INTL JOURNAL OF ELECTRONICS AND TELECOMMUNICATIONS, 2024, VOL. 70, NO. 3, PP. 699-705
Manuscript received October 29, 2024; revised July, 2024. doi: 10.24425/ijet.2024.149599

Application of focusing systems to the protection of information during data transmission in the zone of direct radio visibility

Yelizaveta Vitulyova, Kaisarali Kadyrzhan, Aruzhan Kadyrzhan*, and Ibragim Suleimenov

***Abstract*—It is shown that focusing systems built on the basis of a system of radio receivers spaced apart in space and simulating the operation of a lens can be used to ensure the protection of information during data transmission in the direct radio visibility zone. The synthesis of the lens equivalent in this case is carried out by using a system of phase shifters that change the phase of the oscillations arriving at each of the receivers, so that the receiving system is tuned to a radio wave source located at a specific point in space. In this case, information protection is provided according to the "friend or foe" principle, and any commands coming from other areas of space, except for the point where the authorized operator is located, are ignored. The advantage of this approach is the ability to partially or completely abandon the use of cryptographic methods. It is shown that the proposed approach is of considerable interest for ensuring the stable operation of groups of unmanned aerial vehicles from the point of view of the possibility of intercepting control using electronic warfare methods.**

***Keywords*—information security; unmanned aerial vehicle; electronic warfare; line of sight; focusing system**

I. Introduction

CURRENTLY, information security methods based on the use of physical processes of various natures are being developed [1]–[3]. They fundamentally differ from traditional cryptographic methods in that there is no artificially generated cipher, which makes unauthorized access to such communication lines very difficult.

With the development of unmanned vehicles, including military ones [4]–[6], information security methods based on physical (as opposed to cryptographic) principles are of particular importance.

Namely, as the experience of recent military conflicts shows, unmanned aerial vehicles are beginning to play an increasingly important role, including directly on the line of contact [7], which is especially pronounced during hostilities on the territory of Ukraine. The methods of electronic warfare (EW) are becoming increasingly important, aimed, among other things, at intercepting control of unmanned vehicles [8], [9]. At the same time, the use of unmanned aerial vehicles is often carried out at the level of grassroots units directly involved in the battles. With the massive use of unmanned vehicles, ensuring the protection of information using cryptographic methods is becoming increasingly difficult, including due to the human factor. It is becoming more and more difficult to resist, for example, the actions of enemy agents aimed at accessing information that allows the effective use of electronic warfare.

This makes it very relevant to develop information security tools based on new principles that make it possible to abandon cryptographic methods. In [10], a protection method was proposed based on the analogy between radio and optical signals. This method is based on determining the location of the source of radio waves. In this case, to protect information, it is enough to identify the source of radio waves as "our own", and ignore any other signals. In particular, for this purpose it is permissible to use an analog of a lens assembled from several radio receivers spaced apart in space [10]. We emphasize that the analogy between the processing of radio and optical signals is very deep, which is actively used in modern radio holography [11]–[13].

Such methods, among other things, are intended for diagnosing subsurface objects [14]. For such purposes, the creation of radioholographic lenses that provide focusing on a certain point in space is also of interest.

We emphasize that information security methods based on the identification of the position of the source of radio waves in space are intended for use in the zone of direct radio visibility. However, such systems, due to the above factors (in particular, the use of unmanned aerial vehicles in the immediate vicinity of the contact line) are also of considerable interest. Moreover, such systems are also of interest from the point of view of improving the tactics of using unmanned aerial vehicles. Namely, at present there is a steady trend towards the creation of groups of aircraft controlled by one operator [15], [16]. The next step in the implementation of this trend is the implementation of groups of unmanned vehicles associated with neural networks or artificial intelligence (AI) [17]. Note that the issue of developing AI for military purposes has been standing

This research has been funded by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan (Grant No. AP15473224).

First Author and Second Author are with Almaty University of Power Engineering and Telecommunications named after Gumarbek Daukeev (e-mail: aru.kadyrzhan@gmail.com).

Third Author and Fourth Author are with National Engineering Academy of the Republic of Kazakhstan.

for a long time, therefore, pairing AI with groups of aircraft that implement the “wasp swarm” tactics is indeed a completely logical step.

Such pairing obviously involves the exchange of information between the unmanned vehicles that make up the group. It is this exchange that makes it a systemic whole (using distributed telemetry methods, target identification, etc.). At the same time, the features of the group use of unmanned vehicles obviously involve the exchange of signals in the zone of direct radio visibility, which makes the development of methods for protecting information of the above type even more relevant.

We also emphasize that data transmission channels focused on commands transmitted to unmanned vehicles, and channels focused on collecting information (for example, for transmitting video images) can have different bandwidth. In fact, a limited number of commands are used to control unmanned vehicles, which, among other things, allows the use of fuzzy logic methods [18], [19]. Moreover, it is possible to represent the command language in algebraic form [20], which is closely related to multivalued logic.

This approach, in turn, is closely related to the problems of creating explainable neural networks [21], [22] and explainable artificial intelligence [23], [24], which are actively discussed in the current literature. As shown in [25], [26], it is possible to build explainable neural networks due to the analogy between the functioning of neural networks and noise-correcting coding methods, which corresponds to one of the basic trends in the development of artificial intelligence systems [27]. The above methods are also based on multi-valued logic, and there is every reason to believe [28] that artificial neural networks of this type can be implemented even with a relatively small bandwidth of communication channels between neurons. This makes it possible to focus on the development of information security systems, firstly, intended for use in the zone of direct radio visibility, and, secondly, ensuring the transmission of only relatively small amounts of data.

The aim of this work is to develop a radioholographic lens assembled on the basis of several discrete radio receivers, and providing information protection during data transmission in the line of sight, as well as to prove its performance using the simplest possible examples.

II. METHOD

A. Method for reducing real optical elements to holographic ones

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The method for synthesizing a radioholographic lens is based on the description of the operation of optical elements in terms of Fourier optics [29].

Specifically, in Fourier optics, any optical elements are replaced by their idealization, described by the complex-valued transmission function $T(x,y)$. This corresponds to replacing the real element with an infinitely thin element that performs the transformation described by the formula

$$u(x,y) = T(x,y)u_0(x,y) \quad (1)$$

where $u_0(x,y)$ is the field distribution in the "input" plane of a thin lens, $u(x,y)$ is the field distribution in the "output" plane.

Since the element is considered to be infinitely thin, the geometrically indicated planes coincide.

For optical elements such as a lens, the transmission function $T(x,y)$ is determined by the optical thickness function $D(x,y)$, which is determined from geometric considerations.

Specifically,

$$u(x,y) = \exp[ikD(x,y)]\, u_0(x,y) \quad (2)$$

where $k = \frac{2\pi}{\lambda} n$ – wave number.

The function $D(x,y)$ (Figure 1) is numerically equal to the thickness of an element made of a optically homogeneous material at a point with coordinates (x,y).

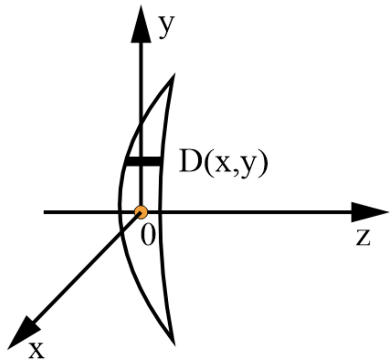

Fig.1. To the definition of the optical thickness function.

Most importantly, the methods used in Fourier optics make it possible to reduce an arbitrary optical element such as a lens to an element that performs a phase shift operation. The adequacy of this approach has been repeatedly confirmed in the literature. In particular, the Fresnel zone plate is an analogue of a lens [30]. This element is a direct analogue of a hologram, since the focusing provided by the Fresnel zone plate is provided by interference and diffraction effects. This is a reflection of the general approach used by Fourier optics. From formula (1) it follows that the real optical element is replaced by its idealization, which corresponds to a hologram that performs the same function.

Therefore, when implementing a virtual radio holographic lens, it is possible to provide only a phase shift transformation. We emphasize that, due to the analogy with the holographic representation of real optical elements, it is permissible to interpret the considered lens as a radio holographic one.

B. Method for reducing wave field converters to a discrete form

It was shown in [31] that it is possible to reduce the description of wave propagation to a discrete form. This possibility is due to the fact that in order to solve many problems of wave physics, it is permissible to neglect inhomogeneous (damped) waves. As a result, the distribution of the wave field on a certain plane is formed by radiation with a limited spectrum of spatial frequencies.

Indeed, in the general case, the distribution of the wave field on an arbitrary plane can be written as an integral

$$u(x,y) = \frac{k^2}{(2\pi)^2} \int_{\alpha,\beta} \exp(-ik[\alpha x + \beta y])\, A(\alpha,\beta) d\alpha d\beta \quad (3)$$

The adequacy of representation (3) follows from the fact that the function $u(x,y)$, which describes the distribution of the wave field in the scalar approximation, can be subjected to a Fourier transform. Formula (3) expresses only the existence of an inverse transformation.

It is essential that in the framework of Fourier optics, the function $A(\alpha,\beta)$ can be interpreted as a spectrum of spatial frequencies.

Indeed, the expression $\exp(-ik[\alpha x+\beta y])$ coincides with the field distribution created on the considered plane by a plane wave

$$f=\exp\left(ik\vec{\xi}\vec{r}\right) \quad (4)$$

где $\vec{\xi}^2=1, \vec{\xi}=(\alpha,\beta,\pm\gamma), \gamma=\sqrt{1-\alpha^2-\beta^2}$

Accordingly, expression (3) can be interpreted as a representation of the wave field as a superposition of plane monochromatic waves with weights $A(\alpha,\beta)$. Physically, this corresponds to the interpretation of this function as a spectrum of spatial frequencies.

Further, the quantity γ can take both real and imaginary values. The last case corresponds to inhomogeneous (damped waves). There are a number of problems [32], [33] in which such waves must be taken into account. However, provided that the waves propagate over a distance much greater than the wavelength, waves of this type can be neglected.

Therefore, in this case, the integration limits in formula (3) can be changed to finite ones. More precisely, these limits are determined by the inequality

$$\alpha^2+\beta^2<0 \quad (5)$$

Consequently, representation (3) allows us to use the same idea that underlies the derivation of the Nyquist-Shannon-Kotelnikov theorem, which finds application not only in the field of classical radio communication [34], [35].

Indeed, let us expand the region defined by inequality (3) to the square defined by the inequalities

$$-1\le\alpha,\beta\le1 \quad (6)$$

Let us define a periodic function $\tilde{A}(\alpha,\beta)$, which will coincide with $A(\alpha,\beta)$ within the region $\alpha^2+\beta^2<0$ and repeat periodically along both coordinate axes with a period of 2.

Such a function expands into a Fourier series

$$\tilde{A}(\alpha,\beta)=\sum_{m,n} U_{m,n}\exp(\pi i[m\alpha+n\beta]) \quad (7)$$

In this case, the distribution of the wave field $u(x,y)$ is expressed in terms of the function $\tilde{A}(\alpha,\beta)$ as

$$u(x,y)=\frac{k^2}{(2\pi)^2}\iint_{-\infty}^{\infty}\exp(-ik[\alpha x+\beta y])\,circ(\alpha,\beta)\tilde{A}(\alpha,\beta)d\alpha d\beta \quad (8)$$

where

$$circ(\alpha,\beta)=\begin{cases}1,\alpha^2+\beta^2<0\\0,\alpha^2+\beta^2\ge0\end{cases} \quad (9)$$

It follows from formula (7) that the distribution of the wave field $u(x,y)$ can be expressed without loss of accuracy in terms of a set of discrete values $U_{m,n}$

$$u(x,y)=\sum_{m,n} U_{m,n}S\left(x-\frac{\pi}{k}m,y-\frac{\pi}{k}n\right) \quad (10)$$

where

$$S(x,y)=\frac{1}{(2\pi)^2}\iint_{-\infty}^{\infty}\exp(-ik[\alpha x+\beta y])\,circ(\alpha,\beta)d\alpha d\beta \quad (11)$$

There is a certain difference from the situation reflected by the Nyquist-Shannon-Kotelnikov theorem: the values $U_{m,n}$ cannot be given the meaning of the solution values at certain points of the plane, since the zeros of the function

$$\hat{F}[circ(\alpha,\beta)]\sim\frac{1}{r}J_1(r) \quad (12)$$

where $J_1(r)$ is the Bessel function, and the polar coordinates $x=rcos\varphi;\ y=rsin\varphi$ are used; do not coincide with the points $x=\frac{\pi}{k}m, y=\frac{\pi}{k}n$.

However, this difference is not significant for the purposes of this work. The consequences of formula (9) make it possible to implement a holographic lens.

III. Results And Discussion

The reasoning leading to formula (9) is also applicable to the case when a specific element that transforms the wave field is considered. Namely, if both the input and output fields are exhaustively characterized by values corresponding to discrete points, then an arbitrary wave field converter can also be reduced to a discrete (tensor) transformation.

In particular, this means that it is possible to implement radio receiving systems built on the analogy with optics and providing radio wave conversion without loss of accuracy. We emphasize that for the optical range this approach is by no means always justified, but it becomes significant for the radio range due to the fact that the distance between discrete receivers in certain cases can be made comparable to the wavelength.

In particular, it is permissible to pass to the scheme of the radioholographic lens shown in Figure 2, and using a maternity set of receivers.

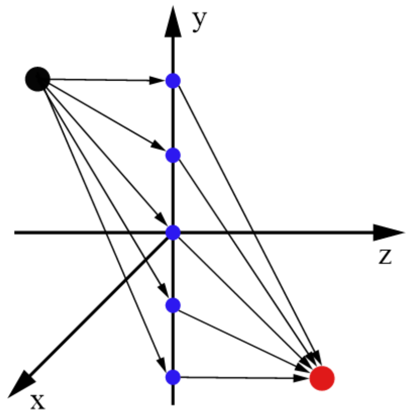

Fig.2. Illustration for the mechanism of operation of a virtual radioholographic lens.

Elements 1 in this scheme must perform an operation similar to that expressed by formula (1) in relation to thin optical elements. This operation for such elements as a lens provides only a phase shift. Therefore, elements 1 can be replaced by phase shifters, provided that harmonic signals are received at the input.

However, there is an important nuance. Harmonic signals by themselves cannot carry information, therefore, in order for the circuit in Figure 2, it was really possible to use classical-type phase shifters, you need to choose the appropriate signal shape that provides control of the unmanned vehicle. As emphasized in the introduction, it is for this kind of purpose that the proposed system is being developed. Among other things, this means that there are certain degrees of freedom in the choice of control signals.

In particular, it is permissible to use a phase-modulated signal $u(t)$ corresponding to binary logic (Figure 3), given by the expression

$$u_0(t) = U_0(t)\cos(\omega t) \tag{13}$$

where ω is the circular frequency, and the function $U_0(t)$ takes the values either +1 or -1 on each of the cycles.

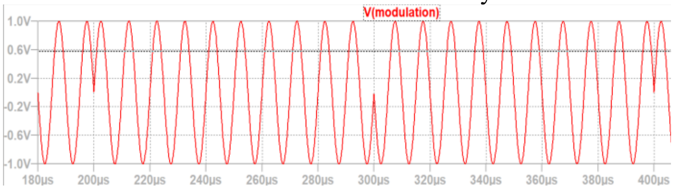

Fig.3. The type of phase-modulated signal used.

The function $U_0(t)$ provides the transmission of commands in binary logic, since its value on each of the cycles can be assigned either a logical zero or a logical one.

Let us consider how the possibilities of using typical schemes of phase shifters for processing signals of the form (12) in the implementation of the scheme of a radio holographic lens, Figure 2.

One of the typical phase shifter circuits is shown in Figure 4. The principle of its operation is based on the use of a high-pass filter, the transfer function of which has the form

$$Q(\omega) = \frac{jRC\omega}{1+jRC\omega} = \frac{j\tau_0\omega}{1+j\tau_0\omega} \tag{14}$$

The phase of the transfer function (13) is given by the expression

$$\Phi(\omega) = \pi - \arctan(RC\omega) \tag{15}$$

Therefore, by changing the filter time constant $\tau_0 = RC$ by changing the resistance value, it is possible to adjust the phase shift. In the circuit under consideration, the change in resistance is provided by a digital potentiometer, which is controlled by a microcontroller via the SPI interface. The digital potentiometer has 256 resistance steps. The operational amplifier in this circuit maintains a constant amplitude of the output signal.

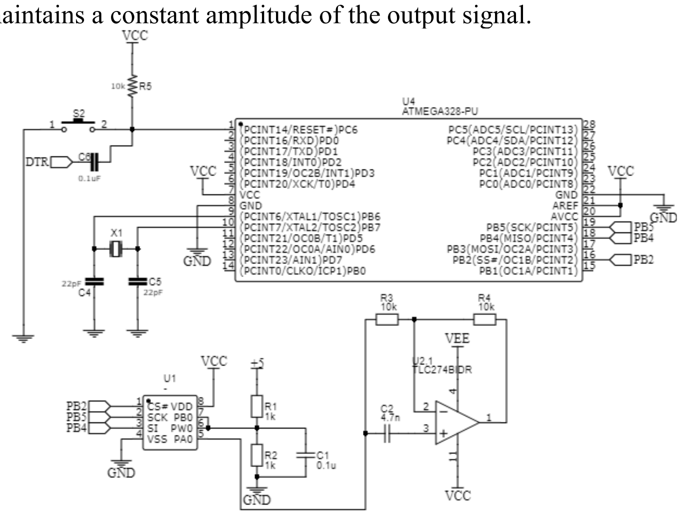

Fig.4. Schematic diagram of the phase shifter.

Transformation with a phase shift (14) is carried out when a strictly harmonic signal is supplied to the phase shifter. Let's consider what kind of transformation the high-pass filter performs with respect to the signal of the form (12). Specifically, we will show that it is possible to select such a duration of the cycles of the function $U_0(t)$ that the cycle can be divided into two parts with durations τ_1 and τ_2, respectively (Figure 5), and during the part of the cycle τ_2 the signal is close to harmonic, t .e. the phase shifter with respect to the signal on this part of the cycle behaves in the same way as in the ideal case. The graph presented in Figure 5 obtained using simulation tools. LTSpice software used.

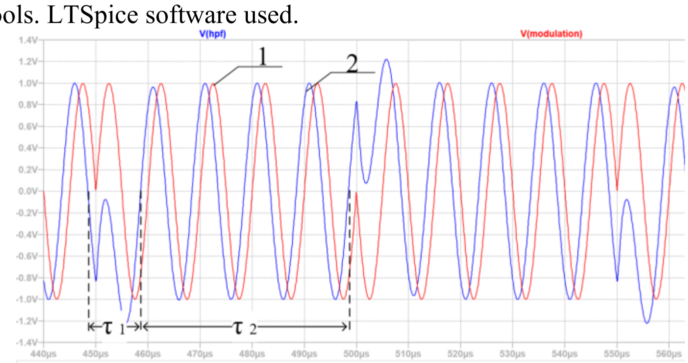

Fig.5. The signal taken from the output of the high-pass filter when a signal of the form (12) is applied to it: 1 - modulated signal at the input; 2 - output signal.

The features of the formation of such a signal follow from elementary considerations. Indeed, consider the equation for the voltage on the capacitor in the RC circuit, provided that an arbitrary signal $u(t)$ is applied to the input.

$$RC\frac{du_C}{dt} + u_C = u(t) \tag{16}$$

The general solution of this equation can be written in terms of the convolution integral of the signal $u(t)$ with the fundamental solution $G(t)$

$$u_C(t) = \int G(t-t_1)u(t_1)dt_1 \tag{17}$$

where the fundamental solution $G(t)$ is determined from the equation

$$\left(RC\frac{d}{dt} + 1\right)G = \delta(t) \tag{18}$$

This solution has the form

$$G(t) = \theta(t)\exp\left(-\frac{t}{RC}\right) \tag{19}$$

As expected, the duration of transients corresponding to the transition from one cycle of the function $U_0(t)$ to another is determined by the time constant of the RC circuit, i.e. we can put $\tau_1 = (3 \div 5)\tau$. This means that for the implementation of the radioholographic lens, Figure 2, you can use that part of the cycle τ_2 of the original signal, for which the phase shifter works in the same way as with respect to the harmonic signal.

We emphasize that this approach is feasible due to the fact that the bandwidth of the communication channel intended for transmitting commands to an unmanned vehicle can be made very low. The typical value of the number of commands is several tens, i.e. it is permissible to focus on the maximum bandwidth of several tens of bits / sec, which corresponds to the signal frequency $U_0(t)$, equal to several tens of Hz. At such a low modulation frequency, phase shifters of even the simplest types ensure the operation of a radioholographic lens even when using a carrier frequency of the order of tens/hundreds of kHz.

A block diagram of a radioholographic lens that implements this approach is shown in Figure 6.

The original signals arrive at receivers 1_n spaced apart in space. The signals from these receivers are fed to 2_n calibration amplifiers equipped with automatic gain control. Their purpose is to bring the amplitude of all received signals to the same value. Further, the signals arrive at the phase shifters 3_n, which ensure the functioning of the lens of the considered type in accordance with formula (2).

Circuit elements 4_n provide for the elimination of sections corresponding to transients that occur during clock modulation in phase. These elements multiply the signal taken from the output of the phase shifters by a rectangular signal equal to one in the main part of the cycle, and equal to zero in the transient region. Next, the signals are summed by the adder 5, which provides artificial focusing of the radio wave.

Tuning, including tuning to a certain position of the transmitter, is carried out using the microcontroller 6, which sets the value for the phase shift of each of the phase shifters 3_n. The control of the circuit elements is carried out using a rectangular pulse generator 7, which is also controlled from the microcontroller 6.

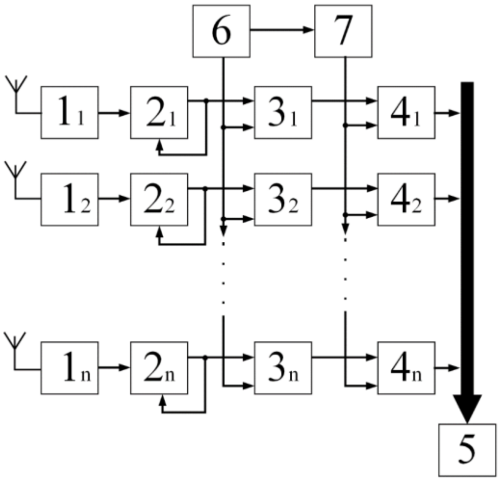

Fig.6. Block diagram of a radioholographic lens.

Proof of the efficiency of the proposed approach was carried out using simulation tools, using the LTSpice software. The corresponding circuit diagram is shown in Figure 7.

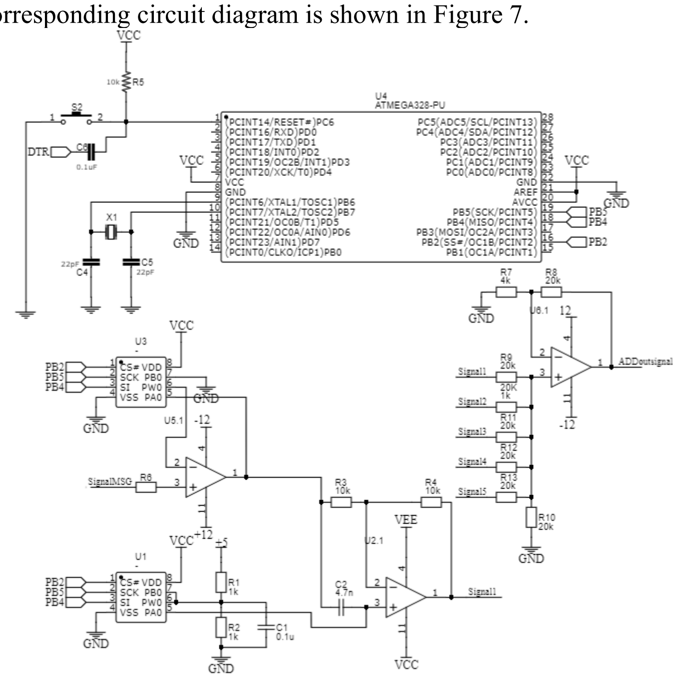

Fig.7. Schematic diagram of the main module of the radioholographic lens.

The electronic circuit is controlled by a microcontroller, which sets the gain of the input signal level calibration blocks using a digital potentiometer U3 controlled via the SPI interface. The angle of rotation of the phase shifter signal is also set by controlling the digital potentiometer U1. In addition, the circuit contains an adder powered by an operational amplifier U6.1 with a gain of 1.

With the help of this scheme, the graphs presented in Figure 8 and Figure 9, which show the total oscillation that is formed at the output of the circuit in Figure 8 for the next two cases. Figure 8 corresponds to the case when the focusing radio receiver system is tuned to the source of radio waves, the location of which is shown in Figure 10, and remote from it at a distance of 3,000 meters. For model calculations, the case corresponding to a carrier frequency of 100 kHz, which corresponds to a wavelength of 2997.92 m, was used. The radio-receiving focusing system contains 5 receivers (and, accordingly, 5 phase shifters) spaced 600 m apart and located on the same straight line.

In both cases, sections of the cycles are selected, on which the considered oscillation is close to harmonic.

Figure 9 corresponds to the case when the same radio holographic lens is tuned to the same source of radio waves, but it receives a signal from a remote source. This, in a first approximation, models an attempt to intercept control of an unmanned vehicle by means of electronic warfare.

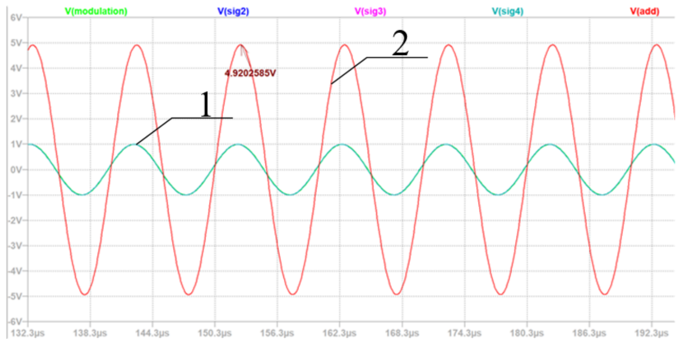

Fig.8. Oscillation at the output of a radioholographic lens when it is tuned to a point source of radio waves.

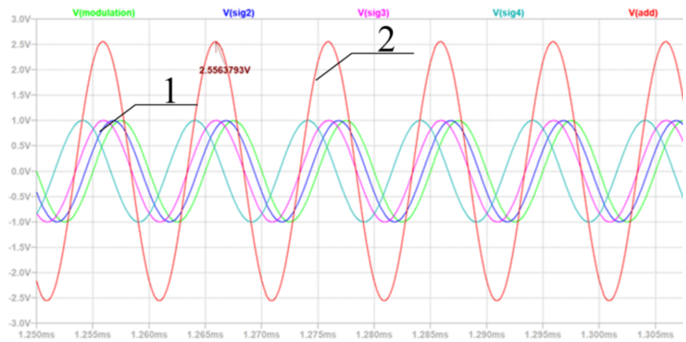

Fig.9. Oscillation at the output of a radioholographic lens when it is tuned to a point source of radio waves and when waves arrive at its input from a remote source.

Each of these figures shows oscillations (1) taken from the outputs of individual phase shifters (for the case of Figure 8, the curves coincide, so the lens adjustment provides a zero phase shift between them), as well as the resulting oscillation obtained as a result of their summation (2).

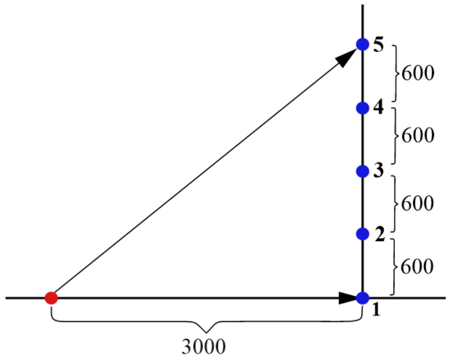

Fig.10. The layout of the receivers of the radio receiving focusing system relative to the authorized signal source.

It can be seen that the amplitude of the signal shown in Figure 8 significantly exceeds the amplitude of the signal shown in Figure 9. In the latter case, the oscillations coming with different phases cancel each other out, at least partially. More precisely, the ratio of the amplitude of the resulting oscillation to the calibrated amplitude of the summed signals in the case of Figure 8 is approximately twice as high as in Figure 9. This is enough to cut off the spurious signal by circuitry.

We emphasize that we deliberately considered a rather simple example, which also corresponds to a small number of unmanned vehicles in use. This example clearly shows that even in such a simple case, it is possible to separate the external signal from the control signal, i.e. ensure information protection only at the expense of hardware without the use of cryptographic methods.

Conclusion

Thus, for transmissions in the line-of-sight zone, it is possible to implement information protection that does not require the use of cryptographic methods. The protection of information in the area of direct radio visibility is becoming increasingly important, in particular, in connection with the increasing use of unmanned vehicles, including those designed to provide certain services to the population.

The proposed principle of information security is based on the obvious fact that both radio waves and light are electromagnetic oscillations that differ only in wavelength. The protection of information in the optical range can only be ensured by linking the signal source to a certain point or to a certain direction. In the case when the signals come from this particular point, they are interpreted as reliable.

Thus, even the extremely simple models considered in this paper show that there is a way to ensure the protection of information, based on the analogy between the problems of radiophysics and physical optics.

Specifically, information protection in this case is ensured by tuning the radio receiving system to a certain point in space, which is interpreted as a source of authorized commands. Signals coming from any other areas of space are ignored and treated as spurious.

Tuning to a specific point in space is provided due to the fact that the radio receiving system imitates the operation of an optical lens, the orientation of the optical axis of which and the focal length of which provides the above setting.

The proposed approach is designed to ensure the protection of information in the zone of direct radio visibility, which is becoming more and more relevant from the point of view of the use of unmanned aerial vehicles near the line of contact of the opposing sides. The approach is focused on the use of groups of unmanned vehicles, which is also in line with emerging trends.

The results of the work also show that in order to implement the proposed approach, it is convenient to use phase-modulated signals that remain harmonic for a sufficiently long cycle. This approach is acceptable, since the bandwidth of a radio channel focused on transmitting commands to a group of unmanned vehicles can be made quite low, down to characteristic frequencies of tens of Hz. This makes it possible to use the simplest phase shifter circuits that form the basis of a system that simulates an optical lens in the radio range.

The advantage of the proposed approach is the most complete exclusion of the human factor (gaining unauthorized access to control cryptographic codes, breaking codes, etc.). The features of the organization of command transmission in the future also make it possible to switch to the use of multi-valued logic, for which it is enough to switch to a phase-modulated signal corresponding to a discrete set of phase shifts by $\frac{\pi}{K}$, where K is the number of variables of multi-valued logic. In this case, it becomes possible to use the advantages of digital signal processing, reflected, in particular, in [36], [37].

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