Applied Science and Innovative Research
ISSN 2474-4972 (Print) ISSN 2474-4980 (Online)
Vol. 8, No. 1, 2024
www.scholink.org/ojs/index.php/asir

Original Paper

Underground Radio Communications and Radio Observation

Boris Levin[1]

[1] Holon Institute of Technology, Holon, Israel

Levinpaker@gmail.com

Received: February 8, 2024 Accepted: February 21, 2024 Online Published: February 27, 2024

doi:10.22158/asir.v8n1p142 URL: http://doi.org/10.22158/asir.v8n1p142

Abstract

The problems of underground radio communications and radio observation are considered. The need for radio communication with people working underground is especially obvious during underground accidents. Radio observation makes it possible to monitor underground channels to detect their changes, caused, for example, by underground tunnel construction work in the border zone. Solving these problems is complicated by the sharp weakening of the signal in the ground and the presence of an interfering parallel signal propagating above the ground. Options for antennas to solve the described problems and methods for dealing with interfering signals are proposed. Receiving and transmitting centers for placing antennas are described.

Keywords

Terms – Antenna theory, Directivity, Current distribution

1. Introduction

Reliable underground radio communications are necessary for many applications, such as communication between people working underground and above ground (Wait, 1981). The need for such communication is especially obvious in case of accidents underground, for example, in mines.

In addition to the need for communication between the underground area and the surface of the earth, a channel between two underground points is often also required. This channel is more complex and its difficulties are increased by the fact that the signal radiated by the underground source is subject to severe attenuation. In addition, it passes in two ways (Doluchanov, 1970). The first path goes in a vertical direction to the earth's surface above the transmitting antenna. After this, the signal propagates in the air along the ground and then vertically down through the earth's layers to the receiving antenna. The second path is horizontal, meaning the signal travels through the ground in a horizontal direction.

As a rule, the signal passing through the first path is larger. On the other hand, the signal passing through the second path can be used to monitor the underground channel and detect changes in it. In this case, the second signal must be significantly larger than the first signal. Or it is need to be able to isolate the second signal from a mixture of signals.

Published works show that currently it is possible to provide underground communication at about 10 km using a transmitter with a power 100-200 W, operating at frequencies of 150-200 kHz (Yazishin, 2011). But to increase the range and to raise the reliability of underground radio communications, antennas with reasonable dimensions and a high directivity coefficient are needed. Director antennas with V-radiators should be considered as this type of antenna. These antennas provide high directivity of the transmitted signal, i.e. have properties useful in environments with high attenuation of signals, including the ground.

The task of creating antennas with the required electrical characteristics is an inverse problem of antenna theory, or a synthesis problem. A special case of this problem is the creation of a wide-range radiator, i.e., the creation of an antenna that provides, over a wide frequency range, a high level of matching with a transmitter or cable and maximum radiation in a plane perpendicular to the antenna axis. A promising method for solving this problem is the use of concentrated loads. By including concentrated loads along the length of the radiator, it is possible to ensure a current distribution other than sinusoidal. In accordance with Hallen's hypothesis (Hallen, 1938), to create a wide-range antenna, loads in the form of concentrated capacitances decreasing towards the free ends of the radiator should be used. An analysis of the characteristics of a linear radiator with loads uniformly placed along its axis is performed by comparing it with a stepped long line, in each section of which the surface impedance is a constant value (Levin, 1998).

The described analysis method has of an approximate nature, but at the same time it allows to obtain analytical expressions for loads magnitudes that provide different laws of current's distribution along the radiator. The magnitudes obtained with its help can be used to solve the antenna optimization problem by the mathematical programming method. In this case, the solution is the result of an iterative process. This task ensures a strict synthesis of an antenna with specified characteristics, or more precisely, with characteristics as close as possible to the specified ones. When solving this problem, the values calculated by the impedance long line method described above are taken as the initial values of the capacitances. The calculation results show that these values speed up the computational process, and most importantly, reduces the probability of error, since with an arbitrary choice of initial antenna sizes and capacitive loads magnitudes, the optimization process can lead to local and not to the true extremum of the objective function.

It is advisable to use a similar approach when solving other synthesis problems. Such tasks include the synthesis of a director antenna. Variants of solving this problem allowed us to obtain many useful results. But generalizing these results to more general structures face problems caused by the lack of approximate physical methods, the results of which can be used as a zero approximation. An approximate method that allows one to obtain such a result for use in the synthesis of director antennas is proposed in Section 2. The synthesis procedure is described in Section 3. Section 4 discusses antenna options that can be used for underground radio communications.

2. Method of Electrostatic Analogy

An increase in the number of linear elements in an antenna complicates the task of its analysis and synthesis. For example, director-type, log-periodic and self-complementary antennas have the complex structures. Solving the problems associated with these antennas requires new approaches and new mathematical methods.

As is known, when solving mathematical problems, a similar form of equations often provides significant assistance. For example, Maxwell's first two equations, which became the basis of the classical theory of electromagnetism, made it possible to substantiate the principles of similarity and duality. In accordance with the principle of duality, by replacing variables and conditionally introducing a magnetic current, it is possible to obtain expressions for currents, fields, and characteristics of a magnetic radiator, like to expressions for an electric radiator.

Generalizing the principle of conformity, it is advisable to compare the electromagnetic fields created by high-frequency currents of linear radiators with the electrostatic fields of charges placed on linear conductors. Charges and currents are evenly distributed along each conductor. Both fields are directly proportional to the magnitude of the current or the magnitude of the charge, and in the far zone they are inversely proportional to the distance from the source.

In accordance with Maxwell's equation $div\varepsilon_0\vec{E} = \rho$, the electrostatic field $\vec{E}$ in free space is proportional to the magnitude of the stationary charge ρ. In accordance with another equation $j\omega\varepsilon_0\vec{E} = curl\vec{H} - \vec{j}$ the electromagnetic field $\vec{E}$ depends on the current $\vec{j}$ - the moving flow of charges. In the far field, the electromagnetic field created by the current is a plane wave, i.e. E and H have the same phase, and one can consider that electromagnetic field E is proportional to the magnitude of the current, and the structures of the electrostatic and electromagnetic fields are the same.

The method of electrostatic analogy is based on the similarity of two structures consisting of high-frequency currents and constant charges. It is assumed that the shape and dimensions of the radiators are the same as the shape and dimensions of the conductors. In the case of several radiators, the ratio of the emf at their centers is equal to the ratio of the charges placed on the conductors. A positive charge equal to Q_0, is located on conductor 0, corresponding to the active radiator. Negative charges (their number is N) are located on conductors i, corresponding to passive radiators. They are equal to $-Q_i$, and the sum of their magnitudes is equal to the magnitudeOнof the positive charge: $\sum_{i=1}^{N}(-Q_i) = -Q_0$. The total sum of all charges is zero, i.e., the conductors form an electrically neutral system in which $Q_i/Q_0 = C_{0i}/\sum_{(i)} C_{0i}$, where C_{0i} is the partial capacitance between conductors 0 and i. Thus, the charges of conductors i are directly proportional to the partial capacitances C_{0i} between these conductors and conductor 0 (see, for example, Iossel, Kochanov, & Strunsky, 1981). An equivalent replacement of the complex design of high-frequency radiators with a design of constant charges placed on conductors dramatically simplifies the problem, reducing it to an electrostatic problem. In accordance with the above, it is natural to call the proposed method "the method of electrostatic analogy."

The described method was proposed in 2017 (Levin, 2017). It allows us to consider the problem in a general form, for example, compare different options for current distribution along the radiators and select the best one. This method corresponds to the physical essence of the problem, i.e., its accuracy is the same for different currents' distributions. Let us consider the order of its application using the Yagi-Uda antenna as an example. The results of its optimization are presented in one of the first and most in-depth works devoted to the optimization of a director-type antenna (Chaplin, Buchazky, & Mihailov, 1983). It should be noted that the first works on optimizing antenna characteristics were devoted to director-type antennas.

The structure of the Yagi-Uda antenna is shown in Figure 1. The antenna consists of four metal radiators (an active radiator, a reflector and two directors), the dimensions are indicated in meters. They were determined by solving the optimization problem in a rigorous formulation. We will start with the capacitance between the wires. If their radii a_0 and a_i are the same and equal to a = 0.001 m, and the lengths l_0 and l_i differ slightly from each other, then the partial capacity C_{0i} in a first approximation is equal to $C_{0i} = \pi\varepsilon_0 l_i/ln(b_i/a)$, where ε_0 is the dielectric constant of the medium, and b_i is the distance between the wires.

Let us divide wire 0 of the antenna into three wires, designate these wires as 0i, and break the antenna circuit into three circuits. Each circuit consists of two conductors: wire i and wire 0i (Figure 2). We will also divide the generator into three generators located in the centers of wires 0i. The values of their emf are determined as

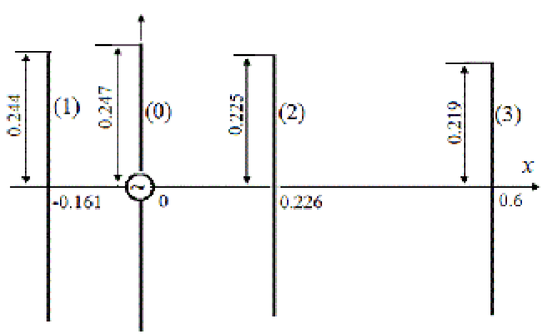

Figure 1. Dimensions of the Optimized Directional Antenna

$e_i = e\, Q_i/Q_0$, (1)

where e is the emf of the active radiator 0. As shown in the theory of folded antennas, a structure of two parallel vertical wires located at a distance b_i from each other can be divided into a dipole and a long line open at the ends.

The current at the center of each dipole is equal to

$J_{id} = e_i/(4Z_{id})$.

The reactive component of its input impe*d*ance is

$$X_{id} = -120\, ln(2L_0/a_{ei})\, cot\, kL_0,$$

where $L_0 = l_0/2$ is the length of the arm, $a_{ei} = \sqrt{ab_i}$ is equivalent radius, *k is* propagation constant. The current in the center of each wire of a long line is equal to

$$J_{il} = e_i/(2jX_{il}),$$

the input reactance of a line with length $L_i = l_i/2$ is equal to

$$X_{il} = -j120\, ln(b_i/a)\, cot\, k\, L_i.$$

The currents of the active and passive radiators are equal to the sum and difference of the currents J_{id} and J_{il}, the total current J_0 of the active radiator and the total current J_i of each passive radiator are equal to

$$J_0 = \sum_{i=1}^{3}(J_{id} + J_{il}),\ J_i = J_{id}.$$

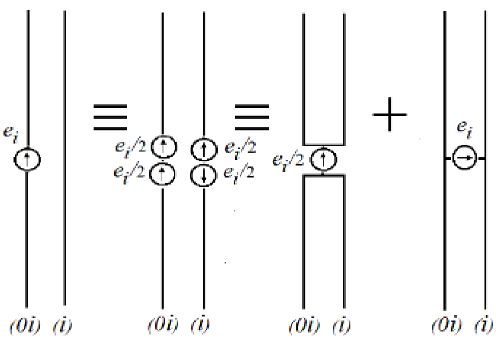

Figure 2. The Chart of Each Circuit

The amplitudes and phases of the fields created by each radiator depend on the law of current distribution along it and are determined by its structure. If the radiator arm is a straight metal conductor, then its current is distributed according to a sinusoidal law

$J(z) = J(0)\, sin\, k\, (L - |z|).$

In this case, the far field of the radiator

$E_\theta = \frac{AJ(0)}{Sin\theta} \cdot \frac{exp(-jkR)}{R} [cos(kL\, cos\, \theta) - cos\, k\, L].$ (2)

As seen from Figure 1, the maximum radiation of this antenna is directed to the right, that is, towards the radiator 3. Since the radiator 1 is located to the left of the active radiator 0 at a distance b_1 from it, its field lags behind the field of the active radiator, firstly, by a phase corresponding to the time signal propagation from radiator 0 to radiator 1, and, secondly, to a phase corresponding to the time of signal propagation in the opposite direction - from radiator 1 to radiator 0 (the signal must arrive at radiator 0 at an angle θ, i.e. length paths between wires is equal to $b_1/\, sin\, \theta.$ The total phase difference is

$$\psi_1 = -kb_1\, (1 + sin\, \theta)/sin\, \theta.$$

Similarly, in the case of radiators 2 and 3, this phase difference is equal to $\psi_2 = kb_2\, (sin\, \theta - 1)/sin\, \theta$

Published by SCHOLINK INC.

and accordingly, $\psi_3 = -kb_3\,(sin\,\theta - 1)/sin\,\theta$.

The described procedure allows us to determine the full field of the director antenna shown in Figure 2. In accordance with (1) the EMF of different radiators is equal to $e_1 = 0.388e$, $e_2 = 0.335e$, $e_3 = 0.277e$. The full field of this antenna with radiators in the form of straight metal wires

$$E = \frac{AJ(0)}{\sin\theta}\sum_{i=1}^{3} e_i \frac{exp(-jkR)}{R}\left\{\left(\frac{1}{4Z_{id}} + \frac{1}{2Z_{il}}\right)[\cos(kL_0\cos\theta) - \cos k\,L_0]\left(\frac{1}{4Z_{id}} - \frac{1}{2Z_{il}}\right)exp(j\psi_i)[\cos(kL_i\cos\theta) - \cos kL_i]\right\}. \quad (3)$$

The inclusion of concentrated capacitive loads along linear radiators, the values of which vary according to a linear or exponential law, makes it possible to create radiators with in-phase current. Keeping the dimensions of the radiators and the distances between them, we obtain a director-type antenna shown in Figure 3. The total field of such an antenna with a current distributed according to a linear law is determined by the formula

$$E = \frac{AJ(0)}{\sin\theta}\sum_{i=1}^{3} e_i \frac{exp(-jkR)}{R}\left\{\left(\frac{1}{4Z_{id}} + \frac{1}{2Z_{il}}\right)[1 - \cos(kL_0\cos\theta)]\left(\frac{1}{4Z_{id}} - \frac{1}{2Z_{il}}\right)[1 - \cos(kL_i\cos\theta)]\right\}. \quad (4)$$

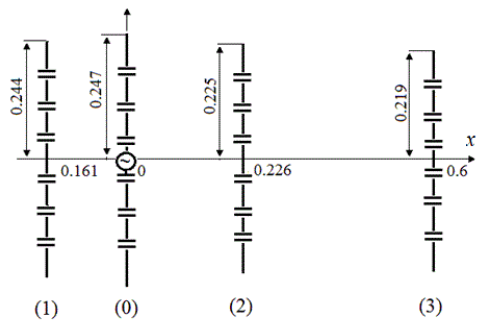

Figure 3. Director Antenna with Direct in-phase Radiators

The results of calculating the directivity and pattern factor of a director antenna with straight metal wires are shown in Figure 4 (curves 1). These results are not identical to the results presented in (Chaplin, Buchazky, & Mihailov, 1983), since an approximate calculation procedure was used here, but the results are similar. The main operating frequencies of both antennas are almost the same. The results of calculating similar characteristics for an antenna with in-phase currents are presented in Figure 4 by curves 2. They speak for themselves. An antenna with in-phase currents operates in a wide range of frequencies, and its directivity increases steadily and smoothly with increasing frequency, that is, the quality factor of such an antenna is low. Of course, one must be borne in mind that these characteristics are only valid if the current is in-phase. At the same time, antennas with capacitive loads simultaneously provide a high level of matching and a frequency overlap coefficient of the order of 10 (at a high level of matching).

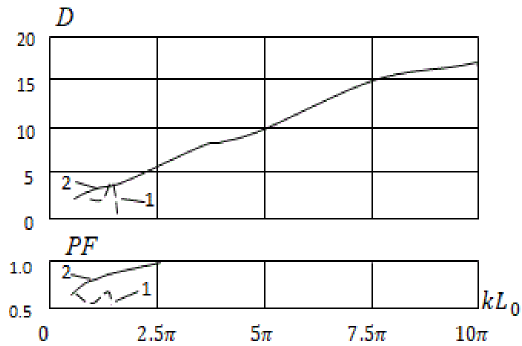

Figure 4. Directional Characteristics of Director-type Antennas with Sinusoidal (1) and in-phase (2) Currents

The results show that the electromagnetic fields created by high-frequency currents of linear radiators are similar in shape to the electrostatic fields of charges placed on the linear conductors of an electrically neutral system, and thereby confirm the similarity of the mathematical structures of both fields. This allows us to propose a simple and effective procedure for calculating the directivity characteristics of director-type antennas consisting of linear radiators, based on information about the main dimensions of the antenna and currents along the radiators. Detailed information about the types and magnitudes of concentrated loads is not required. As calculations show, such antennas, consisting of linear radiators with in-phase currents, provide high directivity and a smooth change in characteristics over a wide frequency range.

The results obtained can be used as a zero approximation when solving the problem of optimizing characteristics using mathematical programming methods. As already mentioned, this allows us to avoid errors due to which the optimization process leads to a local extremum of the objective function.

Calculations also show that the application of radiators with in-phase currents in director-type antennas allows to use these antennas in a wide frequency range. This means that with help of the electrostatic analogy method one may approximately determine the electrical characteristics of directional antennas consisting of other types of radiators, with subsequent optimization of such antennas. At that it is possible to build a directional antenna from V-radiators (Figure 5), for example, from the radiators with capacitive loads.

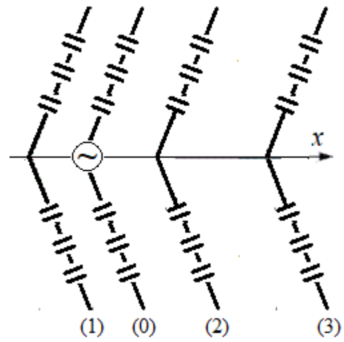

Figure 5. Director-type Antenna from V- radiators with in-phase Currents

Such antennas, compared to antennas made from direct radiators, can significantly increase directivity, if to increase the angle θ_0 between the antenna arm and the vertical. If the angles θ_0 between the arms of the radiators and the vertical in such an antenna are the same, then the total field of the antenna is equal to

$$E = \frac{AJ(0)}{\sin\theta}\sum_{i=1}^{3} e_i \frac{exp(-jkR)}{R}\left\{\left(\frac{1}{4Z_{id}}+\frac{1}{2Z_{il}}\right)[1-cos(kL_0\, cos\langle\theta-\theta_0\rangle)]\left(\frac{1}{4Z_{id}}-\frac{1}{2Z_{il}}\right)exp(j\psi_i)[1-cos(kL_0\, cos\langle\theta-\theta_0\rangle)]\right\}. \quad (5)$$

The directivity characteristics of directional antennas with V-radiators are shown in Figure 6.

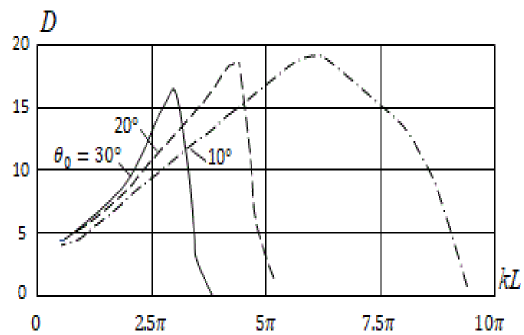

Figure 6. Directivity of a Director Antenna Made of V-radiators with in-phase Current Distribution

3. Method of Mathematical Programming

As stated in the Introduction, the mathematical programming method ensures the synthesis of antennas with characteristics as close as possible to the specified ones. The reservation about maximum proximity is explained by the fact that the range of changes in antenna parameters is limited, different characteristics are optimal for different parameter values, and at different frequencies these values should be different. Therefore, the parameters are the result of a compromise that is achieved by the method used.

The problem of mathematical programming in the general case is formulated as a search for a vector of parameters $\vec{x}$, that minimizes the objective function $\Phi(\vec{x})$ under the imposed restrictions. Since in this case the type of function is unknown, the problem is solved using nonlinear programming. The objective function (or general functional) is the sum of partial functionals $\Phi(\vec{x})$ with weighting coefficients p_j and penalty functions $\Phi_{iш}$:

$$\Phi(\vec{x}) = \sum_j p_j \, \Phi_j(\vec{x}) + \sum_i \Phi_{iш} \, . \qquad (6)$$

Partial functional is an error function for one of the characteristics. The weighting function considers the importance of the characteristic and the sensitivity of the vector $\vec{x}$ to its change. The penalty function is zero if the parameters lie in a required interval, and is large when leaving it.

For the directional antenna, the adjustable parameters are the dimensions of the dipole arms (lengths and radii), the distances between dipoles and the angles of inclination, as well as the characteristic impedance of the cable and the magnitude of the loads if they are used. The most important characteristics to be optimized are the directivity (DC) and the pattern factor (PF), as well as the level of matching with the cable and efficiency when using resistors. As an error function (partial functional), the quasi-Chebyshev criterion $\Phi_j(\vec{x})$ gives good results:

$$\Phi_j(\vec{x}) = \frac{1}{N_f}\left[\frac{f_{jo}}{f_{jmin}(\vec{x})} - 1\right]\left\{\sum\nolimits_{n_f}\left[\frac{\frac{f_{jo}}{f_j(\vec{x})}-1}{\frac{f_{jo}}{f_{jmin}(\vec{x})}-1}\right]^S\right\}^{1/S} . \qquad (7)$$

Here N_f is the number of points of the independent argument (for example, the number of directions in a required sector or the number of frequencies in a required range), n_f is the number of direction (frequency), $f_j(\vec{x})$ is one of the electrical characteristics of the antenna (for example, directivity), $f_{jmin}(\vec{x})$ is its minimum value in a given interval, f_{jo} is its value to strive for, S is an exponent of a power that regulates the method's sensitivity.

The minimum of the objective function is determined by a numerical method based on gradient search [9]. The gradient method (steepest descent method) is an iterative procedure in which one moves step by step from one set of parameters to another in the direction of maximizing the reduction of the function:

$$\vec{x}_{m+1} = \overrightarrow{\mathrm{x_m}} - \alpha^m \mathrm{grad}\Phi(\vec{\mathrm{x}}_{\mathrm{m}}). \qquad (8)$$

Here *m* is the iteration number, α^m is the scale factor, which is determined as a result of a linear search for the minimum of the functional in the direction of the antigradient. The calculation ends when the decrease in the objective function from iteration to iteration becomes less than the specified value or the number of iterations exceeds a certain value.

The described method involves repeated calculations of the electrical characteristics of the antenna for various initial parameters in accordance with the method of moments. To speed up calculations, it is advisable to fix the division of the antenna structure into short dipoles so that their own and mutual resistances do not change.

4. Using Directional Antennas for Underground Communications and Observation

Directional antennas provide high directivity of the transmitted signal, i.e. have properties useful in environments with high attenuation of electromagnetic signals, including through the earth. Reliable underground radio communications are necessary for many applications, for example, as already mentioned, for communication between people working underground and above ground (Wait, 1981). The channel between two underground points is more complex, highly attenuated, and takes two paths. As a rule, the signal traveling the first path (along the earth's surface) is larger. On the other hand, the signal passing through the second path can be used to monitor the underground channel and detect changes in it. In this case, the second signal must be significantly larger than the first signal. Or you need to be able to isolate the second signal from a mixture of signals.

When operating at high frequencies, losses in the ground increase sharply; when using low frequencies, large radiating structures are needed. These contradictory properties require a compromise solution to be found. One must also be considered that the horizontal component of a signal propagating in the ground attenuates more slowly than the vertical component. Since the efficiency of a radiator located close to the ground is low, it is advisable to create a large air cavity around the transmitting antenna. It should also be noted that the presence of a metal sheet under the transmitting antenna increases the first signal and interferes with communication and observation. To reduce the first signal, you can use a metal sheet, placing it above the transmitting antenna, for example, on the ground surface. To weaken the interfering signal, one can install an auxiliary antenna on the surface of the earth near the transmitter, radiating an additional signal in antiphase. In contrast to the short and rectangular main (underground) signal, the additional signal must be long and slowly decrease to compensate for the interfering signal at the right time and ensure the reception of the main signal.

The rigorous approach used in [10] made it possible to compare the results of using sinusoidal and cosine distributions of linear current in the radiator and showed that the use of cosine distributions is inappropriate.

As follows from the above, to increase the range and the reliability of underground radio communications, antennas of reasonable dimensions with a high directivity are needed. Director-type antennas with V-radiators should be considered as this type of antenna. The use of capacitive loads will ensure the required operating range.

The results of the work on creating an underground communication system confirm the possibility of creating a monitoring system for underground communication channels to detect their changes, which may be caused, for example, by the construction of underground tunnels in the border zone. Considering the sharp attenuation of the underground signal, the controlled zone should be divided into sections about ten kilometers long, on the boundaries of which receiving and transmitting centers should be located. The transmitter of the observation system, like the transmitters of the underground radio communication system, must create a signal of sufficient magnitude. A receiver located in a nearby center must ensure that changes in the received signal are recorded. A reasonable choice of the section length allows to make the solution of the problem real.

Compliance with the requirements for signal frequency, transmitter power, transmitting antenna, and structure of the transmitting center should ensure that the neighboring center receives a high-quality and intelligible signal. The difference in operating frequencies in different sections of the control zone should ensure simultaneous observation in all sections. A significant excess of the signal level over the required minimum guarantees the receipt of high-quality and reliable information.

References

Chaplin, A. F., Buchazky, M. D., & Mihailov, M. Yu. (1983). Optimization of director-type antennas. *Radiotechnics*, *7*, 79-82 (in Russian).

Doluchanov, M. P. (1970). Underground wave propagation, *Radio*, *1*, 42-43 (in Russian).

Hallen, E. (1938). Theoretical investigations into the transmitting and receiving qualities of antennae, *Nova Acta Regiae Soc. Sci. Upsaliensis*, *IV*(2), 1-44.

Iossel, Yu. Ya., Kochanov, E. S., & Strunsky, M. G. (1981). *Calculation of Electrical Capacitance*. Leningrad: Energoisdat (in Russian).

Levin, B. M. (1998). *Monopole and Dipole Antennas for Marine-Vehicle Radio Communication*. Petersburg: Abris (in Russian).

Levin, B. M. (2017). Director antennas with in-phase currents, *Proc. of Conf. ICATT*, *17*, 110-113.

Wait, J. R. (1981). Wave Pergamon Theory. New York: Pergamon.

Yazishin, V. I. (2011). Underground Radio Communication in Mines (bibliographic index). Kharkov (in Russian).