{W\theta} \cdot c^2}{\omega_\theta^2 \cdot T_a \cdot \mu_I \cdot \Delta\omega_M \cdot (Z/2) \cdot K^2{}_\theta \cdot A^2 \cdot (0{,}5 \cdot d \cdot Z)^2 \cdot \sin^2\theta} + \\ + \frac{K_{Bt\Sigma}^2 \cdot c^2}{\omega_0^2 \cdot \mu_r \cdot K_{M\theta}^2 \cdot A_P^2 \cdot (0{,}5 \cdot d \cdot Z)^2 \cdot \sin^2\theta} = \\ = \frac{c^2}{F_2[\mu_{rnI.l}] \cdot \omega_0^2 \cdot K_{M\theta}^2 \cdot A_P^2 \cdot (0{,}5 \cdot d \cdot Z)^2 \cdot \sin^2\theta}, \quad (26)$$

where KMθ, Ap are the coefficients of coherent amplification and parasitic modulation of the weight function Wθ(z) of the spatial digital diagram formation [12];

$$F_2[\mu_{rnI.l}] = \left(\frac{2\pi \cdot K_{W\theta}}{T_a \cdot \mu_I \cdot \Delta\omega \cdot (Z/2)} + \frac{K_{Bt\Sigma}^2}{\mu} \right)^{-1}$$

is the functional of the input signal/(interference+noise) ratio for the known direction finder.

Taking into account (25) and (26), estimate the value of coefficient $V = \sigma_{\theta.l}^2 / \sigma_\theta^2$ of the relation between the variances of the error of estimation of direction to the l-th RES for the method under investigation and the known one:

$$V = F_2[\mu_{rnI.l}] \cdot m_S \cdot K_{M\theta}^2 \cdot A_P^2 / F_1[\mu_{rnI.l}] \cdot (W_\theta(z_1) \cdot W_\theta(z_2)).$$

Make estimation of factor V value for the following conditions of realization of compared methods of direction finding: 2πΔfk=Δωa; Hamming weighting function Wθ(z) with parameters KWθ=1.36; KMθ=0.54; Ap=0.82; mS=4; (z2–z1)=Z/2; z1=21; z2=43; Wθ (z1)=Wθ (21)=0.756; Wθ(z2)=Wθ (43)=0.756 [12].

Under the condition that $\sigma_{\theta n.l}^2 << \sigma_{\theta r.l}^2$ for the functionals $F_1[\mu_{rnI.l}]$ and $F_2[\mu_{rnI.l}]$ of equations (25) and (26), obtain:

$$\frac{2\pi \cdot K_{W\theta}}{T_a \cdot \mu_I \cdot \Delta\omega_a \cdot (Z/2)} << \frac{K_{Bt\Sigma}^2}{\mu_r}, \quad \frac{K_{W\theta}}{T_a \cdot \mu_{nI.l} \cdot \Delta f_k \cdot Z} << \frac{K_{Bt\Sigma}^2}{\mu_{r1.l}},$$

respectively. Then the value of the coefficient:

$$V = m_S \cdot K_{M\theta}^2 \cdot A_P^2 / W_\theta(z_1) \cdot W_\theta(z_2) = 1{,}37,$$

which corresponds to an increase in the RMS error of bearing estimate by a factor of $\sqrt{1{,}37} = 1{,}17$, i. e. by 17 %.

Under the condition that $\sigma_{\theta n.l}^2 >> \sigma_{\theta r.l}^2$ for the functionals $F_1[\mu_{rnI.l}]$ and $F_2[\mu_{rnI.l}]$ of equations (25) and (26), obtain:

$$\frac{2\pi \cdot K_{W\theta}}{T_a \cdot \mu_I \cdot \Delta\omega_a \cdot (Z/2)} >> \frac{K_{Bt\Sigma}^2}{\mu_r}, \quad \frac{K_{W\theta}}{T_a \cdot \mu_{nI.l} \cdot \Delta f_k \cdot Z} >> \frac{K_{Bt\Sigma}^2}{\mu_{r1.l}},$$

respectively. Then the value of the coefficient:

$$V = m_S \cdot K_{M\theta}^2 \cdot A_P^2 / 2 \cdot W_\theta(z_1) \cdot W_\theta(z_2) = 0{,}69,$$

which corresponds to a decrease in the RMS error of bearing estimation by 17 %.

Thus, for the direction-finding method developed in [10] compared to the known method, deterioration of noise immunity at strong interferences corresponds to an increase in RMS error of bearing estimation by 17 %. At a greater influence of intrinsic noise, the RMS error of bearing estimation decreases by 17 %. Thus, the objective has been accomplished.

5. The results of modeling direction finder operation

Software simulation of operation and a study of the direction finding accuracy with the help of the developed software model of the studied direction finder in the MathCad environment have been carried out. The signal processing algorithm corresponds to the proposed direction finding method [10] and equation (2).

Initial simulation conditions:

– number of received emissions: L=2;

– signal and interference type: continuous, with linear frequency modulation;

– signal spectrum width: Δfs=0.6 MHz;

– frequency of the carrier signal and interference: fs==fr=2 GHz;

– sampling rate: Δfd=20 MHz;

– analysis time Ta=0.1 ms;

– AA type: linear with the number of direction finding channels Z=64;

– spatial shift: Δz=22, numbers of selected AA elements: z1=21, z2=43.

A family of dependences of the RMS error of the bearing estimation on the μnI.l signal/noise ratio at the inputs of the direction-finding radio channels for various types of the weight function Wθ(z) of the spatial digital diagram formation was obtained (Fig. 2). Number of experiments to evaluate one count: 50. The chosen dimensionality of the signal group mS=6 for all types of windows. The specified direction to the RES was θ=60°.

The following is shown in Fig. 2:

row 1: for the 3-rd order Blackman window with a side lobe level of –58 dB;

row 2: for the fourth-order Blackman-Natall window with a side lobe level of –98 dB;

row 3: for the Hamming window with a side lobe level of –43 dB;

row 4: the analytical dependence calculated according to the noise component of equation (25) for the weighting function Wθ (z) of the Hamming window.

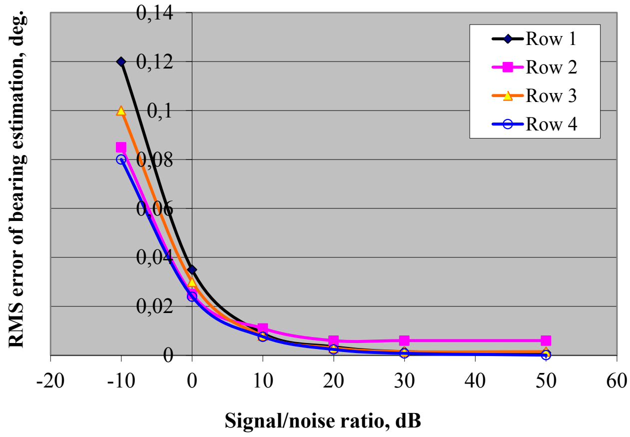

Fig. 2. A family of dependences of the RMS error of the bearing estimation on the μnl.l signal/noise ratio at the inputs of the direction-finding radio channels

Analysis of Fig. 2 shows that the type of the weight function Wθ(z) significantly affects the direction finding accuracy. To ensure maximum interference immunity and accuracy of direction finding, it is advisable to use a weight function with a low level of side lobes, for example, the 4-th order Blackman-Natall with a side lobe level of –98 dB, row 2. This provides maximum direction finding accuracy for a signal-to-noise ratio less than 5dB when using the signal group mS=6. However, for a signal-to-noise ratio greater than 5 dB, the RMS error in the bearing estimate for the 4-th order Blackman-Natall function Wθ(z) is greater than when using other functions. This is due to the methodological component of the reconstruction error resulting from the use of mS=6 counts of the signal group instead of the real value mS=8 for the 4th-order Blackman-Natall window.

The theoretical dependence for the Hamming weight function Wθ (z), row 4 in Fig. 2, calculated using equation (25), practically coincided with the dependence, row 3, obtained by simulation. This confirms effectiveness of the obtained estimate of the error variance in the direction finding given in (25).

For the condition when $\sigma^2_{\theta n.l} \ll \sigma^2_{\theta r.l}$, at a signal/interference ratio of 0 dB, a family of dependencies of the bearing estimation error variance because of separation by direction to the signal source and interference at different frequency values was obtained, Fig. 3. The specified direction to the signal source was θ=60 and the direction to the source of the interference varied within θ=[40;59]. The rest of interference parameters were chosen to be identical to the signal S(t). The type of the weight function Wθ(z) of the Blackman “window” of the third order for which the width BWθ of the main lobe of the partial DPs at the level of –6 dB was equal to BWθ=2.35.

The following is shown in Fig. 3:

row 1: for the frequency of signal and interference 1GHz;

row 2: for the frequency of signal and interference 2 GHz;

row 3: for the frequency of signal and interference 3 GHz.

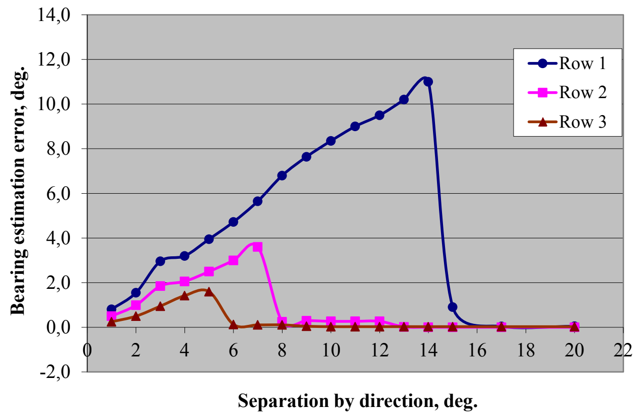

Fig. 3. A family of dependencies of the bearing estimation error Δθ on the separation by direction to the sources of two signals

Analysis of Fig. 3 shows that the accuracy of direction finding increases stepwise with the possibility of spatial signal and interference resolution followed by spatial signal selection. As can be seen from Fig. 3, the direction resolution essentially depends on the frequency of the sought radio emission and it improves from 15 deg to 6 deg with increase in frequency of the sought signal and interference to the value of 3GHz, the upper operating frequency of the AA. The theoretical value of the minimum direction resolution Δθp [12] is as follows: Δθp≥180·BWθ/Z=180·2.35/64=6.6 which agrees with the simulation results.

6. Discussion of the results obtained in the studies of analysis of direction finding noise immunity and modeling of the direction finder

The results of the studies confirmed abibility of the method under investigation to ensure radio emission direction finding in a complex EMS at high accuracy. Its advantage is high noise immunity which is ensured by the use of preliminary spatial selection by synthesis of a multilobe DP. Also, it has a high speed due to the searchless direct correlational estimation of directions to the RES. Thus, the obtained results were determined by the analytical estimation of the direction finding error vaiance which takes into account the input signal/(interference+noise) ratio.

It is expedient to use the obtained results in implementation of equipment of radio monitoring and radio navigation systems which function in a complex dynamic EMS.

Limitations to the use of the obtained results include the linear proportional dependence of accuracy and resolution of the direction finder on the signal frequency. This makes it necessary to use several sets of AA for operation of the direction finder in a wide range of operating frequencies.

These studies are a continuation of development of digital correlation-interferometric direction finders. In the future, it is necessary to carry out parametric optimization of the studied direction finding method.

The results of modeling the direction finder work confirm correctness of the obtained analytical estimate of the direction finding error variance as well as the high accuracy of direction finding in a wide direction sector.

7. Conclusions

1. An analytical estimation of the direction finding error variance for the searchless digital method of correlation-interferometric direction finding with reconstruction of the spatial analytical signal consisting of the noise and interference components was obtained. It takes into account the input signal/(interference+noise) ratio and will be useful in estimating accuracy of direction finding in complex EMS.

2. The simulation results have shown that the direction finding method under consideration provides high accuracy of direction finding. To ensure high noise immunity and minimum RMS error in estimation of bearing, it is advisable to use a weight function with a low level of side lobes, for example, the 4th order Black-Nathall function with a side lobe level of –98 dB. It provides maximum accuracy of direction finding for a signal-to-noise ratio less than 5 dB when using a signal group with a value of mS=6. It was also determined that at a signal-to-noise ratio of 0 dB, direction finding at the RMS error of bearing estimation of 0.03 deg is ensured. High accuracy is ensured by accumulating signal energy in time and space as well as using spatial signal selection in complex EMS.

3. The calculated theoretical dependence of the RMS error in bearing estimation on the signal-to-noise ratio for the Hamming weight function Wθ(z) practically coincided with the dependence obtained in simulation. This confirms effectiveness of the obtained analytical estimate of the noise component of the error variance in estimation of the direction to the RES.

Thus, at practically the same noise immunity and resolution, the studied method of direction finding is faster and, accordingly, more efficient by space and correlation analysis compared with the known search method.

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