Radioelectronic and Computer Systems, 2023, no. 4(108)

ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

UDC 621.396.75:621.391.8

doi: 10.32620/reks.2023.4.08

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FOUR-ANTENNA AMPLITUDE DIRECTION FINDER: STATISTICAL SYNTHESIS AND EXPERIMENTAL RESEARCH OF SIGNAL PROCESSING ALGORITHM

The subject of this study *is the algorithms for measuring the angular positions of radio emission sources.* ***The goal*** *of this study is to develop an improved algorithm for signal processing in amplitude direction finders that will provide several unambiguous measurement angles at high steepness of the discrimination characteristic by combining measurements of systems with different widths of antenna patterns.* ***The task****: to develop an optimal signal processing algorithm for a four-antenna amplitude direction finding system, two antennas of which have a wide radiation pattern and the other two have a narrow one; to test the overall performance of the resulting algorithm by simulating the direction finder; to develop and conduct a study of an experimental model of a four-antenna direction finder, which includes two antennas with wide radiation patterns, two antennas with narrow radiation patterns, radio frequency paths, and a signal processing unit that implements the developed algorithm; to analyze the effectiveness and features of the application of the developed algorithm, and to compare the results of simulation modeling and experimental research.* ***The methods used are*** *statistical methods and optimal solutions for solving problems of statistical synthesis of signal processing algorithms in passive radio systems, computer simulation modeling methods, and experimental research methods. The following* ***results*** *were obtained. The algorithm for signal processing in a four-antenna direction finding system was synthesized using the maximum likelihood method. By simulation modeling, the overall effectiveness of measurement integration in multi-antenna amplitude direction finders was confirmed, and the peculiarities of the synthesized algorithm application were revealed, namely, the need to introduce additional proportionality coefficients into the measurement channels. During the experimental studies of the developed model of the direction finder, the results of the simulation modeling were confirmed.* ***Conclusions.*** *To determine the direction of radiation sources by amplitude direction finders, it is advisable to simultaneously use systems with wide and narrow antenna patterns, the measurements of which are combined by the proposed algorithm. This makes it possible to simultaneously expand the range of unambiguous measurement angles and increase the accuracy of measurements within the equal-signal zone. The disadvantage of using the algorithm is the nonlinear form of the obtained discrimination characteristics and the need to determine additional proportionality coefficients heuristically.*

Keywords: *radio direction finder; observation characteristic; power measurement; optimal signal processing; experimental research.*

Introduction

Motivation. Modern advances in radio element base, devices, and algorithms for analog and digital information processing make it possible to create highly efficient and affordable miniaturized radio data channels in the frequency range from tens of MHz to a few GHz [1, 2]. Such channels are now widely used in personal communication devices for organizing local and global data transmission lines, remote control of devices for various purposes, information collection, and navigation [3, 4].

Despite the general convenience of using radio communications, there are situations in which the existence of an unknown signal source in the air can cause problems. For example, an extraneous radio signal can disable equipment sensitive to radio radiation, distort the results of experiments, suppress a critical data transmission channel, or indicate a possible danger to others [5, 6]. This is especially relevant to open and unlicensed frequency bands, among which the most common are 433/868 MHz and 2.4 GHz, and important radio channels, such as the bands in which global satellite navigation systems transmit radio signals [7, 8].

Therefore, tools capable of both detecting the presence of radio sources and determining their direction have become particularly relevant today. These systems include Direction Finders [9].

State of the Art. Currently, there are many different algorithms used in direction finders. The most modern and advanced systems are those based on correlation signal processing or correlation-interferometric direction-finding methods [10, 11]. Correlation systems use several antennas spaced over considerable distances (from several meters to kilometers). In this case, the direction of signal arrival is determined by calculating the delay time of the same signal to different elements of the antenna system [12]. Correlation-interferometric systems are based on measuring the phase difference of signals received by different elements of the antenna system and performing additional sequential correlation analysis of the measurement results [13, 14]. The advantage of a correlation-interferometric system over a correlation system is high direction-finding accuracy without the need to use an antenna system with a large base between individual elements. At the same time, both correlation and correlation-interferometric systems require high-speed analog-to-digital converters and digital information processing devices to achieve high direction-finding accuracy [15]. This significantly increases the cost of direction-finding devices and makes them affordable for a limited number of consumers. Therefore, the classic two-antenna amplitude and phase direction finding radars remain relevant.

In an amplitude direction finder, the direction to the signal source is determined by comparing the powers of the signals received by the two directional antennas [16, 17]. In the case of phase direction finding, the direction is determined by comparing the phases of the signals received by the two omnidirectional antennas [18]. The main advantage of amplitude and phase direction finding methods is their simplicity and low cost of implementation, which makes such systems relevant today. Thus, considering the achievements of the modern element base, the radio frequency paths of such systems can consist of a minimum number of components. Further processing of information, even in digital form, does not require significant power and can be implemented on a single microcontroller. The disadvantage of these systems is the provision of high accuracy and unambiguity of direction finding only in a limited range of angles, which depends on the parameters of the antenna system [19]. At the same time, an increase in the viewing area leads to a decrease in the accuracy of direction finding due to a decrease in the steepness of the observational characteristic, which is especially inherent in amplitude direction finders. This requires a constant search for a compromise between the viewing area and direction-finding accuracy.

A possible solution to this problem is to combine the two direction finders into one complex. One direction finder will have a wide field of view and low accuracy, and the other will have a narrow field of view with high accuracy. By combining the measurements of the two systems, we will be able to obtain an increased field of view and increased accuracy in determining the angular position of the radio source. However, such a combination is not an easy task and requires a special processing algorithm. The development of such an algorithm can be performed heuristically by studying the features of individual systems and finding possible ways to combine measurements. However, this option does not always provide the best or most accurate solutions to the problem. A more expedient and effective approach is to synthesize a measurement combination algorithm based on the statistical theory of signal processing optimization in radio remote sensing systems [19, 20]. This will allow both to obtain the optimal processing algorithm for the task at hand and to preliminarily estimate the limits of measurement error.

Objectives. This paper proposes an optimal algorithm for signal processing in a direction-finding complex consisting of two amplitude dual-antenna direction finders. One of the direction finders has a wide viewing area and low accuracy, whereas the other has high direction-finding accuracy in a limited sector. The effectiveness of the proposed algorithm is investigated both by simulation modeling and during an experiment involving a model of a direction-finding system.

Initial data. Description of the problem geometry and the main parameters

Fig. 1 shows the general structure of the direction-finding system and the main geometric relationships required to synthesize the optimal signal processing algorithm. The complex consists of two pairs of antennas. Antennas A_1 i A_2 have wide radiation patterns rotated at angles $\pm 0.5\theta_{\delta 1}$ relative to the equivalent direction They belong to a direction-finding system with a wide viewing angle and low discrimination slope. The antennas A_3 i A_4 have narrow radiation patterns and are deviated by an angle $\pm 0.5\theta_{\delta 2}$ relative to the equisignal direction θ_0. The direction finder with these antennas provides high direction-finding accuracy with a narrow area of unambiguous measurements. All antennas are located on the axis x and the equal-signal direction is on the linear section of the radiation patterns. The radio source is located toward θ_s

Signal $u_i(t)$ from the output of the antenna on the radio frequency front-end, in which it is pre-processed (amplification, filtering, detection, etc.) and then sent to the processor unit, which calculates the estimate of the direct radiation source θ_s.

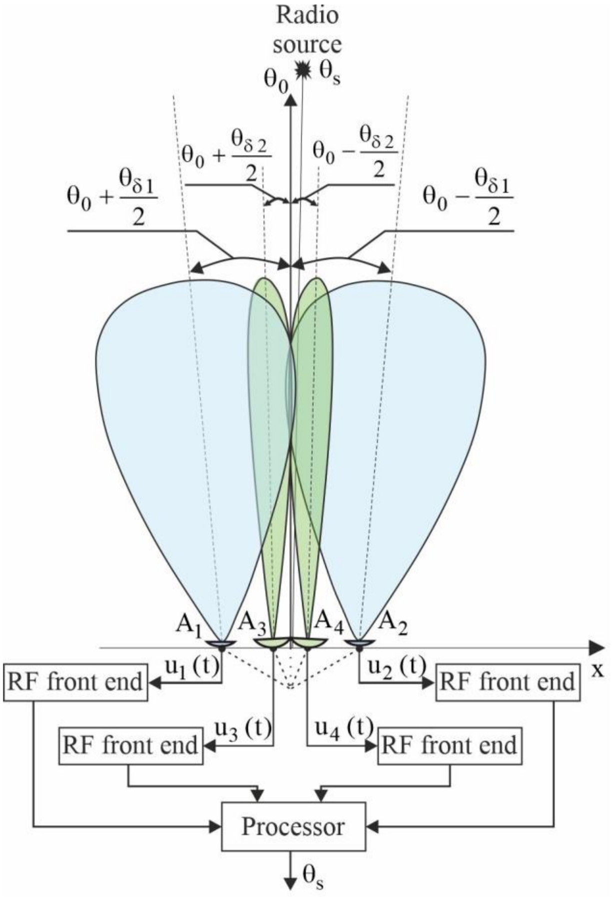

Fig. 1. General structure of direction finding complex and basic geometric relations of the direction-finding problem

To synthesize the optimal signal processing algorithm for the direction finding complex, it is necessary to determine the observation equation. In radio systems, useful signals are always received against a background of external and internal noise. Therefore, it is advisable to represent the observation at the antenna output as an additive mixture of useful signals and noise for each receiving channels:

$$u_i(t) = \mathrm{Re}\left\{\dot{s}_{\mathrm{res}\ i}\ (t,\lambda)\right\} + n_i(t)\ , \qquad (1)$$

were $\dot{s}_{\mathrm{res}\ i}$ is an useful signal received by the i-th antenna; $n_i(t)$ is a noise in the i-th receiving channel, recalculated to the antenna output.

Consider the useful signals at the output of the antennas as follows:

$$\dot{s}_{\mathrm{res}\ 1}(t,\lambda = \theta_s) =$$

$$= \int_{\Theta} G_1\left(\theta - \theta_0 + \frac{\theta_{\delta 1}}{2}\right)\delta(\theta - \theta_s)\dot{A}(t)e^{-j2\pi f_0 t}d\theta, \quad (2)$$

$$\dot{s}_{\mathrm{res}\ 2}(t,\lambda = \theta_s) =$$

$$= \int_{\Theta} G_1\left(\theta - \theta_0 - \frac{\theta_{\delta 1}}{2}\right)\delta(\theta - \theta_s)\dot{A}(t)e^{-j2\pi f_0 t}d\theta, \quad (3)$$

$$\dot{s}_{\mathrm{res}\ 3}(t,\lambda = \theta_s) =$$

$$= \int_{\Theta} G_2\left(\theta - \theta_0 + \frac{\theta_{\delta 2}}{2}\right)\delta(\theta - \theta_s)\dot{A}(t)e^{-j2\pi f_0 t}d\theta, \quad (4)$$

$$\dot{s}_{\mathrm{res}\ 4}(t,\lambda = \theta_s) =$$

$$= \int_{\Theta} G_2\left(\theta - \theta_0 - \frac{\theta_{\delta 2}}{2}\right)\delta(\theta - \theta_s)\dot{A}(t)e^{-j2\pi f_0 t}d\theta, \quad (5)$$

were λ is evaluated parameter; $G_1\left(\theta - \theta_0 \pm \frac{\theta_{\delta 1}}{2}\right)$ are radiation patterns of antennas A_1 and A_2; $G_2\left(\theta - \theta_0 \pm \frac{\theta_{\delta 2}}{2}\right)$ are radiation patterns of antennas A_3 and A_4; $\dot{A}(t)$ is complex envelop of the received signal.

In the following calculations, we assume that the receiving paths have identical characteristics and that the noise $n_i(t)$ are white delta-correlated Gaussian processes with power density $0.5N_0$ and the following correlation functions:

$$R_{n_i}(t_1 - t_2) = \frac{N_0}{2}\delta(t_1 - t_2). \qquad (6)$$

In accordance with this task, it is necessary to synthesize the optimal algorithm for processing the observations received by the four-antenna direction finder (1) to estimate the angular position θ_s radio signal sources.

Algorithm for received signals processing

To solve the problem of optimizing signal processing, we use the criterion of the maximum likelihood function, which for the case of joint optimization of four processes will be as follows [21]:

$$P[\vec{u}(t) \mid \lambda] =$$

$$= P[u_1(t) \mid \lambda]\ P[u_2(t) \mid \lambda] P[u_3(t) \mid \lambda]\ P[u_4(t) \mid \lambda] =$$

$$= \kappa \exp\left\{-\frac{1}{N_0}\sum_{i=1}^{4}\int_{T}\left[u_i(t) - \mathrm{Re}\left\{\dot{s}_{\mathrm{res}\, i}\ (t,\lambda)\right\}\right]^2 dt\right\}, (7)$$

where κ is a coefficient that depends on the energy parameters of the signal; T is the time at which the signal was observed.

Let’s define the maximum of function (7). To achieve this, it is necessary to differentiate it and set the result to zero. However, to simplify the calculations, it is advisable to differentiate not the likelihood function (7) itself, but its logarithm:

$$\left.\frac{d\ln P[\bar{u}(t)\,|\,\lambda]}{d\theta_s}\right|_{\theta_s=\theta_{s\,opt}}=0\,. \qquad (8)$$

Because of differentiation, we obtain the following likelihood equation:

$$-\frac{2}{N_0}\sum_{i=1}^{4}\int_T\left[u_i(t)-\mathrm{Re}\left\{\dot{s}_{res\,i}\left(t,\lambda\right)\right\}\right]\times$$
$$\times\left(-\mathrm{Re}\left\{\frac{d\,\dot{s}_{res\,i}\left(t,\lambda\right)}{d\theta_s}\right\}\right)dt=0. \qquad (9)$$

We obtain the following equation by expanding the derivatives of the useful signal:

$$\left.\frac{dG_1(\theta-\theta_0+0{,}5\theta_{\delta1})}{d\theta}\right|_{\theta=\theta_s}\int_T u_1(t)\mathrm{Re}\{\dot{A}\left(t\right)\times$$
$$\times e^{-j2\pi f_0 t}\}\,dt+\left.\frac{dG_1(\theta-\theta_0-0{,}5\theta_{\delta1})}{d\theta}\right|_{\theta=\theta_s}\times$$
$$\times\int_T u_2(t)\mathrm{Re}\,\{\dot{A}\left(t\right)e^{-j2\pi f_0 t}\}dt+$$
$$+\left.\frac{dG_2(\theta-\theta_0+0{,}5\theta_{\delta2})}{d\theta}\right|_{\theta=\theta_s}\int_T u_3(t)\mathrm{Re}\{\dot{A}\left(t\right)\times$$
$$e^{-j2\pi f_0 t}\}\,dt+\left.\frac{dG_2(\theta-\theta_0-0{,}5\theta_{\delta2})}{d\theta}\right|_{\theta=\theta_s}\times$$
$$\times\int_T u_4(t)\mathrm{Re}\,\{\dot{A}\left(t\right)e^{-j2\pi f_0 t}\}dt=$$
$$=\left.\frac{dG_1(\theta-\theta_0+0{,}5\theta_{\delta1})}{d\theta}\right|_{\theta=\theta_s}\times$$
$$\times\int_T \mathrm{Re}\{\dot{s}_{res1}\left(t,\lambda\right)\}\mathrm{Re}\{\dot{A}\left(t\right)e^{-j2\pi f_0 t}\}\,dt+$$
$$+\left.\frac{dG_1(\theta-\theta_0-0{,}5\theta_{\delta1})}{d\theta}\right|_{\theta=\theta_s}\times$$
$$\times\int_T \mathrm{Re}\{\dot{s}_{res2}\left(t,\lambda\right)\}\mathrm{Re}\{\dot{A}\left(t\right)e^{-j2\pi f_0 t}\}dt+$$
$$+\left.\frac{dG_2(\theta-\theta_0+0{,}5\theta_{\delta2})}{d\theta}\right|_{\theta=\theta_s}\times$$
$$\times\int_T \mathrm{Re}\{\dot{s}_{res3}\left(t,\lambda\right)\}\mathrm{Re}\{\dot{A}\left(t\right)e^{-j2\pi f_0 t}\}\,dt+$$
$$+\left.\frac{dG_2(\theta-\theta_0-0{,}5\theta_{\delta2})}{d\theta}\right|_{\theta=\theta_s}\times$$
$$\times\int_T \mathrm{Re}\{\dot{s}_{res4}\left(t,\lambda\right)\}\mathrm{Re}\{\dot{A}\left(t\right)e^{-j2\pi f_0 t}\}dt. \qquad (10)$$

To simplify equation (10), let’s consider the following equation [21]:

$$\mathrm{Re}\,\dot{A}\,\mathrm{Re}\,\dot{B}=\frac{1}{2}\mathrm{Re}\,\dot{A}\dot{B}+\frac{1}{2}\mathrm{Re}\,\dot{A}\dot{B}^{*}\approx\frac{1}{2}\mathrm{Re}\,\dot{A}\dot{B}^{*}\,. \qquad (11)$$

In this case, the left-hand side of (10) will be equal to the right-hand side under the following condition:

$$\left.\frac{dG_1(\theta-\theta_0+0{,}5\theta_{\delta1})}{d\theta}\right|_{\theta=\theta_s}\int_T u_1(t)\dot{A}\left(t\right)e^{-j2\pi f_0 t}\,dt+$$
$$+\left.\frac{dG_1(\theta-\theta_0-0{,}5\theta_{\delta1})}{d\theta}\right|_{\theta=\theta_s}\int_T u_2(t)\dot{A}\left(t\right)e^{-j2\pi f_0 t}dt+$$
$$+\left.\frac{dG_2(\theta-\theta_0+0{,}5\theta_{\delta2})}{d\theta}\right|_{\theta=\theta_s}\int_T u_3(t)\dot{A}\left(t\right)e^{-j2\pi f_0 t}\,dt+$$
$$+\left.\frac{dG_2(\theta-\theta_0-0{,}5\theta_{\delta2})}{d\theta}\right|_{\theta=\theta_s}\int_T u_4(t)\dot{A}\left(t\right)e^{-j2\pi f_0 t}dt=$$
$$=\frac{1}{2}E_s\,G_\Sigma(\theta_s,\theta_0,\theta_{\delta1},\theta_{\delta2})\;, \qquad (12)$$

$$E_s=\int_T\left|\dot{A}\left(t\right)\right|^2 dt\,, \qquad (13)$$

$$G_\Sigma(\theta_s,\theta_0,\theta_{\delta1},\theta_{\delta2})=$$
$$=\left.\frac{dG_1(\theta-\theta_0+0{,}5\theta_{\delta1})}{d\theta}\right|_{\theta=\theta_s}G_1(\theta_s-\theta_0+0{,}5\theta_{\delta1})+$$
$$+\left.\frac{dG_1(\theta-\theta_0-0{,}5\theta_{\delta1})}{d\theta}\right|_{\theta=\theta_s}G_1(\theta_s-\theta_0-0{,}5\theta_{\delta1})+\;,$$
$$+\left.\frac{dG_2(\theta-\theta_0+0{,}5\theta_{\delta2})}{d\theta}\right|_{\theta=\theta_s}G_2(\theta_s-\theta_0+0{,}5\theta_{\delta2})+$$
$$+\left.\frac{dG_2(\theta-\theta_0-0{,}5\theta_{\delta2})}{d\theta}\right|_{\theta=\theta_s}G_2(\theta_s-\theta_0-0{,}5\theta_{\delta2})\;, \qquad (14)$$

where E_s is an energy of received signals; $G_\Sigma(\theta_s,\theta_0,\theta_{\delta1},\theta_{\delta2})$ is weighting factor, which makes sense for weight averaging of measurements of each channel.

The left side of the likelihood equation (12) corresponds to the signal processing algorithm in a four-antenna direction finder, and the right side corresponds to its discrimination characteristic without the influence of noise. According to the obtained mathematical model (12), the signal processing diagram for i-th receiving channel is shown in Fig.. 2. According to the diagram, the optimal detection of the signal $u_i\left(t\right)$ received by the i-th antenna is performed first. This is performed by multiplying the received signal by a complex envelope and then averaging it in a low-pass filter. To consider the influence of the radiation pattern, the signal from the filter output is multiplied by a coefficient proportional to the derivative of the radiation pattern of the corresponding antenna. The signals obtained from the output of each such channel are further summed in the adder. The decision on the presence of a radio signal source in angle θ_s is made when the signal from the adder output reaches or exceeds the threshold E_s .

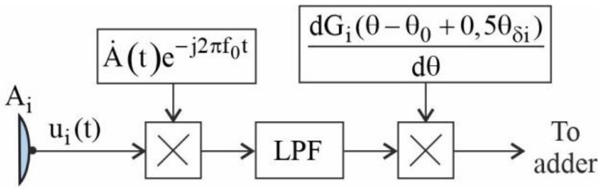

Fig. 2. The signal processing diagram for i-th receiving channel, where LPF is low pass filter

Simulation modeling of the direction finder observation characteristics

Let's consider the overall performance of the obtained mathematical model (12) of the signal processing algorithm with simulation modeling. To do this, we obtain discrimination characteristics for several cases: separately for direction finders with antennas that have wide or narrow radiation patterns and for the case of combining two systems into one complex using the mathematical model (12).

The main lobes of the radiation patterns of most real antennas have a shape close to the Gaussian. Therefore, for simulation modeling of the radiation patterns, we use the following records of the shape of the radiation pattern and its derivative:

$$G_i\left(\theta-\theta_0 \pm 0.5\theta_{\delta i}\right)=\exp\left\{-\frac{\left(\theta-\theta_0 \pm 0.5\theta_{\delta i}\right)^2}{2\sigma_i^2}\right\},\quad(15)$$

$$\frac{dG_i(\theta-\theta_0 \pm 0,5\theta_{\delta i})}{d\theta}=\frac{\left(\theta_s-\theta_0 \pm 0.5\theta_{\delta i}\right)}{\sigma_i^2}\times$$

$$\times G_i\left(\theta_s-\theta_0 \pm 0.5\theta_{\delta i}\right),\quad(16)$$

were $\theta_{\delta i}$ is a shift of the radiation pattern relative to the equal-signal angle θ_0 .

For the first example, we assume that the width of the normalized radiation patterns at the 0.5 power level is 75 degrees, and the shift relative to the central direction is 32.5 degrees. In the Fig. 3 the relative positions of the radiation patterns for this case are shown, and the normalized discrimination characteristic of the direction finder for this antenna configuration is constructed.

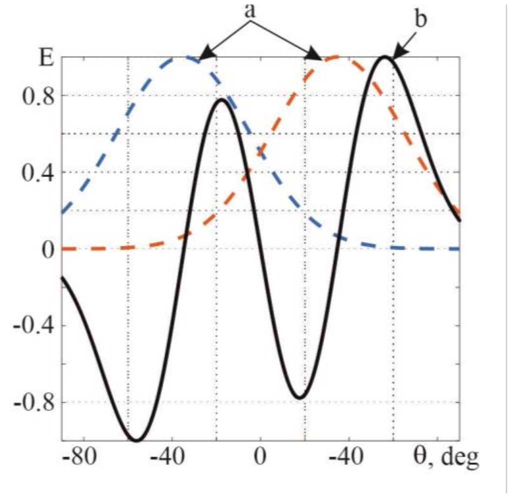

Fig. 3. Directional patterns (a) and observation characteristic (b) of amplitude direction finder with wide beamwidth antennas

To compare the quality of direction finding of different systems, we use two indicators: the width of the area of unambiguous measurements and the steepness of the discrimination characteristic. The area of definite measurements is determined by the angular width of the discriminating characteristic to its first extrema relative to the equal-signal zone (in the graphs, the equal-signal zone corresponds to the angle 0 degrees). The steepness is calculated as the modulus of the ratio of the increase in the amplitude of the discriminative characteristic to the increase in the angle in the region of the equal-signal zone. Analyzing the discrimination characteristic of the Fig. 3 it was determined that the range of unambiguous measurements is 33 degrees, and the steepness of the discriminative characteristic – 0.046 unit/degree.

Consider a similar graph for the case of narrowly directed antennas with a radiation pattern width of 15 degrees and a shift of 7.5 degrees. The resulting graphs are shown in Fig. 4.

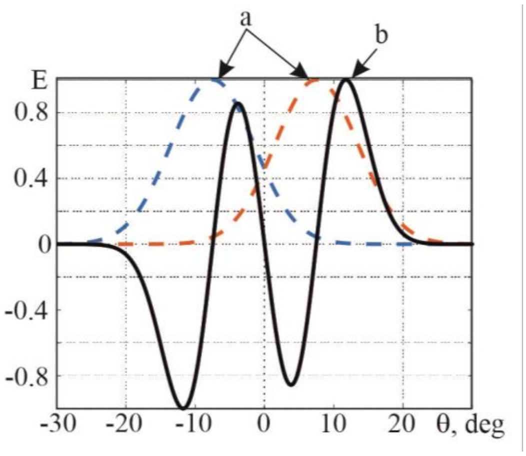

Fig. 4. Directional patterns (a) and observation characteristic (b) of amplitude direction finder with narrow beamwidth antennas

The range of unambiguous measurements of the discrimination characteristics shown in Fig. 4 is 7 degrees, and the steepness is 0.24 degrees per unit.

It is expected that the use of a direction finder whose antennas have a wide radiation pattern will provide a wider area for unambiguous measurements. At the same time, antennas with a narrow radiation pattern have a higher direction finding accuracy (in the case under consideration, the steepness of the discriminative characteristic is more than 5 times higher), but in a narrow range of unambiguous measurement angles.

Next, we obtain the discrimination characteristic for the case of combining two direction finding systems using the mathematical model (12), as shown in Fig. 5. Because there are additional weighting factors in the equation, for comparison, the amplitude of measurements by antennas with wide radiation patterns was multiplied by additional proportionality coefficients $A = 1, 3, 6$, obtained heuristically.

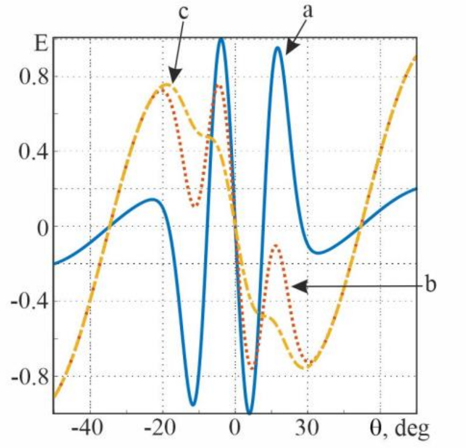

Fig. 5. Observation characteristics of four antenna direction finders: a) $A = 1$; b) $A = 3$; c) $A = 6$

In Fig. 5, the range of unambiguous measurements is 7, 8.6 and 37 degrees at A=1, 3 and 6, respectively. At the same time, the steepness of the discrimination characteristic on linear sections is 0.24, 0.22, and 0.09 units/degree at A=1, 3 and 6.

Experimental research of the direction finding complex

Simulation modeling was performed under the conditions of an idealized radiation pattern without side lobes and a receiving path without internal noise. Therefore, before analyzing the results, it is advisable to perform additional experimental research on the proposed signal processing algorithm in the direction finding complex. For this purpose, based on the structure of Fig. 1, the system shown in Fig. 6 was created.

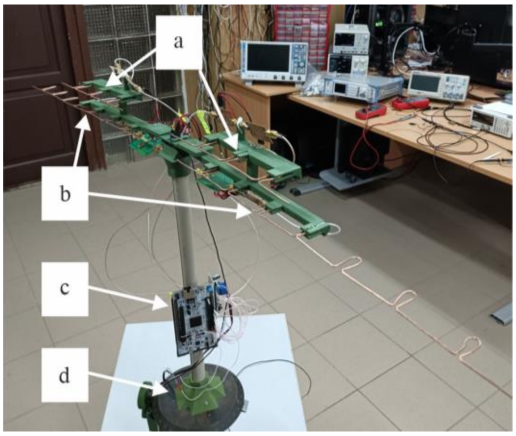

Fig. 6. Experimental layout of a four-antenna beacon system, where a) is antenna with wide beam, b) is antenna with narrow beam, c) is processor with ADC, d) is antenna rotation system.

It consists of four receiving antennas with radio frequency paths tuned to the frequency range of 2.4-2.48 GHz, a microprocessor-based information acquisition unit, and an automatic rotary device.

A collinear antenna array was selected for antenna system implementation. Such an array is easy to implement and tune, does not require complex calculations, and the width of its radiation pattern can be easily controlled by the number of dipole elements. Geometric ratios of antenna elements to wavelengths λ_{ant} without considering the wavelength-shortening effect are shown in Fig. 7 [22]. However, when the antenna is implemented in conductors, the effect of wavelength-shortening appears, and the actual dimensions of the antenna become smaller. In the case of specialized materials, the wave shortening level can be calculated in advance. However, we used a copper cable, the parameters of which are not known at 2.4 GHz. Therefore, the antenna dimensions were experimentally adjusted according to the minimum standing wave ratio criterion. The best standing wave ratio (about 1.3) was obtained for the geometrical dimensions L=54 mm, d=22 mm, which were further used as references. The connection point of the cable with an impedance of 50 ohms on the central loop was experimentally determined. The antenna with a wide radiation pattern consists of four receiving elements, whereas the narrow one consists of eight.

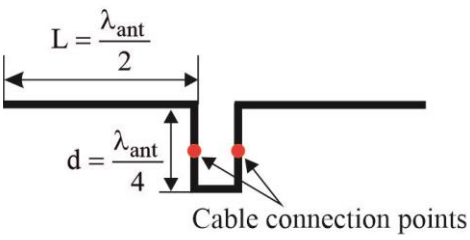

Fig. 7. Geometric ratios of antennas elements

The antenna outputs are connected to radio paths, one of which is shown in Fig. 8. It consists of a low-noise amplifier based on a chip MGA-86563 and a power detector AD8361. The measured path gain is 19.5 dB, and the difference between the parameters of different implementations does not exceed 0.3 dB.

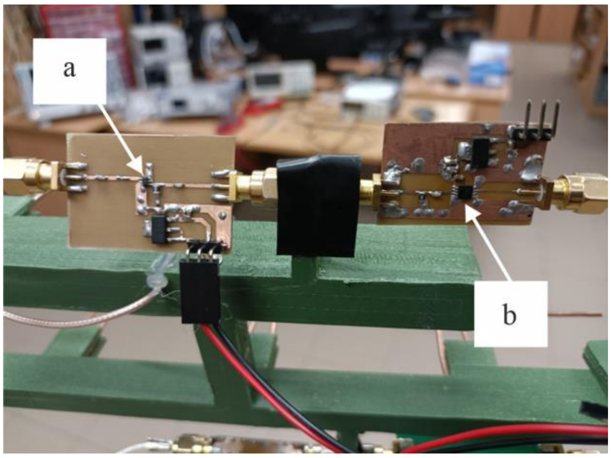

Fig. 8. RF front end, where a) is low noise amplifier MGA-86563, b) is power detector AD8361

A 1-watt video transmitter with a 2.4 GHz patch antenna was used as a test radio signal source, as shown in Fig. 9.

Fig. 9. Test radio signal source

During the experiment, the transmitter and the direction finder were placed 20 m apart, as shown in Fig. 10.

Initially, the radiation patterns of the receiving antennas were measured, and their relative positions were adjusted. The shape and angular relationship of the directional patterns of the direction finder antennas after adjustment are shown in Fig. 11. For convenience of comparison, the amplitudes were prorated.

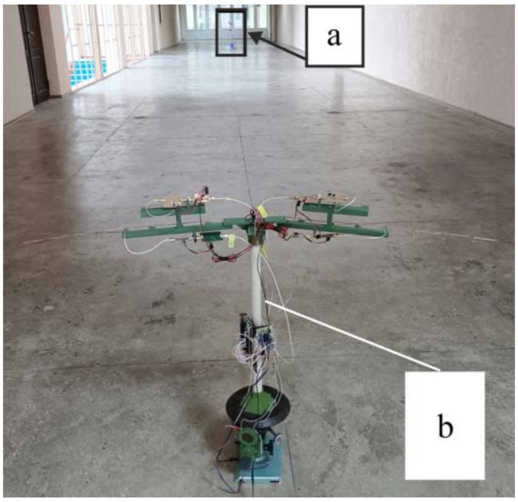

Fig. 10. Experimental radio beacon setup with the following components: a) is transmitter, b) is direction finder

Based on Fig. 11, it was determined that the width of the radiation pattern of the eight-element antennas is 17 degrees, and that of the four-element antennas is 37 degrees. The diagrams of all the antennas intersect at the level of 0.5 at an angle of -3 degrees. Shifting the intersection point from zero is not fundamental and will only result in a shift of the direction-finding characteristics to zero. In addition, in Fig. 11, we can see that the radiation patterns of different antennas are not symmetrical and have side lobes at the 0.5 level. This is due to inaccuracies in the manufacture and alignment of individual antenna elements; however, for the first tests, such deviations are acceptable.

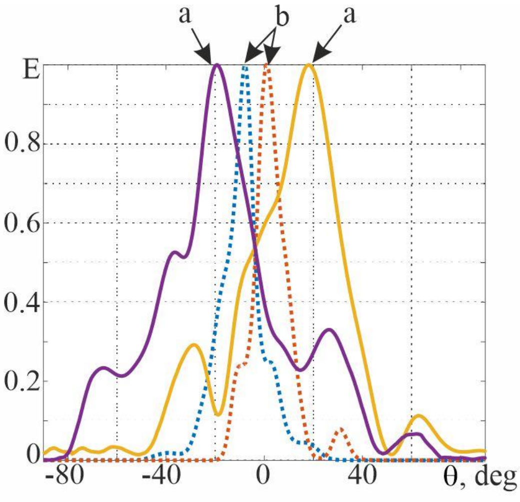

Fig. 11. Directional patterns of antennas with 4 (a) and 8 (b) elements

Next, the normalized discrimination characteristics were plotted separately for pairs of antennas with wide and narrow lobes. The resulting graphs are shown in Fig. 12.

The unambiguous measurement area for wide-beam antennas is 36 degrees, and for narrow-beam antennas it is 8 degrees. Antennas with four elements provide a steepness observational characteristic 0.05 units/degree, and antennas with eight elements provide 0.25 units/degree.

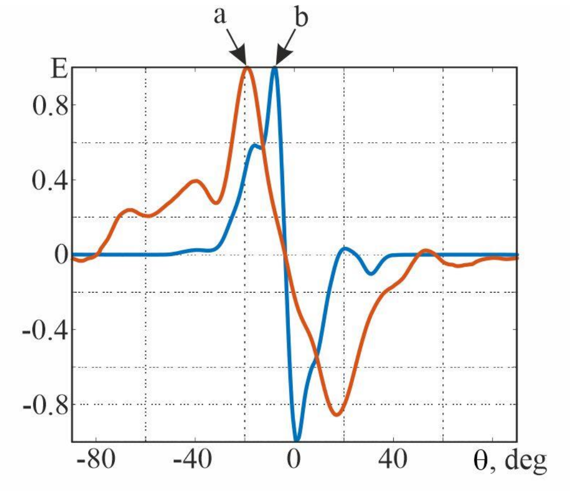

Fig. 12. Observational characteristics
for antennas with 4 (a) and 8 (b) elements

Next, the developed mathematical model (12) of the signal processing algorithm was implemented into the system, and by analogy with the simulation modeling, the observational characteristics of the four-antenna direction finder were constructed under the conditions of additional amplification of measurements in channels with wide beamforming diagrams in $A=1, 2, 4$ times. Gain factors were chosen experimentally. The resulting graphs are shown in Fig. 13.

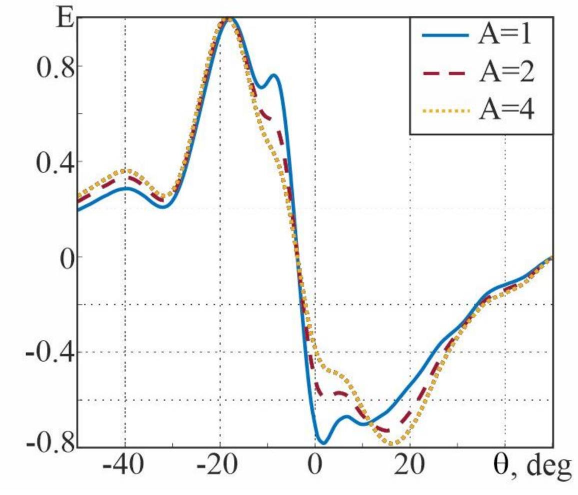

Fig. 13. Observational characteristics
for 4-antennas direction finder

Angle range with unambiguous measurements at $A=1, 2, 4$ amounts to 9, 18 and 33 degrees respectively. Within the equal-signal zone at $A=1$ steepness of direction-finding characteristics is achieved 0.17 units/degree, with $A=2$ – 0.14 units/degree, and when $A=4$ – 0.1 units/degree.

Discussion

The results of the simulation modeling of the mathematical model (12) confirmed its general performance and highlighted some features of its application. Thus, when measurements by two pairs of antennas are made with the same proportionality coefficients, the four-antenna system has no advantages over a two-antenna direction finder with a narrow radiation pattern. The steepness of the discrimination characteristic and the range of unambiguous measurements remained unchanged (0.24 units/degree with 7 degrees, respectively).

Expanding the range of angles with unambiguous measurements is achieved if the proportionality factor for measurements with wide-beam antennas is greater than that for narrowly directed antennas. The discrimination characteristics in Fig. 5 at provide unambiguous measurements in the range of angles of 37 degrees, which corresponds to the case of using wide-directional antennas. At the same time, in the region of the equal-signal zone, the steepness of the discrimination characteristic is 0.09 units/degree, which is almost twice as much as in the case of using only wide-directional antennas. That is, the four-antenna system can provide greater accuracy in determining the angular direction to the radio source with the same angular range of unambiguous measurements. The disadvantage of applying the developed algorithm based on the modeling results is the nonlinearity of the obtained discrimination characteristic and the need to find the proportionality coefficients by experimental means. However, these shortcomings can be considered in practice at the stage of direction finder calibration.

During the experimental studies, it was possible to develop antennas with radiation patterns close to those used in the simulation modeling. The experiment further confirmed the modeling results. The use of mathematical model (12) in a four-antenna direction finder allows obtaining a wide sector of unambiguous angle measurements and increasing the steepness of the discriminative characteristic, if measurements by wide-directional antennas are accounted for with an additional proportionality coefficient greater than one. Simultaneously, the integration of measurements of many antennas in practice is complicated by the possible asymmetry and high levels of the side lobes of the antenna patterns. For example, in Fig. 13(A=2), at an angle of 7 degrees, an additional extreme appears in the discrimination characteristic, which is absent in a symmetrical angle relative to the equal-signal zone (-13 degrees). In practice levelling of such effects requires careful calibration of the direction-finding system, the use of highly stable platforms [24], and accurate positioning of the device [25], etc. In addition, special algorithms for determining the detection threshold and digital filters can be used in secondary signal processing to reduce the impact of noise on measurements [26, 27]

Conclusions

When implementing amplitude direction finding systems, engineers always need to find a compromise between the range of angles at which a single-valued measurement of the direction to the radio source will be provided and the angular accuracy of determining this direction. This paper considers a possible solution to this problem, which consists of the complex measurement of two systems simultaneously. One of them has two antennas with wide radiation patterns, which provides unambiguous measurements over various angles. The other system uses two narrowly focused antennas. This ensures high direction-finding accuracy over a small range of angles.

To combine the measurements of the two systems using the maximum likelihood method, the mathematical model (12) of the optimal algorithm was developed. In accordance with the algorithm, it is necessary to summarize the measurement results from the output of each antenna, accounting for additional proportionality factors. Such processing allows simultaneous provision of a wide operating range of angles of the complex and increased accuracy of the location near the equal-signal zone.

The performance of the obtained algorithm was verified by simulation modeling and studying an experimental sample of a four-antenna direction finding complex, which showed similar results. Thus, several measurement angles and increased accuracy of measurements around the equilateral zone are achieved if measurements by antennas with wide radiation patterns are considered with greater weighting factors than measurements by narrowly directed antennas. In this case, both in simulation modeling and experimental studies, a range of unambiguous measurements was achieved that fully corresponds to the use of wide-directional antennas, and the slope of the direction-finding characteristic was twice as large as the original value for a wide-directional system. The disadvantages of using the algorithm include the nonlinearity of the obtained discrimination characteristic and the need to select proportionality coefficients for individual channels. However, these shortcomings can be resolved at the calibration stage of the final system.

Further work on this subject is being conducted in several directions. First, optimal methods for selecting proportionality coefficients for measurements of different channels are being developed. This will greatly simplify the system setup. We are also working on optimal algorithms for combining measurements made using amplitude and phase direction finders. Considering the high accuracy of phase direction finding in a narrow range of angles and the need to use compact non-directional antennas, the amplitude-phase direction finding complex will have reduced dimensions. This is achieved by rejecting highly directional antennas, which usually have significant geometric dimensions.

Contribution of authors: conceptualization – **Eduard Tserne**, **Oleksandr Pidlisnyi**; methodology – **Anatoliy Popov, Oleksandr Pidlisnyi**; simulation – **Danyil Kovalchuk, Anatoliy Popov**; validation – **Eduard Tserne,**; experimental research – **Eduard Tserne, Danyil Kovalchuk, Anatoliy Popov, Oleksandr Sereda**; formal analysis – **Anatoliy Popov**; investigation – **Danyil Kovalchuk**; resources – **Oleksandr Sereda**; data curation – **Danyil Kovalchuk**; writing original draft – **Eduard Tserne**; writing-review and editing – **Oleksandr Pidlisnyi, Danyil Kovalchuk**, **Oleksandr Sereda**; supervision – **Eduard Tserne**; project administration – **Anatoliy Popov**; funding acquisition – **Anatoliy Popov**.

All authors have read and agreed to the published version of this manuscript.

Acknowledgement. This work was funded by the Ministry of Education and Science of Ukraine. The state registration number of the project «*Development of an on-board radar complex for high-precision direction finding of enemy EW stations and autonomous guidance of kamikaze winged UAVs on them*» is No. 0123U101074.

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Received 01.09.2023, Accepted 20.11.2023

ЧОТИРЬОХАНТЕННИЙ АМПЛІТУДНИЙ ПЕЛЕНГАТОР: СТАТИСТИЧНИЙ СИНТЕЗ ТА ЕКСПЕРИМЕНТАЛЬНЕ ДОСЛІДЖЕННЯ АЛГОРИТМУ ОБРОБКИ СИГНАЛІВ

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Предметом дослідження є алгоритми вимірювання кутових положень джерел радіовипромінювання. **Метою** роботи є розробка удосконаленого алгоритму оброблення сигналів у амплітудних пеленгаторах, який забезпечить широкий діапазон кутів однозначних вимірювань при високій крутизні дискримінаційної характеристики шляхом комплексування вимірювань систем з різними ширинами діаграм спрямованості антен. **Завдання:** розробити оптимальний алгоритм оброблення сигналів у чотирьохантенній амплітудній пеленгаційній системі, дві антени якої мають широку діаграму спрямованості, інші дві – вузьку; перевірити загальну працездатність отриманого алгоритму шляхом імітаційного моделювання чотирьохантенної пеленгаційної системи; розробити та провести дослідження експериментального зразка чотирьохантенного пеленгатора, який у своєму складі має дві антени з широкими діаграмами спрямованості, дві антени з вузькими діаграмами спрямованості, радіочастотні тракти та блок обробки сигналів, що реалізує розроблений алгоритм; проаналізувати ефективність та особливості застосування розробленого алгоритму, порівняти результати імітаційного моделювання та експериментального дослідження. Використовуваними **методами** є: методи математичної статистики та оптимальних рішень при вирішенні задач статистичного синтезу алгоритмів обробки сигналів у пасивних радіосистемах; методи комп’ютерного імітаційного моделювання; методи проведення експериментальних досліджень. Отримано наступні **результати.** Методом максимальної правдоподібності синтезовано алгоритм обробки сигналів у чотирьохантенній пеленгаційній системі. Шляхом імітаційного моделювання підтверджено загальну ефективність комплексування вимірювань у багатоантенних амплітудних пеленгаторах та виявлено особливості застосування синтезованого алгоритму, а саме – необхідність впровадження додаткових коефіцієнтів пропорційності у вимірювальні канали. Під час експериментальних досліджень розробленого макету пеленгатора додатково підтверджено результати імітаційного моделювання. **Висновки.** Для визначення напрямку на джерела радіовипромінювання амплітудними пеленгаторами доцільно одночасно залучати системи з широкими та вузькими діаграмами спрямованості антен, вимірювання яких комплексуються запропонованим алгоритмом. Це дозволяє одночасно і розширити діапазон кутів однозначних вимірювань, і підвищити точність вимірювань в межах рівносигнальної зони. Недоліком застосування алгоритму є нелінійна форма отриманих дискримінаційних характеристик та необхідність визначення додаткових коефіцієнтів пропорційності евристичним шляхом.

Ключові слова: радіопеленгатор; дискримінаційна характеристика; вимірювання потужності; оптимальна обробка сигналів; експериментальне дослідження.

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