1. Vasily YUDIN[1], 2. Nikolay OSAVCHUK[1], 3. Anton VOLKOV[1]

Moscow Aviation Institute (National Research University) (1)

doi:10.15199/48.2022.06.25

Characteristics of angular panorama of errors in the phase difference direction finding of two-point coherent emitter

***Abstract**. This work is devoted to obtaining and analyzing quantitative estimates of the influence of various parameters of the "emitter - direction finder" system on the levels of direction finding errors of a two-point coherent emitter. The obtained results of a quantitative assessment of the dependence of the angular panorama parameters of the direction finding errors of a two-point coherent emitter on the magnitude of the base of the emitter provide the basis for justifying the choice of the base value and other parameters when solving practical problems.*

***Streszczenie.** Praca poświęcona jest uzyskaniu i analizie ilościowej oceny wpływu różnych parametrów układu „emiter - dalmierz" na poziomy błędów kierunkowości emitera koherentnego dwupunktowego. Uzyskane wyniki ilościowej oceny zależności parametrów panoramy kątowej błędów kierunkowości emitera spójnego dwupunktowego od wielkości podstawy emitera stanowią podstawę do uzasadnienia wyboru wartości bazowej i innych parametrów przy rozwiązywaniu praktycznych problemów. (**Charakterystyka panoramy kątowej błędów w wyznaczaniu kierunku różnicy faz dwupunktowego spójnego emitera**)*

Keywords: coherent, direction, emitter, finder, phase.
Słowa kluczowe: koherentny, kierunek, emiter, szukacz, faza.

Introduction

The angular direction to the point source of radiation can be determined by the magnitude of the phase difference of the oscillations at the outputs of the receiving antennas, spaced apart in space. This principle is used by phase direction finders, which are widely used in radio engineering. Errors in the phase difference direction finding of emitters arise due to the influence of various factors, which include the following:

- possible ambiguity in measuring the phase difference;
- subjective noise and parasitic phase shifts in the receiving and amplifying paths of the direction finder;
- errors of phase difference meters;
- external conditions (environment of propagation of radio waves, underlying surface, reflections from various objects located in the area of coverage of the direction finder);
- presence at the radiation source of the dependence of the phase of the emitted wave on the angular direction in the direction finding plane (phase-angular dependence). The issues of the accuracy of phase difference direction finding were considered in a number of works, for example, in [1, 2]. This work develops the results of [3] and is devoted to obtaining and analyzing quantitative estimates of the influence of various parameters of the "emitter - direction finder" system on the levels of bearing errors [3]. The relevance of such a study is due to the fact that the issues of the influence of the phase-angular dependence on the accuracy of the phase difference direction finding have not been sufficiently studied at present. At the same time, there is a need to study these issues in connection with the solution of a number of applied problems.

Theoretical Basis

One of the tasks solved by means of radio observation and having important applied value is to determine the angular direction to the observed radiation sources, in other words, in the direction finding of the emitters. The angular direction to a point radiation source can be determined by the magnitude of the phase difference of oscillations at the outputs of the receiving antennas, spaced apart in space. This principle is used by phase direction finders, which are widely used in radio engineering. If the receiving antennas A_1 and A_2 of the direction finder are located in the far-field region of the radiation source, then, as is known [2], the angle α defining the direction to the radiation source in the direction finding plane relative to the normal to the straight line connecting A_1 and A_2 can be defined as

$$\alpha = arcsin(\frac{\Delta\varphi}{kb}), \quad (1)$$

where: b is the distance between A_1 and A_2 (base of the direction finder); $\Delta\varphi$ is the phase difference of oscillations at the outputs of antennas A_1 and A_2; $k=2\pi/\lambda$ is the wavenumber; λ is the radiation wavelength of the radiation source [2].

Errors arising in the phase difference direction finding of radiation source based on the given formula relation are associated with the influence of a number of factors, which include:

- possible ambiguity in determining the angular direction according to the measurement results, which occurs if the difference in the path of the beams from the radiation source to the antennas A_1 and A_2 exceeds the value λ;
- external conditions (environment of propagation of radio waves, underlying surface, reflections from various objects located in the coverage area of the direction finder) and others.

The influence of various interfering factors on the magnitude of bearing errors is considered in a number of publications, for example, in [2, 3]. The present work is devoted to the study of the influence of such a factor as the presence of the dependence of the phase of the emitted wave on the angular direction in the direction finding plane in the direction finding radiation source on the error of phase difference direction finding. Such a dependence (phase-angular dependence) usually takes place in multipoint and spatially extended emitters, the radiation field of which at any point in space is formed as a result of interference, while there are curvatures of the phase front line of the total wave [4, 5]. The question of the influence of the phase-angular dependence on the accuracy of the phase difference direction finding has not been sufficiently studied at present.

The simplest version of an emitter with a phase-angular dependence is a two-point (paired) coherent emitter considered in this work. The study of issues related to the direction finding of two-point coherent emitters is of great practical importance.

The explanatory Fig. 1., two-point emitter is formed by radiators E_1 and E_2, the straight distance between them is *d* (base of the paired emitter).

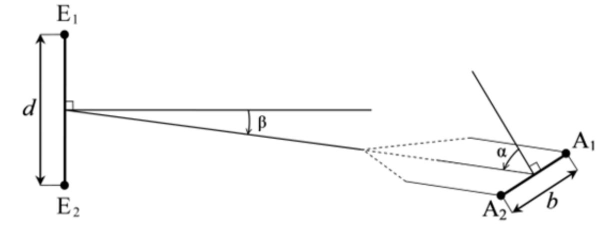

Fig.1. Phase difference direction finding of a two-point coherent emitter

Fig. 1. also shows a phase difference direction finder, which includes antennas A_1 and A_2 located in a plane common with radiators E_1 and E_2, the distance between A_1 and A_2 (the base of the direction finder) is *b*, the orientation of the base relative to the direction to the paired emitter is set by the angle *α*, measured relative to the normal to the base line of the direction finder.

The direction of the radiation to the direction finder is given by the angle β measured from the normal to the base line set in its center.

As is known [6], in the case when the antennas E_1 and E_2 are vibrators, the amplitude-angular and phase-angular characteristics of the paired emitter in the equatorial plane of the vibrators, without taking into account their mutual influence, have the following form, respectively:

$$A(\beta) = \sqrt{1 + \rho^2 + 2 \cdot \rho \cdot cos(k \cdot d \cdot sin(\beta) + \Psi)}, \quad (2)$$

$$\varphi(\beta) = -arctg\left[\frac{sin\left(\frac{k \cdot d}{2} \cdot sin(\beta)\right) - \rho \cdot sin\left(\frac{k \cdot d}{2} \cdot sin(\beta) + \Psi\right)}{cos\left(\frac{k \cdot d}{2} \cdot sin(\beta)\right) + \rho \cdot cos\left(\frac{k \cdot d}{2} \cdot sin(\beta) + \Psi\right)}\right], \quad (3)$$

where ρ≤1 is the ratio of the amplitudes of the currents flowing in the second and first vibrators; Ψ is the phase difference of the currents flowing in the second and first vibrators; λ is the radiation wavelength [6]. The presence of the dependence φ(β) of the wave phase on the angular direction β in the direction finding plane leads to the fact that the phase difference of oscillations at the outputs of the antennas A_1 and A_2 of the direction finder depends not only on the angle of incidence of the wave on the base of the direction finder. Unlike the case of a point emitter, the phase-angular characteristic of which is uniform in the 360° sector and the wave front is flat at any point in the far zone, the phase difference Δφ of oscillations at the outputs of the direction finding antennas A_1 and A_2 contains the component $\Delta\varphi_{add}$, due to the presence of the phase-angular dependence, namely:

$$\Delta\varphi = \frac{2\pi}{\lambda} b \cdot sin(\alpha) + \Delta\varphi_{add}. \quad (4)$$

The value $\Delta\varphi_{add}$ is the difference $\Delta\varphi_{add}=\varphi(\beta_1)-\varphi(\beta_2)$, where β_1 and β_2 are the angular directions to antennas A_1 and A_2 from the point of the phase center of the emitter in the direction finding plane. The addition $\Delta\varphi_{add}$ causes the appearance of a bearing error, which depends on the angle β. This error is in addition to other components of the error [2, 4].

An additional component of the bearing error due to the presence of the phase-angular dependence of the emitter was studied in the work [3].

This work is a development of work [3] in the direction of studying the influence of the main parameters of the problem under consideration on the value of the bearing error.

Methodology

Bearing error of a two-point coherent emitter

The presence of the phase-angular dependence (3) leads to the fact that the bearing value of the radiation source obtained from the results of measuring the phase difference (the measured value of the bearing) is

$$\alpha_{msr} = arcsin\left(\frac{\frac{2\pi}{\lambda} \cdot b \cdot sin(\alpha) + \Delta\varphi_{add}}{\frac{2\pi}{\lambda} \cdot b}\right) = arcsin\left(sin(\alpha) + \frac{\Delta\varphi_{add}}{\frac{2\pi}{\lambda} \cdot b}\right), \quad (5)$$

for any fixed α value

$$\alpha_{err} = arcsin\left(sin(\alpha) + \frac{\Delta\varphi_{add}}{\frac{2\pi}{\lambda} \cdot b}\right) - \alpha. \quad (6)$$

is an error in measuring the angle α, due to the presence of a phase-angular dependence of the direction finding emitter.

With the known nature of the phase-angular dependence φ(β), the value $\Delta\varphi_{add} \equiv \Delta\varphi_{add}(\beta)$ can be defined in the first approximation as

$$\Delta\varphi_{add}(\beta) \approx \frac{d\varphi(\beta)}{d\beta} \cdot \delta. \quad (7)$$

where $\delta=\beta_1-\beta_2$ is the angle at which the base of the direction finder is observed from the point of the phase center of the radiation source. For the angle δ, the approximation is valid

$$\delta \approx \frac{b \cdot cos(\alpha)}{r}. \quad (8)$$

where *r* is the distance between the points of the phase center of the radiation source and the center of the direction finder base. Taking into account (7) and (8), the bearing error (6) is determined as

$$\alpha_{err} = arcsin\left(sin(\alpha) + \frac{\frac{d\varphi(\beta)}{d\beta} cos(\alpha)}{\frac{2\pi}{\lambda} \cdot r}\right) - \alpha. \quad (9)$$

In the particular case of greatest interest α=0 (the normal to the base of the direction finder at the point of its center is oriented towards the point of the phase center of the direction finding emitter), instead of (9) we obtain

$$\alpha_{err_{\alpha=0}} = arcsin\left(\frac{\frac{d\varphi(\beta)}{d\beta}}{\frac{2\pi}{\lambda} \cdot r}\right). \quad (10)$$

Relation (10) shows that the error of the phase-difference direction finding caused by the presence of a phase-angular dependence in the direction finding radiation source is different for various angular directions β and is determined by the rate of change (derivative) of the phase-angular characteristic in the corresponding direction, as well as by the radiation wavelength of the radiation source and the distance between the radiation source and a direction finder. The derivative of the phase-angular characteristic (3), which appears in (9) and (10), as can be seen from the corresponding calculations, is determined by the relation

$$\frac{d\varphi(\beta)}{d\beta} = -\frac{k \cdot d \cdot (1-\rho^2) \cdot cos(\beta)}{2 \cdot [1 + \rho^2 + 2 \cdot \rho \cdot cos(k \cdot d \cdot sin(\beta) + \Psi)]}. \quad (11)$$

Taking into account (11), relation (10), which determines the bearing error of a paired vibrator coherent emitter as a function of the angle β, takes the form

$$\alpha_{err}(\beta)_{\alpha=0} = arcsin\left(-\frac{d \cdot (1-\rho^2) \cdot cos(\beta)}{2 \cdot r \cdot [1 + \rho^2 + 2 \cdot \rho \cdot cos(k \cdot d \cdot sin(\beta) + \Psi)]}\right). \quad (12)$$

The results of calculations performed on the basis of (2), (3) and (12) are presented below in the figures in the form of families of graphs.

In Fig. 2 and Fig. 3 shows the amplitude-angular (A(β)) and phase-angular (φ(β)) characteristics of the paired radiator calculated on the basis of (2) and (3) with the following parameters of the problem: λ=20 cm, *d*=350 m, *r*=10 km, ρ=0.85. It can be seen from the Fig. 2 that there is a significant dependence of the phase of the oscillation emitted by the paired radiator on the angle β. The phase-angular characteristic (PhAC) φ(β) takes zero values only for the angles β corresponding to the maxima of the amplitude-angular characteristic (AAC) A(β). In the directions where AAC A(β) takes minimum values, there are extrema of PhAC φ(β). The extreme values of the PhAC are determined by the parameters of the paired emitter.

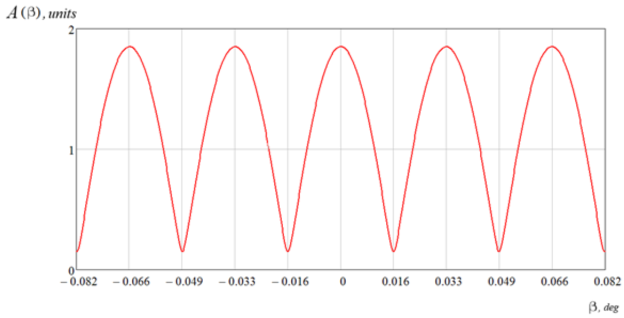

Fig.2. The amplitude-angular characteristic of the paired emitter

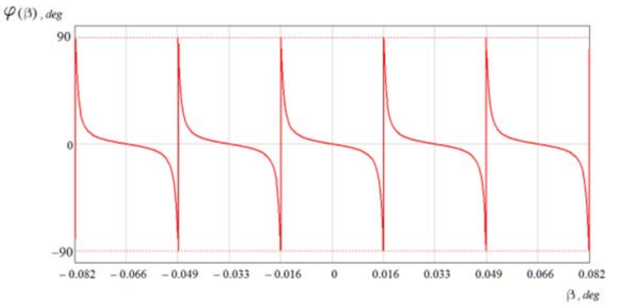

Fig.3. Phase-angular characteristic of the paired emitter

In Fig. 4 shows the dependence of the modulus of the bearing error of the paired emitter $\alpha_{err}(\beta)_{\alpha=0}$, arising due to the presence of the phase-angular dependence, on the angular direction β to the center of the direction finder base ("angular panorama of bearing errors" (APBER)). The APBER calculations were carried out on the basis of (12) with the above initial data. It can be seen that the bearing error is maximum at the points where the AAC takes the minimum, and the PhAC takes the extreme values. The values of the error maxima are determined by the parameters of the problem. In the intervals between the maxima of the PhAC, the error decreases rapidly, and at the points of the maxima, the AAC takes zero values.

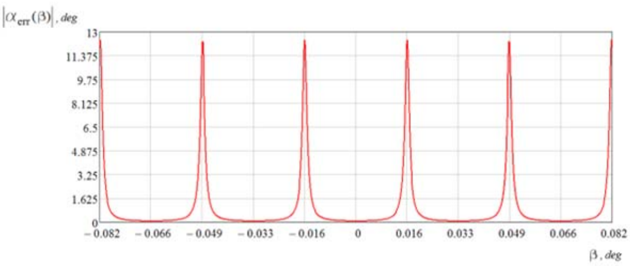

Fig.4. Angular panorama of the bearing errors of the paired emitter

The dependence $\alpha_{err}(\beta)_{\alpha=0}$ - contains important information about the achievable accuracy of the phase difference direction finding of a paired coherent emitter and about the influence of various parameters of the "emitter - direction finder" system on the levels of bearing errors. The results of calculations carried out in [3] have shown that the APBER is a quasi-periodic function of the angle β with alternation of zones (angular sectors) with high and low levels of bearing errors (zones of HLBER and LLBER). In [3], the dependences of the maximum values of the bearing error in the first (closest from the normal to the baseline) HLBER zone on some parameters of the problem were calculated. However, consideration of applied problems shows that the characteristics of the APBER need more detailed study. In particular, of interest are quantitative estimates of the influence of the base value of a paired coherent emitter on the error levels of the phase difference direction finding of this emitter at different distances *r* to the direction finder, as well as on the ratio of the widths of zones of high and low levels of bearing errors [3].

Influence of the base of a paired coherent emitter on the characteristics of APBER

Directly based on relation (12), the dependences $\alpha_{err}(d,\beta)_{|\alpha=0,\Psi=0,\rho,r}$ of the level of the bearing error modulus of the paired emitter at the maximum point of the first HLBER zone (at the point β = βmax) on the value base *d* of the emitter at fixed values of the parameter ρ and distance *r*. The value $\alpha_{err}(d,\beta=\beta_{max})_{|\alpha=0,\Psi=0,\rho,r}$ determines the maximum level of bearing error at the given levels of the specified parameters. From the results given in [3], it follows that this value is the same for all APBER maxima. The calculation results are presented in the form of graphs in Fig. 5, Fig. 6, Fig. 7 and Fig. 8. The graphs are calculated for a wide range of values of the distance *r* between the paired transmitter and the direction finder (from 2 to 40 km). The values of the parameter ρ are chosen equal to 0.95 (Fig. 5), 0.9 (Fig. 6), 0.7 (Fig. 7), 0.5 (Fig. 8), λ = 0.2 m [3].

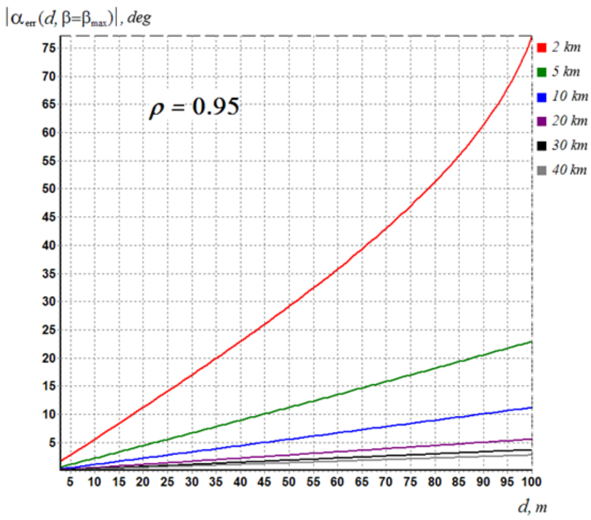

Fig.5. The dependence of the bearing error of a paired emitter at the maximum point of the first HLBER zone on the magnitude of the emitter base in ρ=0.95 and r=(2…40) km

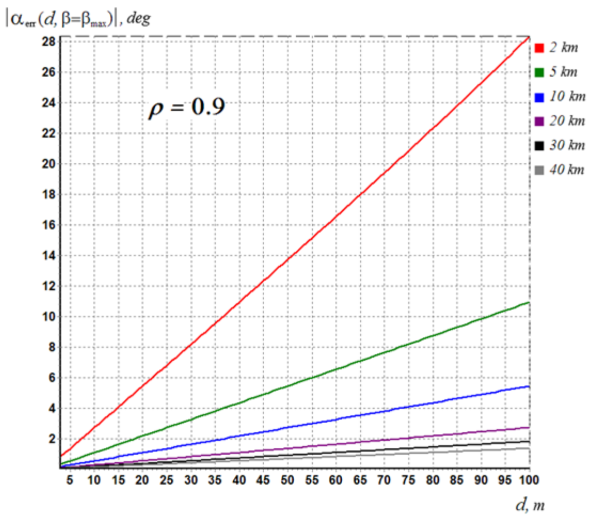

Fig.6. The dependence of the bearing error of a paired emitter at the maximum point of the first HLBER zone on the magnitude of the emitter base in ρ=0.9 and r=(2…40) km

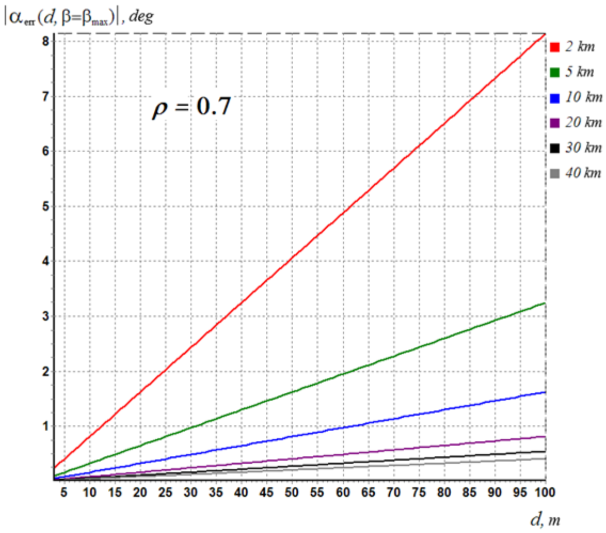

Fig.7. The dependence of the bearing error of a paired emitter at the maximum point of the first HLBER zone on the magnitude of the emitter base in ρ=0.7 and r=(2…40) km

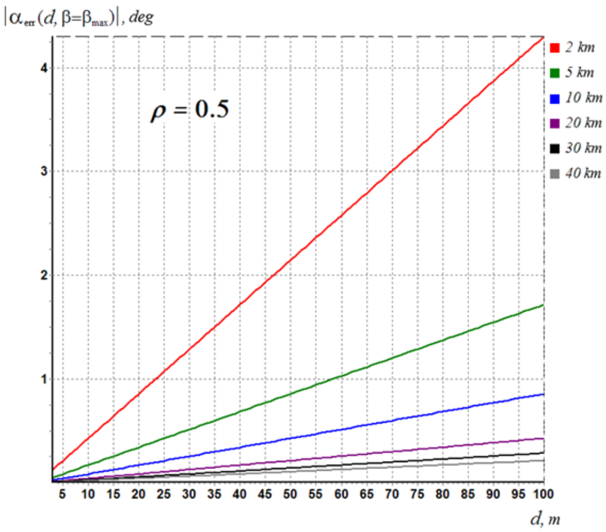

Fig.8. The dependence of the bearing error of a paired emitter at the maximum point of the first HLBER zone on the magnitude of the emitter base in ρ=0.5 and r=(2…40) km

Analysis of the graphs indicates the following:

1. An increase in the base *d* of a paired coherent emitter for any values of other parameters of the "emitter - direction finder" system leads to an increase in the bearing error at the maximum point of the HLBER zone $\alpha_{err}(d,\beta=\beta_{max})_{|\alpha=0,\Psi=0,\rho,r}$. In the considered range of distances *r*=(2...40)km in the given graphs the dependence of the maximum error on the base *d* is close to linear, the rate of increase of the error increases with decreasing distance *r* and at $\rho\to1$;
2. For any fixed values of the base d of the paired emitter and the distance *r*, the bearing error at the maximum point of the HLBER zone $\alpha_{err}(d,\beta=\beta_{max})_{|\alpha=0,\Psi=0,\rho,r}$ increases with increasing speed at $\rho\to1$;
3. For any fixed values of the base d and the parameter ρ of the emitter, the level of the bearing error at the maximum point of the HLBER zone increases with the approach of the direction finder to the emitter. The specific values of the reached levels can be seen from the graphs.

From the point of view of practical problems, it is also of interest to assess the influence of the base value of a paired emitter on the absolute and relative width of the HLBER zones. The relative width of the n-th zone of the HLBER (HLBER $_n$), n=1, 2, ... is understood as the value $\Delta\beta_{n\ rel}=\Delta\beta_n/(\beta_{max,n+1}-\beta_{max,n})$ of the ratio of the absolute width of this zone $\Delta\beta_n$ to the angular distance $\beta_{max,n+1}-\beta_{max,n}$ between neighboring maxima.

Fig. 9 shows the dependence $\Delta\beta_1(d)$ of the absolute width of the first zone of the HLBER $\Delta\beta_1$, measured at the level of 0.5 from the maximum, on the value of the base *d* of the paired emitter with the values of the parameter ρ equal to 0.5, 0.7, 0.8, 0.85, 0.9, 0.95; Ψ=0; *r*=10 km.

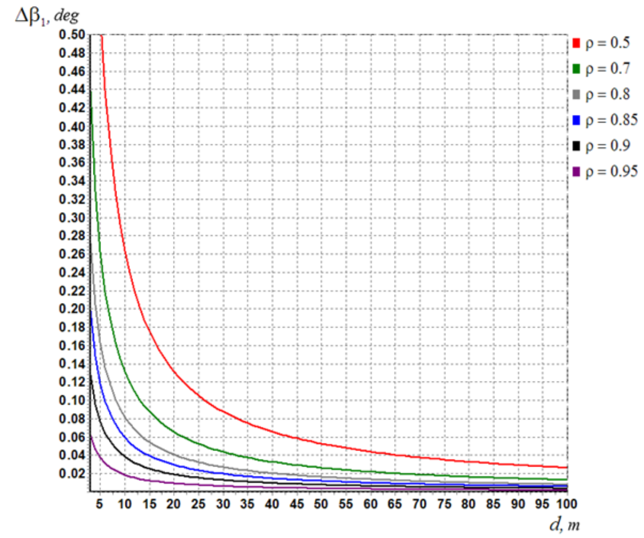

Fig.9. The dependence of the absolute width on the first HLBER zone on the emitter base in r=10km

The dependence of the relative width of the first HLBER zone $\Delta\beta_{1rel}$ on the value *d* of the base of the emitter at Ψ=0, *r*=10km and the same values of the parameter ρ is shown in Fig. 10.

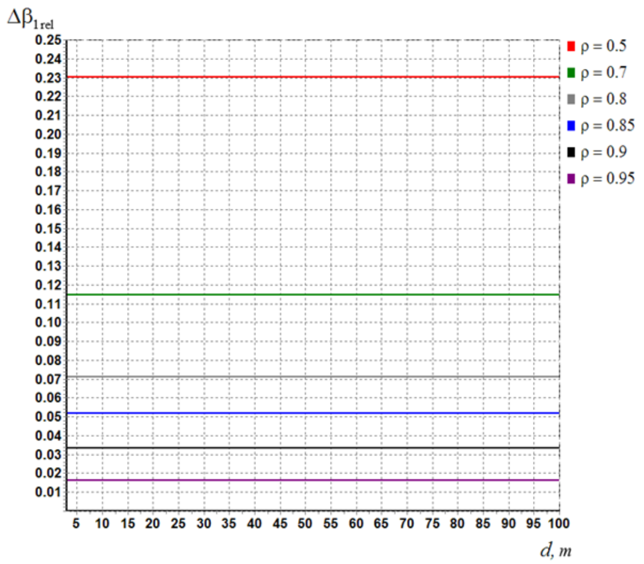

Fig.10. The dependence of the relative width of the first HLBER zone in r=10km

Analysis of the graphs shows the following:

1. The absolute width of the HLBER zone decreases with an increase in the base of the paired emitter, and at *d*=10m, 20m, 30m, 40m, 50m, 70m, 100m (respectively *d/λ*=50, 100, 150, 200, 250, 350, 500) exceeds, respectively, 0.26˚, 0.14˚, 0.09˚, 0.06˚, 0.04˚, 0.03˚. The HLBER zones are very narrow angular sectors, the

width of which in the case of r=10km is tenths ... hundredths of an angular degree. It is easy to verify that with increasing distance r, the width of the HLBER zones decreases and can reach hundredths or thousandths and less fractions of a degree;

2. The relative width of the HLBER zone in the considered range d=(5 ... 100) at ρ=(0.5 ... 0.95) practically does not depend on the size of the base of the paired emitter and is: 0.230 (ρ=0.5), 0.117 (ρ=0.7), 0.072 (ρ=0.8), 0.052 (ρ=0.85), 0.035 (ρ=0.9), 0.017 (ρ=0.95). At ρ→1, the value of $\Delta\beta_{1rel}$ monotonically decreases to levels of 0.01 and below.

4. Results and Discussion

In the well-known literary sources devoted to the direction finding of a two-point coherent emitter, an approach to the analysis of bearing errors is adopted, which is based on the assumption that the direction to the direction finding emitter from the observation point coincides with the normal to the phase front of the electromagnetic wave generated by the emitter at this point. This approach is contained, for example, in the fundamental sources on this topic [12], which are usually referred to when considering the issues discussed here, as well as in relatively recent publications, such as [9, 10]. Consequently, the direction finder, which determines the direction to the emitter from the point in space in which it is located, detects the phase front of the wave incident on it and builds a normal to it. However, according to [4], this assumption is valid only for point emitters, which create a wave in the far-field region with a linear ("flat") front. Multi-point (including two-point), as well as spatially extended emitters, are characterized by the fact that the wave front of the field generated by them can differ from the linear one even in the far-field region [4, 5]. In this regard, let us point out the following.

With regard to multipoint and extended radiators, the assumption that the direction to the radiator coincides with the direction of the normal to the phase front of the wave can be accepted only with one or another degree of approximation, which needs to be substantiated for each case under consideration.

The statement that the direction finder determines the direction of the normal to the front of the incident wave requires justification. Consideration of survey (non-tracking) amplitude and phase direction finders used in radio monitoring (electronic intelligence) technology allows us to state the following.

In the case of a survey amplitude direction finder, information about the direction to the direction finding emitter is contained in the ratio of the signal amplitudes of this emitter at the outputs of a set of receiving channels (multichannel ("monopulse") amplitude direction finder) or at the output of one channel at successive times (single-channel ("scanning") amplitude direction finder). The informational parameters measured by the direction finder are the amplitudes of the received signals. Analysis of the phase ratio of channel signals is useless, since the phase centers of the channel antennas coincide and the phases of the signals at the channel outputs are the same. Consequently, the construction of the phase front of the incident wave in the survey amplitude direction finder is not performed.

In the case of a survey phase direction finder, the measured information parameters are the phase ratios (for example, the phase difference) of the signals of the direction finding emitter at the outputs of the receiving channels, the antennas of which are spaced apart in space. Determination of the direction to the emitter is based on the analysis of the measured phase relationship. Revealing the line of the phase front of the wave and building the normal to this line is not required.

In contrast to the traditional approach considered above, the study carried out in this work was based on the assumption that the direction finder determines the direction to the emitter only on the basis of its measurements of the signal parameters at the outputs of the receiving channels. In this work, a phase direction finder was considered, which measures the phase difference of channel signals (phase difference direction finder). The use of this assumption made it possible to construct a model for the formation of an additional component of the bearing error due to the presence in the considered two-point coherent emitter of the dependence of the phase of the emitted oscillations on the angle (phase-angular dependence) (see relations (6)-(12)).

The obtained relations, which determine the bearing error of a two-point coherent emitter, are valid for any angles β, measured relative to the normal to the base line of the two-point emitter. This makes it possible to plot the dependence of the bearing error on the angle, measured from the normal to the base line of the two-point emitter (angular panorama of bearing errors (APBER)) for any values of the parameters about the emitter and at any distances between the emitter and the direction finder (for the far-field region of the emitter).

The relationships given in the above sources [5, 11] determine the angular mismatch between the normal to the phase front of the wave at the observation point (the point of the direction finder location) and the true direction to the emitter (radius vector drawn from the middle of the base of the two-point emitter to the observation point). This value coincides with the bearing error of a two-point emitter only in cases when the direction finder, based on the results of observing the emitter signals, actually determines the line of the phase front of the wave and the direction of the normal to it at the observation point [7, 12].

Thus, the approach to the analysis of the bearing errors of a coherent two-point emitter, the proposed method for calculating the bearing errors and the analysis results obtained in this work are more informative and adequate to the real processes of direction finding of emitters during radio monitoring (electronic reconnaissance) in comparison with the traditional approach.

Conclusions

The obtained results of a quantitative assessment of the dependence of the angular panorama parameters of the bearing errors of a two-point coherent emitter on the size of the emitter base and other parameters provide the basis for justifying the choice of emitter parameters when solving practical problems associated with the use of point-to-point emitters. These results are also useful in substantiating the requirements for survey means of direction finding in terms of their technical characteristics. In addition, they can be used in organizing the processes of radio suppression of phase difference direction finders in the interests of protecting various radiation sources from radio intelligence equipment.

***Authors**: Professor Vasily Yudin, Doctor in Technical Sciences, Department of Theoretical Radio Engineering, Moscow Aviation Institute (National Research University), Volokolamskoe Highway, 4, Moscow, Russia, E-mail: yudin_mai@mail.ru; Associate Professor Nikolay Osavchuk, PhD in Technical Sciences, Department of Theoretical Radio Engineering, Moscow Aviation Institute (National Research University), Volokolamskoe Highway, 4, Moscow, Russia, E-mail: nickos@inbox.ru; Postgraduate Anton Volkov, Department of Theoretical Radio Engineering, Moscow*

Aviation Institute (National Research University), Volokolamskoe Highway, 4, Moscow, Russia, E-mail: afv92@yandex.ru.

REFERENCES

[1] Chmykh M.K. *Digital phase measurement*. Moscow: Radio and Connection (1993).
[2] Denisov V.P., Dubinin D.V. *Phase radio direction finders*. Tomsk: Tomsk State University of Control Systems and Radioelectronics (2002).
[3] Yudin V.N., Volkov A.M. Differential phase direction finding errors for emitters with phase-angular dependence. *Telecommunication*, 12 (2020), 50-53.
[4] Leonov A.I., Fomichev K.I. *Monopulse radar*. Moscow: Soviet radio (1970).
[5] Leonov A.I., Fomichev K.I. *Monopulse radar*. Moscow: Radio and Communication (1984).
[6] Markov G.T., Sazonov D.M. *Antennas. Textbook for radio technicians of universities*. Moscow: «Energy» (1975).
[7] Maksimov M.V. *Protection from radio interference*. Moscow: Soviet radio (1976).
[8] Dyatko A.A, Kostromitsky S.M., Shumsky P.N., Davydenko I.N. Analysis of the front of the electromagnetic wave generated by the coherent radiation sources of the two points of space. *Reports of the Belarusian State University of Informatics and Radioelectronics*, 6 (2018), No. 116, 5-11.
[9] Dyatko A.A, Kostromitsky S.M., Shumsky P.N., Davydenko I.N. Operation of a radar goniometric system under conditions of a signal generated by coherent radiation sources from two points in space. *Reports of the Belarusian State University of Informatics and Radioelectronics*, 7-8 (2019), No. 126, 22-29.
[10] Perunov Yu.M. *Radioelectronic suppression of information channels of weapons control systems*. Moscow: Radio and Communication (2008).
[11] Vakin S.A., Shustov L.N. *Basics of jamming warfare and radio reconnaissance*. Moscow: Soviet radio (1968).
[12] Dokk A.S. *Projectile control*. Moscow: Gostekhizdat (1957).