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DEVELOPMENT OF A DIRECT PENETRATING SIGNAL COMPENSATOR IN A DISTRIBUTED RECEPTION CHANNEL OF A SURVEILLANCE RADAR

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General structure of a compensator of a direct penetrating signal in the diversed reception channel was developed. It is advisable to use the antenna and the receiver of the auxiliary diverted reception channel as an auxiliary antenna and an auxiliary channel. To be able to suppress the penetrating signal in the band of the receiving device of the surveillance radar, distance between the antennas should be up to 6 m. In general, the compensator of the penetrating signals should contain an adder in which the signals received by the main channel are added with the signals received by the auxiliary channel and sent through the amplifier with a corresponding complex transmission coefficient. The direct penetration signal compensator features the obligatory condition of adjusting the value of the complex transmission coefficient of the auxiliary channel signal amplifier.

The direct penetration signal compensator is digital and uses the direct method of forming weighting coefficients without the use of feedback. To reduce the time of formation of weighting coefficients when using direct methods of calculation of the correlation matrix, the technology of parallel computational processes was used.

The quality of operation of the direct penetrating signal suppression system in the diverted reception channel was evaluated. It was established that without the use of suppression of direct penetrating signals, their powerful response at the output of the matched filter mask weak echo signals. When using a direct penetrating signal in the main channel of the compensator, its response at the output of the matched filter is significantly reduced. This makes it possible to observe weak echoes against the background of a strong penetrating signal. The use of the developed direct penetrating signal compensator provides suppression of the direct penetrating signal from 57 dB to 70 dB

Keywords: air object, suppression, direct penetrating signal, external radiation source, radar

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1. Introduction

In today's conditions, surveillance radars use radiation of exterior sources (e. g. signals of cellular communication, space navigation, digital television of DVB-T2 standard, etc.) to detect hardly noticeable air objects (AO). Undoubtedly, the use of radiation from external sources improves the quality of detection of hardly noticeable AOs by surveillance radars.

When using radiation from external sources, a powerful penetrating signal occurs in the diverted reception channel of the surveillance radar. The influence of a powerful penetrating signal in this channel leads to a significant reduction in the quality of detection of hardly noticeable AOs. Therefore, when using radiation from external sources in the diverted reception channel of the surveillance radar, it is necessary to provide for the availability of a compensator for direct penetrating signals. The presence of a compensator for direct penetrating signals in the diverted reception channel of the surveillance radar will allow the detection of weak echo signals against the background of powerful penetrating signals.

Therefore, the development of a system for suppressing penetrating signals in the diverted reception channel of the surveillance radar with the additional use of radiation from external sources is an urgent task.

2. Literature review and problem statement

It is known that today's hardly noticeable AOs are flying at low altitudes, have small effective scattering surfaces, and a wide range of flight speeds [1–3]. Current trends in the development of modern AOs were confirmed e. g. by last year's military conflict in Nagorny Karabakh [4]. Undoubtedly, this reduces the efficiency of AO detection by surveillance radars designed for various purposes.

Conventional methods of improving the quality of detection of hardly noticeable AOs were analyzed in detail in [5–10]. The use of multiradar surveillance radar systems was proposed in [5]. The main disadvantage of [5] consists in the need for an increased number of surveillance radars. Measures of compaction of the location of surveillance radars [6], use of radars of different ranges [7], a complication of algorithms of radar information processing [8] were proposed in [6–8]. The use of phased array antennas as antenna systems was proposed in [9]. Methods of coherent signal processing when combining two surveillance radars in a multiradar system were proposed in [10]. The need to ensure synchronous operation of surveillance radars in space and time is the main disadvantage of [10]. E.g., analysis of [5–10] shows that the main disadvantage of the existing methods applied to improve detection of hardly noticeable AOs consists in the need to increase the number of radars, raise radar power potential, restructure the radar antenna systems, or complicate the radar information processing methods.

Auxiliary use of radiation from external sources is one of the alternative ways to improve the quality of detection of hardly noticeable AOs. For example, the use of radiation from GSM mobile cellular communication was proposed in [11, 12]. It was noted in [11] that activities are underway in the UK and Germany to develop active systems with background radiation using signals from cellular communication stations. The problem of synchronizing positions of the spaced system with cellular communication stations was solved and the geometry of the multi-position radar system was estimated in [11] but the problem of suppressing powerful penetrating signals of cellular communication stations was not considered.

The possibility of detecting objects using a two-position system using cellular communication signals was assessed in [12]. It has been shown that the auxiliary use of cellular communication signals improves the quality of AO detection. The problem of suppression of penetrating signals from cellular communication stations was not solved in [11, 12].

The possibility of detecting objects with additional use of signals from space navigation systems was assessed in [13]. It was concluded that the use of signals from space navigation systems improves the flying object detection quality. An algorithm of processing navigation signals scattered by AOs was synthesized and the structure of the corresponding consumer ground receiving equipment was substantiated. A method of suppressing direct penetrating signals was proposed in [13]. The method essence consists of compensating for the direct penetrating signal in the receiving channel by means of a reference signal entering the reference channel. The presence of an error in adjusting elements of the analog compensation unit (tunable attenuator, delay line, phase inverter) is the main disadvantage of this method.

A method of detecting hardly noticeable AOs by surveillance radars was proposed in [14]. In this case, the radar should include a single-position reception channel and a diverted reception channel (Fig. 1).

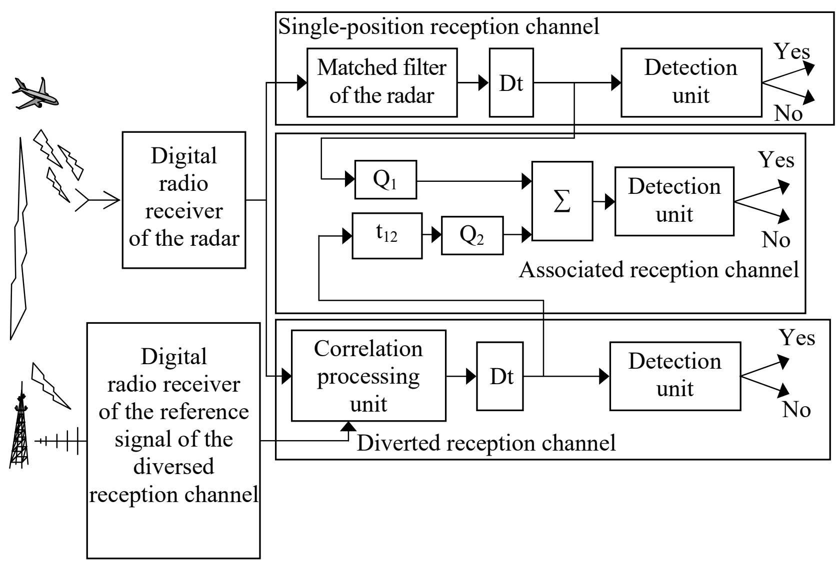


Fig. 1. Channels of echo signal reception and processing in the surveillance radar when combining single-position and diverted receptions [14]

The following notation is used in Fig. 1 [14]: Dt: detector; Q_1, Q_2: weight coefficients; t_{12}: signal delay time determined by different distances between the receiving and transmitting positions. The essence of the method of detecting the hardly noticeable AOs by surveillance radars was stated in [14]. The method involves coordinated processing of received signals, quadratic detection, and weight summation of the detector outputs. These operations must be performed in each processing channel in each element that corresponds to the respective resolution volume and respective Doppler resolution frequency. The problem of suppressing powerful penetrating signals in the diverted reception channel was not considered in [14].

Detection zones of surveillance radars were assessed in [15] with additional use of radiation from external sources. The studies were conducted under the assumption that direct signals from external radiation sources do not affect the main channel of the receiving radar (single-position reception channel). The problem of suppressing powerful penetrating signals in the diverted reception channel was not considered in [15] as well.

It was noted in [16] that one of the main problems consists in the reception of a weak signal reflected from the AO against the background of a strong direct penetrating signal from an external source. It was noted that the direct penetrating signal can differ from the signal reflected from the AO by up to 100 dB. An electrodynamic method of suppressing direct penetrating signals was proposed in [16]. The essence of the method consists in that a wire screen is set between the receiving antenna of the radar and the radiation source. The degree of direct penetrating signal suppression reaches 40–50 dB. The screen stationarity and complexity of its arranging are the main disadvantages of this method.

A method of polarization notching of the direct penetrating signals was proposed in [17]. The method is based on the fact that depolarization occurs when the signal is reflected from the AO and cross-polarization components appear. Reception of just the cross-polarization component makes it possible to achieve suppression of a direct penetrating signal of an order of 10 dB. The main disadvantages of the method include the complexity of its technical implementation and that it is applicable for the signals of external radiation sources with linear polarization.

A method of nulling the antenna directivity diagram in the direction of the source of the direct penetrating signal was proposed in [18]. The method makes it possible to conduct adaptive suppression of direct penetrating signals. For example, it was possible to achieve a 35 dB suppression of a direct penetrating signal with an eight-element antenna array. This method disadvantage consists in the reduction of suppression quality with a small number of antennas in the array and distortion of the major lobe of the antenna directivity diagram.

Methods of electronic suppression of a direct penetrating signal in the main channel of a semi-active coherent bistatic DVB-T2 radar (Republic of Belarus) were analyzed in [19]. A method of electronic compensation of a direct penetrating signal was proposed. Use of the following adaptive filters that implement the [19] findings was offered:

– least mean square (LMS) method;
– normalized least mean square (NLMS) method;
– recursive least square (RLS) method.

It was established that the use of adaptive filters proposed in [19] provides suppression of the direct penetrating signal. The main disadvantages of the methods proposed in [19] are as follows:

– high computational complexity of RLS and ECA filters;
– inability to apply methods in real time;
– the NLMS method is only applicable when the receiving and transmitting antennas are stationary.

Thus, in known systems with additional use of radiation from external sources in surveillance radars [11–19], suppression of a powerful penetrating signal is either not considered at all [11, 12, 14, 15] or known methods are used [16–19] which have abovementioned disadvantages.

There are a large number of known studies in which methods and technical solutions for suppressing powerful interferences in the detection of useful signals have been developed, e. g., [20–25]. It was noted in [20, 21] that the known methods of suppressing impulse interference are aimed at reducing the likelihood of false alarms. Known methods [20, 21] require the availability of additional channels for multi-channel interference protection methods which makes them inapplicable to the radars without additional channels.

The methods of suppression of one of the interfering components of the processed radar information often increase the effect of the other components and thus the effectiveness of other protecting or detecting devices is reduced [22]. For example, blanking devices in conditions of simultaneous influence of passive and impulse interferences replace the suppressed impulse interference with another one which is inverse to the corresponding component of passive interference. Because of the nonlinearity of processing in chopping devices, weak signals from AOs are suppressed by strong ones. Also, mutually exclusive approaches are used to suppress short- and long-pulse interferences. In addition, the methods discussed in [21–23] are characterized by the decreased signal-to-noise ratio.

Existing interference autocompensators, e.g. those considered in [6–9, 22–25] are aimed mainly at suppressing uncorrelated active interference on the side lobes of the antenna pattern. Suppression of active interference in the main lobe of the antenna directivity diagram encounters significant difficulties of implementation. This is because of the need to use two-antenna systems with coinciding antenna directivity diagrams and the signals at their outputs to be orthogonal. Problems are further complicated when suppressing correlated active interferences.

Suppression of active noise interferences [22] necessarily involves the use of a compensation receiver with its antenna receiving mainly active interferences. Compensation is performed by subtracting the interference signals of the compensation channel from interference signals of the main channel. The use of methods [6–9, 22–25] in the systems with additional use of auxiliary radiation sources was not considered.

Thus, the use of radiation of external sources in surveillance radars improves the quality of detection of hardly noticeable AOs. At the same time, the influence of a powerful penetrating signal in the diverted reception channel leads to a significant reduction in the quality of detection of hardly noticeable AOs. Methods of suppressing strong penetrating signals are either not considered in known studies at all or known methods of suppressing active interference are used. Existing methods have essential shortcomings, the main of which are related to the presence of feedback, errors in setting up the elements of the analog compensation unit, the complexity of technical implementation, etc. The above indicates the feasibility of developing a compensator for the suppression of direct penetrating signals in the diverted reception channels of the surveillance radars.

3. The aim and objectives of the study

The study objective consisted of developing a compensator for suppression of a direct penetrating signal in the diverted reception channel of the surveillance radar station with additional use of radiation from external sources.

To achieve this goal, it was necessary to solve the following tasks:

– develop the general structure of a compensator of a direct penetrating signal in the diverted reception channel;

– describe the operation of the obtained compensator of the direct penetrating signal in the diverted reception channel;

– assess the quality of operation of the direct penetrating signal compensator in the diverted reception channel.

4. The materials and methods used in studying the system of penetration signal suppression

The study used methods of probability theory, mathematical statistics, statistical theory of detection and measurement of radar signals, methods of systems analysis, theory of a multi-position radar, statistical radio engineering, and methods of mathematical modeling and digital signal processing. The method of statistical tests (Monte Carlo method) was used in the experimental studies. Analytical and empirical methods of comparative study were used in the validation of the proposed solutions.

The following limitations and assumptions were taken in the study:

– surveillance two-coordinate radars with mechanical rotation were considered as radars;

– the possibility of realization of the mode of diverted reception was provided in the surveillance radar;

– there were two receiving channels: a main (single-position reception channel) and an auxiliary (diverted reception channel);

– synchronization of work of the main and auxiliary reception channels of surveillance radars was provided;

– radio receiving devices with digital signal processing were considered;

– the type of interference components of the input signal was not taken into account.

5. The results obtained in the study of the development of a system for suppressing penetrating signals

5. 1. Development of the general structure of the compensator of a direct penetrating signal in the channel of diverted reception

It is known from [6–9, 22–25] that the classical procedure of suppressing active interferences is as follows. In addition to the main receiver which processes interferences and useful signals, an auxiliary (compensation) receiver was used with its antenna receiving the interferences. Compensation was performed by subtracting the interference signals of the auxiliary channel from the interference signals of the main reception channel. In this case, the interference is compensated and the signal remains undistorted [6–9]. Therefore, the presence of at least two receiving channels is the prerequisite for interference compensation.

To enable detection of echo signals as a result of radiation from external sources, it is necessary that suppression of the direct penetrating signal from the source of external radiation is provided in the receiving device of the radar. The penetration signal suppression is based on spatial and frequency differences between direct penetration and echo signals. The use of an active interference compensator is the most effective means of suppressing direct penetrating signals when using their spatial diversity with the echo signals. It is known that the number of channels in the active interference compensator is determined by the number of active interference sources in the space [26].

In the case of using additional radiation from external sources, the number of sources of active interference is one. Therefore, in the presence of interference from one source, it is sufficient to have one auxiliary antenna directed to the interference source and one auxiliary receiving channel. It is advisable to use the antenna and the receiver of the auxiliary diverted reception channel as an auxiliary antenna and an auxiliary channel in the case under consideration. In this case, the distance between the phase centers of the main and auxiliary antennas should be such that the occurring relative time shift does not lead to decorrelation of the signals received by the main and auxiliary antenna. To ensure this, condition (1) must be met:

$$\frac{c}{d_a} >> \Delta f_{zd}, \tag{1}$$

where c is the speed of light; d_a is the distance between phase centers of the main and auxiliary antennas; f_{zd} is the width of the signal spectrum emitted by an external source.

It does not cause difficulties for surveillance radars [27] to ensure compliance with condition (1). To be able to suppress the penetrating signal in the band of the surveillance radar receiver (approximately 2 MHz [27]), the distance between the antennas should be up to 6 m. If condition (1) and identity of the amplitude-frequency characteristics of the receiver are ensured, direct signals from an external radiation source will differ only in amplitude and phase shift (expressions (2), (3)):

$$\dot{U}_0(t) = a_0 \dot{U}_{zd}(t) e^{j\phi_0}, \tag{2}$$

$$\dot{U}_1(t) = a_1 \dot{U}_{zd}(t) e^{j\phi_1}, \tag{3}$$

where $\dot{U}_0(t)$, $\dot{U}_1(t)$ is a complex envelope of the signal emitted by an external source and received in the main and auxiliary receiving channels, respectively;

$\dot{U}_{zd}(t)$ is the complex envelope of the signal emitted by an external source;

a_0, a_1 are the coefficients determining the amplitude of the signal from an external source in the main and auxiliary receiving channels, respectively;

φ_0, φ_1 are the phase shifts of the signal from an external radiation source in the main and auxiliary channels, respectively.

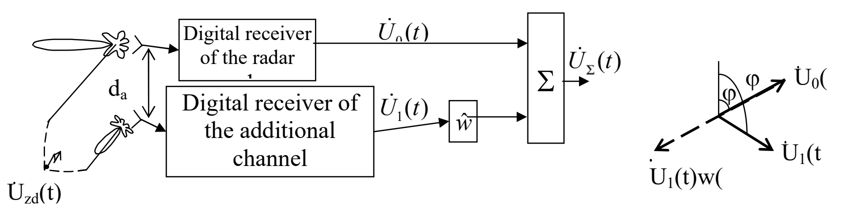
Thus, to suppress the direct penetrating signal in the main channel, it is necessary to add it to the signal received by the auxiliary channel and passed through the amplifier with a transmission factor a_0/a_1 and phase shift $(\varphi_0-\varphi_1+\pi)$. Therefore, the penetrating signal in the main channel after suppression, taking into account expressions (2), (3), takes the form (4):

$$\dot{U}_\Sigma(t) = a_0 \dot{U}_{zd}(t) e^{j\phi_0} + a_1 \dot{U}_{zd}(t) e^{j\phi_1} \times \\ \times (\hat{a}_0/\hat{a}_1) e^{j(\hat{\phi}_0-\hat{\phi}_1+\pi)} = \dot{U}_0(t) + \hat{w}(t)\dot{U}_1(t), \tag{4}$$

where $\dot{U}_\Sigma(t)$ is the penetrating signal in the main channel after suppression; $\hat{a}_0$, $\hat{a}_1$, $\hat{\phi}_0$, $\hat{\phi}_1$ are estimates of relevant values; $\hat{w}(t)$ is the estimation of the weighting coefficient.

Expression (4) takes into account the process of comparing the signals in the main and auxiliary channels and describes the process of operation of the penetrating signal compensator. The more accurate the estimation of the values ($\hat{a}_0, \hat{a}_1, \hat{\phi}_0, \hat{\phi}_1$) and the weighting coefficient included in expression (4), the lower the level of the penetrating signal will be in the main channel after suppression.

According to expression (4), the penetration signal compensator must contain an adder in which the signal received by the main channel is added to a signal received by the auxiliary channel and passed through the amplifier with the corresponding complex transmission value $\hat{w}$. Values of a_0, a_1, φ_0, φ_1 in expressions (2), (3) may change due to rotation of the surveillance radar antenna. A variant of the general structure of the direct penetrating signal compensator which corresponds to expression (4) is shown in Fig. 2, *a*. Fig. 2, *b* shows a vector diagram that explains the principle of operation of the direct penetrating signal compensator.



a *b*

Fig. 2. A variant of the general structure of the compensator of direct penetrating signals: *a* – block diagram; *b* – vector diagram of the compensator operation

The direct penetrating signal compensator (expression (4), Fig. 2, *a*) features a mandatory condition for adjusting the value of the complex transmission coefficient $\hat{w}$. of the auxiliary channel signal amplifier.

The use of a compensator (expression (4), Fig. 2, *a*) (provides in principle the possibility of compensation of the direct penetrating signal in the receiving channel of the surveillance radar using the auxiliary channel and the device of forming the weighting coefficient). However, when the surveillance radar antenna rotates, the rate of change of the amplitude and phase of the penetrating signal significantly exceeds the rate of human response.

5. 2. Description of the direct penetrating signal compensator in the diverted reception channel

Various methods can be used to automatically generate values of the weighting coefficient w [27]:

– gradient methods using correlation feedback;

– direct methods without the use of feedback which are based on a direct inversion of the correlation matrix.

The main disadvantage of using feedback to form weighting coefficients consists in a low rate of convergence of estimates which depends on the signal level, gain in the feedback loop, etc. The schemes of forming the weighting coefficients using the direct methods of forming weighting coefficients (without the use of feedback) are free from these disadvantages. The use of these methods is characterized by stability, high rate of convergence which is weakly dependent on external conditions. The main disadvantage of direct methods of forming the weighting coefficients consists in increased computational costs [27]. However, the current level of development of the digital element base provides the possibility of digital implementation of direct methods.

Therefore, in further studies, it is advisable to construct a direct penetrating signal compensator in a digital form using the direct method without the use of feedback. With this in mind, the digital direct penetrating signal compensator which uses direct methods of forming weighting coefficients must implement the following algorithm (expressions (5), (6)):

$$\dot{U}_\Sigma(k)=\dot{U}_0(k)+\dot{W}(k)\dot{U}_1(k), \tag{5}$$

$$\dot{W}(k)=-\frac{\overline{\dot{U}_0(k)\dot{U}_1^*(k)}}{\overline{\dot{U}_1(k)\dot{U}_1^*(k)}}=-\frac{\dot{\rho}\sigma_0\sigma_1}{\sigma_1^2}=-\dot{\rho}\frac{\sigma_0}{\sigma_1}, \tag{6}$$

where $\dot{U}_0(k)$, $\dot{U}_1(k)$, $\dot{U}_\Sigma(k)$ are the k-th readings of complex enveloping processes at the inputs of the main and auxiliary receiving channels and at the output of the autocompensator, respectively;

$\dot{w}(k)$ is the k-th count of the complex weighting coefficient;

"*" is the sign of complex conjugation;

$\dot{\rho}$ is the complex correlation coefficient of the processes $\dot{U}_0(k)$ and $\dot{U}_1(k)$;

σ_0, σ_1 are root mean square values of the processes $\dot{U}_0(k)$ and $\dot{U}_1(k)$, respectively;

"---" is the sign of mathematical averaging over time;

k is the running number of numeric readouts at the output of the analog-to-digital converter (ADC).

Taking into account expressions (5), (6), concretize the variant of the general structure of the direct penetrating signal compensator (Fig. 2, *a*). Therefore, the block diagram of the digital direct penetrating signal compensator which uses direct methods of forming weighting coefficients is as shown in Fig. 3.

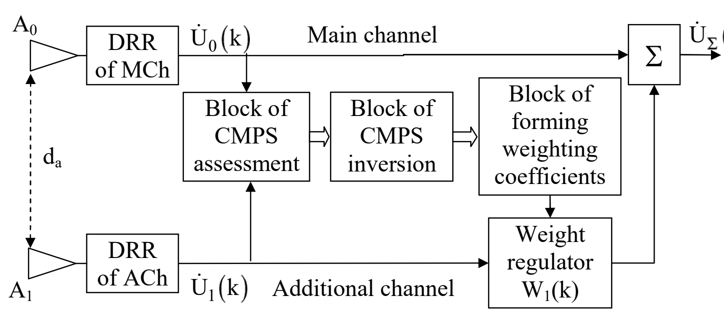


Fig. 3. Block diagram of a digital compensator of a direct penetrating signal which uses direct methods of forming weighting coefficients

Operation of the digital direct penetrating signal compensator which uses direct methods of forming weighting coefficients can be described as follows. Digital codes from outputs of digital radio receivers (DRR) of the main channel (MCh) and the auxiliary channel (ACh) are fed to the digital processor. The digital processor assesses the correlation matrix of the penetrating signal (CMPS) at the digital level, inverses it, and then forms complex weighting coefficients. Weighting coefficients are formed for each k-th count.

The formed complex weighting coefficients enter the weight regulator where they are multiplied by the digital codes of the auxiliary channel. The result of the multiplication is fed to the adder in which the direct penetrating signal in the main channel is suppressed.

Estimates of the weighting coefficients are formed in a digital processor based on the results of processing N digital readouts from the DRR outputs of the main and auxiliary channels according to expressions (7), (8):

$$\hat{\dot{w}}_1 = -\frac{\hat{\mu}_{U_0U_1}}{\hat{\sigma}_1^2}, \qquad (7)$$

$$\hat{\mu}_{U_0U_1} = M(U_0U_1) - M(U_0)M(U_1)^*, \qquad (8)$$

where $\hat{\dot{w}}_1$ is the estimate of the complex weighting factor;

$\hat{\mu}_{U_0U_1}$ is the estimate of the correlation moment of complex arrays $\dot{U}_0$ and $\dot{U}_1$ (samples of the signals from the main and auxiliary receiving channels);

$M(U_0)$, $M(U_1)$, $M(U_0U_1)$ are mathematical expectations of arrays $\dot{U}_0$, and $\dot{U}_1$ and their products, respectively, which are determined from expressions (9) to (11):

$$M(U_0U_1) = \frac{1}{N+1}\sum_{k=0}^{N} U_0(k)U_1^*(k), \qquad (9)$$

$$M(U_0) = \frac{1}{N+1}\sum_{k=0}^{N} U_0(k), \qquad (10)$$

$$M(U_1) = \frac{1}{N+1}\sum_{k=0}^{N} U_1(k), \qquad (11)$$

$\hat{\sigma}_1^2$ is the estimate of dispersion of the array $\dot{U}_1$ (samples of a signal from the auxiliary receiving channel) which is determined from expressions (12), (13):

$$\hat{\sigma}_1^2 = M(U_1^2) - M(U_1)^2, \qquad (12)$$

$$M(U_1^2) = \frac{1}{N+1}\sum_{k=0}^{N} |U_1(k)|^2. \qquad (13)$$

To reduce the time of formation of weighting coefficients when using direct methods of calculating the correlation matrix, it is advisable to use the technology of parallel computational processes. The algorithm of forming the weighting coefficients using parallel calculations is shown in Fig. 4. The algorithm shown in Fig. 4 can be implemented in digital processors based on program logic or in multiprocessor systems. In Fig. 4, readings of the signal of the main and auxiliary channel $\dot{U}_0(k)$, $\dot{U}(k)$ are marked as $\dot{U}_{0,k}$ and $\dot{U}_{1,k}$, respectively. Marks "Re" and "Im" denote real and imaginary parts of the complex number, respectively.

It is known that when using direct methods of calculating the correlation matrix, the losses in the signal/noise ratio which are caused by errors in estimating the matrix elements are determined by expression (14) [27]:

$$q_{km} = 10\lg\left(\frac{K+2-N}{K+1}\right), \qquad (14)$$

where q_{km} are equivalent losses in the signal/noise ratio which are caused by the replacement of the correlation matrix by its estimate; K is the number of samples used to estimate the correlation matrix; N is the number of compensator channels.

It follows from the analysis of expression (14) that to ensure losses in the signal-to-noise ratio of not more than 0.5 dB in a single-channel compensator (N=2), at least 8 samples of the signal must be used when estimating the correlation matrix.

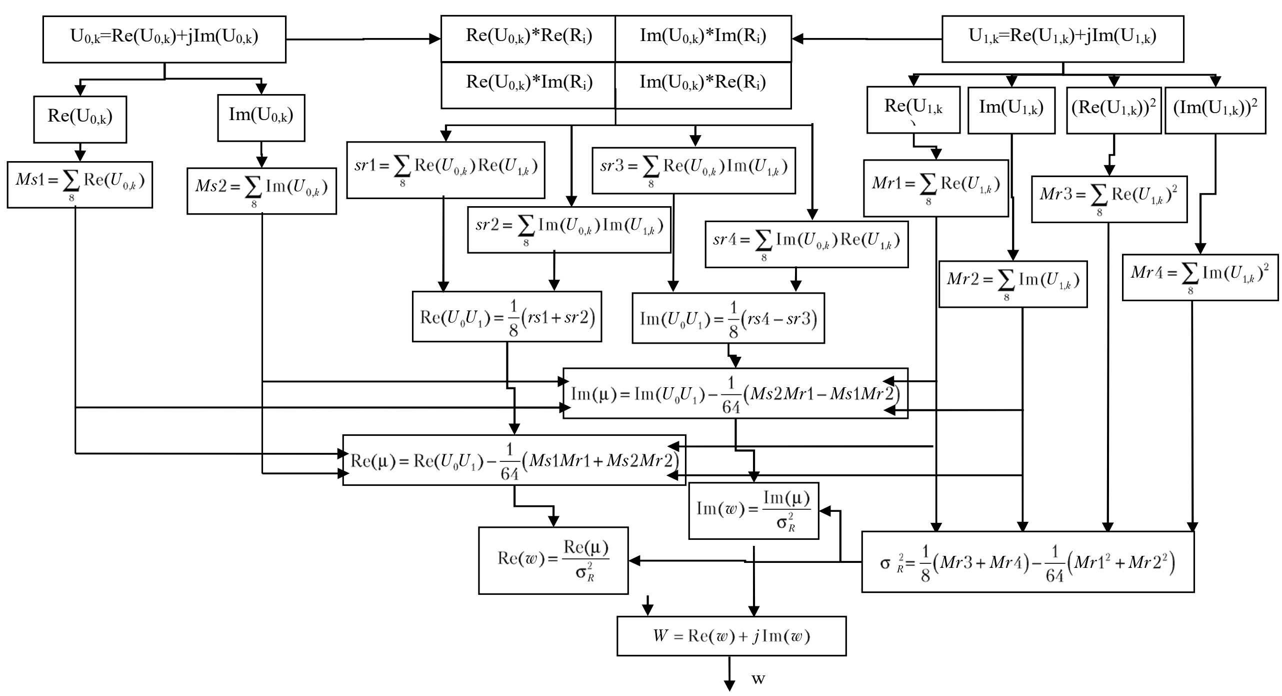


Fig. 4. The algorithm of forming weighting coefficients for penetrating signal compensation with the use of parallel computations and the direct method of correlation matrix computation

The process power at the output of the autocompensator taking into account (5) is determined by expression (15):

$$\sigma_\Sigma^2 = \frac{1}{2}\overline{\dot{U}_\Sigma(k)\dot{U}_\Sigma^*(k)} = \sigma_0^2\left(1-|\dot{\rho}|^2\right), \qquad (15)$$

where σ_Σ^2 is the power of the penetrating signal at the output of the autocompensator; σ_0^2 is the power of the penetrating signal at the input of the autocompensator.

The coefficient of suppression of the direct penetration signal is defined as a ratio of the process power (penetration signal) at the input of the autocompensator to the process power at its output. Taking into account (15), the coefficient of suppression is described by expression (16):

$$K_\Pi = \frac{\sigma_0^2}{\sigma_\Sigma^2} = \frac{1}{1-|\dot{\rho}|^2}. \qquad (16)$$

It is seen from expression (16) that the degree of suppression of the direct penetrating signal in the main channel by means of a single-channel compensator is determined by the degree of correlation of the processes operating in the main and auxiliary channels. When $|\dot{\rho}| \to 1$, power of the penetrating signal at the output of the compensator is $\sigma_\Sigma^2 \to 0$ (15). In real conditions, the complex correlation coefficient of the processes at the output of two receiving devices is always less than one $|\dot{\rho}|<1$. This is explained, firstly, by the presence of uncorrelated intrinsic thermal noise of the receiving channels and, secondly, by non-identity of amplitude-frequency characteristics (AFC).

Influence of the intrinsic thermal noises of the main and auxiliary receiving channels on the value of the complex correlation coefficient of the penetrating signal, provided that the frequency response of the receiving channels is identical, is determined from expression (17) [26]:

$$|\dot{\rho}| = \frac{\overline{\dot{U}_0(t)\dot{U}_1^*(t)}}{\sigma_0\sigma_1} = \frac{\overline{\left(\dot{U}_{zd}(t)+\dot{U}_{s0}(t)\right)\left(\dot{U}_{zd}^*(t)+\dot{U}_{s1}^*(t)\right)}}{\sqrt{\sigma_{zd}^2+\sigma_{s0}^2}\sqrt{\sigma_{zd}^2+\sigma_{s1}^2}} =$$
$$= \frac{\sigma_{zd}^2}{\sqrt{\sigma_{zd}^2+\sigma_{s0}^2}\sqrt{\sigma_{zd}^2+\sigma_{s1}^2}} = \frac{1}{\sqrt{\left(1+\frac{1}{q_0}\right)\left(1+\frac{1}{q_1}\right)}}, \qquad (17)$$

where $\dot{U}_{zd}(t)$ is the complex amplitude in the receiving channel which is determined by action of the signal from an external radiation source;

$\dot{U}_{s0}(t)$, $\dot{U}_{s1}(t)$ is the complex amplitude determined by intrinsic noise of the main and auxiliary receiving channels, respectively;

$\sigma_{zd}^2, \sigma_{s0}^2, \sigma_{s1}^2$ is the signal strength of an external source and intrinsic noise of the main and auxiliary channels, respectively;

q_0, q_1 is signal-to-noise ratio in the main and auxiliary receiving channels, respectively.

Influence of non-identity of the frequency response of the receiving channels on the value of the complex correlation coefficient of the penetrating signal in the absence of its own noise of the receiving channels is determined from expression (18):

$$\dot{\rho} = \frac{\overline{\dot{U}_0(t)\dot{U}_1^*(t)}}{\sigma_0\sigma_1} =$$
$$= \frac{\int_{-\infty}^{\infty} G(\omega)\dot{A}_0(\omega)\dot{A}_1^*(\omega)d\omega}{\sqrt{\int_{-\infty}^{\infty} G(\omega)\left|\dot{A}_0(\omega)\right|^2 d\omega}\sqrt{\int_{-\infty}^{\infty} G(\omega)\left|\dot{A}_1(\omega)\right|^2 d\omega}}, \qquad (18)$$

where $G(\omega)$ is the energy spectrum of the external source signal; $\dot{A}_0(\omega)$, $\dot{A}_1(\omega)$ is the complex frequency response of the main and auxiliary receiving channel, respectively; ω is the circular frequency.

Analysis of expressions (17), (18) shows that the correlation of direct penetrating signals at the input of the compensator largely depends on their power (signal-to-noise ratio in the receiving channels). At the same time, the amplitude of the direct penetrating signal in the receiving channels should not exceed the dynamic range. In this case, the condition of linearity of the receiving channel is violated which causes decorrelation of the penetrating signals. The difference in the frequency response of the receiving channels also significantly affects the correlation of penetrating signals. The non-identical frequency response has a smaller effect on the correlation of signals in the bandwidths of the receiving channels greater than the width of the spectrum of received signals. Therefore, in order to maintain the correlation of the penetrating signal at outputs of main and auxiliary receiving channels, it is necessary to ensure a sufficient dynamic range and identity of the frequency response of the respective receiving channels.

5. 3. Estimating quality of operation of the direct penetrating signal compensator in a diverted reception channel

The quality of operation of the direct penetrating signal compensator in the diverted reception channel was estimated by the method of statistical modeling. The penetrating signal compensator was considered using the direct method of calculating the correlation matrix and the proposed algorithm of formation of weighting coefficients (Fig. 3). A simulation model was used for statistical modeling. Its block diagram is shown in Fig. 5.

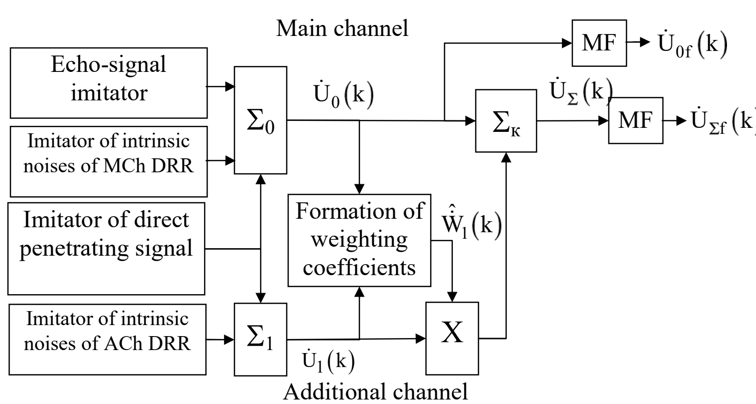


Fig. 5. Block diagram of the simulation model of the direct penetrating signal compensator

The signal at the output of the main channel adder $\left(\dot{U}_0(k)\right)$ consists of an additive mixture of an echo signal, a direct penetrating signal, and intrinsic noises of MCh DRR. The signal at the output of the adder of the auxiliary channel $\left(\dot{U}_1(k)\right)$ consists of an additive mixture of a direct penetrating signal and intrinsic noises of ACh DRR. Value of the weighting coefficient $\left(\dot{w}(k)\right)$. is formed in the block of formation of weighting coefficients based on the results of processing N counts of the mix of signals of the main $\left(\dot{U}_0(k)\right)$ and auxiliary $\left(\dot{U}_1(k)\right)$ channels. The signal of the main channel is formed at the output of the adder of the penetrating signal compensator (S_k) with suppression by the penetrating signal $\left(\dot{U}_\Sigma(k)\right)$. The possibility of detecting echo-signals in the main channel was estimated from the results of comparison of signals at outputs of matched filters (MF). The signal $\dot{U}_{0f}(k)$ corresponded to the results of the matched filtering of the additive mixture of signals of the main channel $\left(\dot{U}_0(k)\right)$ without suppression of the direct penetrating signal. The signal $\dot{U}_{\Sigma f}(k)$ corresponded to the results of matched filtering of the additive mixture of signals of the main channel after the suppression of the direct penetrating signal $\left(\dot{U}_\Sigma(k)\right)$ using the proposed algorithm of formation of weighting coefficients.

The signals used in radars of P-18MA, P-18MU, P-18 Malakhit types (all manufactured in Ukraine [28–30]) were considered in carrying out modeling. The digital television signal of DVB-T2 standard was modeled as a penetrating signal [31].

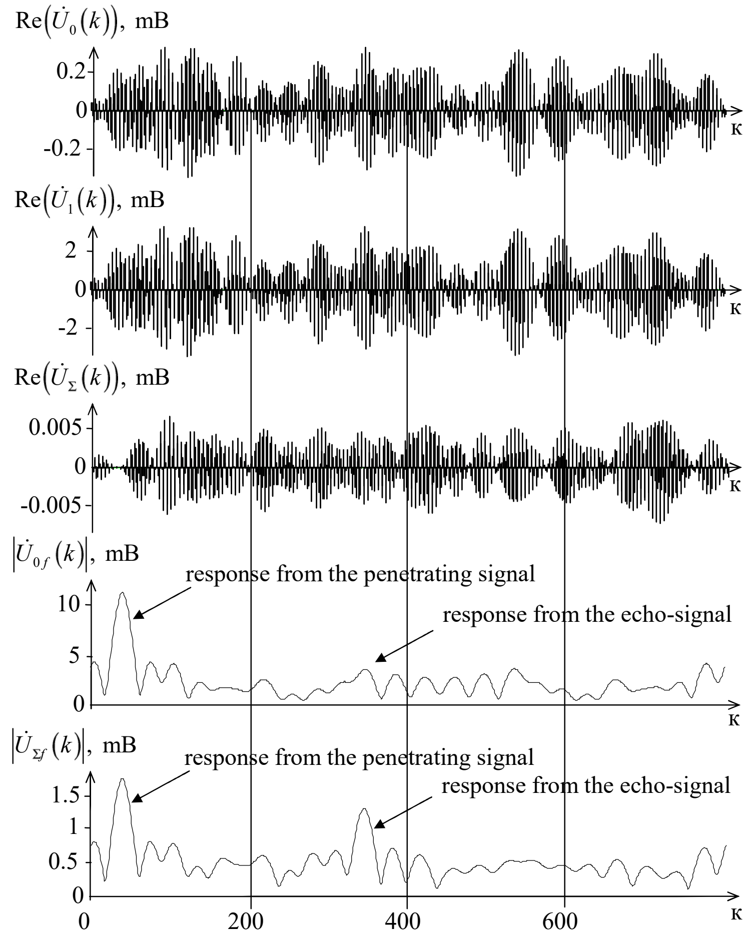


Fig. 6. The results of modeling the process of suppression of a direct penetrating signal using a simulation model (Fig. 5) and the proposed algorithm of formation of weighting coefficients

The results of statistical modeling the process of suppression of the direct penetrating signal which were obtained using the model (Fig. 5) are shown in Fig. 6. Fig. 6 shows that a non-suppressed direct penetrating signal having a powerful response at the output of the matched filter (oscillogram of $\left|\dot{U}_{0f}(k)\right|$) is masking a weak echo signal making the detection impossible.

When a direct penetrating signal compensator is used in the main channel, its response at the output of the matched filter is greatly reduced (oscillogram $\left|\dot{U}_{\Sigma f}(k)\right|$, Fig. 6), which makes it possible to observe weak echoes against the strong penetrating signal.

The result of modeling operation of the direct penetrating signal compensator during rotation of the surveillance radar antenna is shown in Fig. 7.

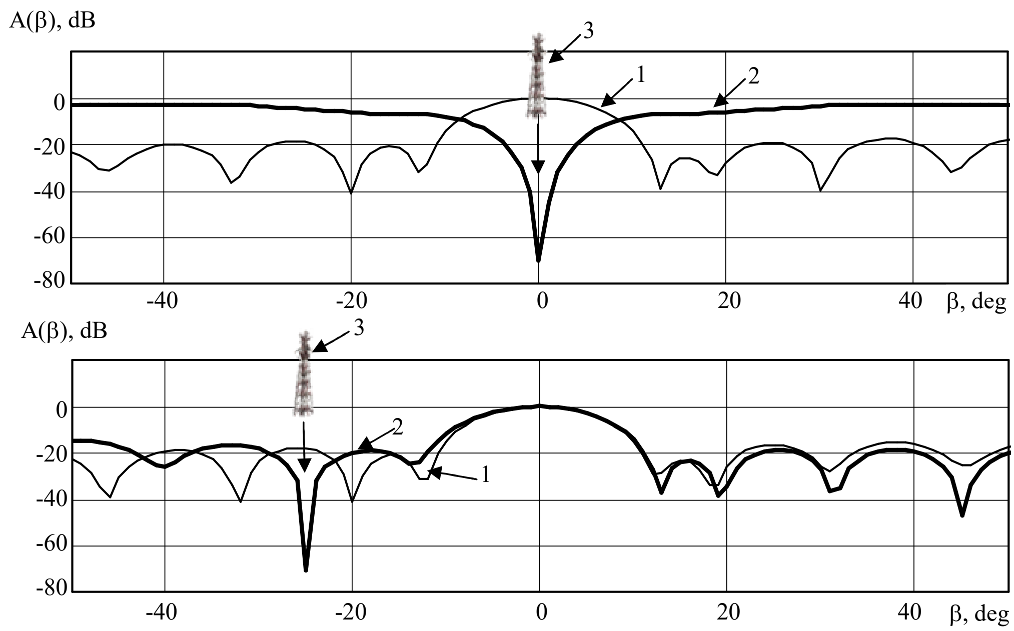


Fig. 7. The results of modeling the antenna diagram of the surveillance radar:
1 – antenna diagram without the use of a penetrating signal compensator;
2 – antenna diagram when using the penetrating signal compensator;
3 – position of the external radiation source

It is seen from the analysis of Fig. 7 that the use of the developed compensator of the direct penetrating signal provides suppression of the direct penetrating signal from 57 dB to 70 dB.

Thus, the use of the compensator of the direct penetrating signal from an external radiation source in the main receiving channel enables the detection of weak echoes against the background of powerful direct penetrating signals. The design of the compensator of the direct penetrating signal should be carried out in digital form using the direct method of forming weighting coefficients without the use of feedback. It is expedient to reduce the time of formation of weighting coefficients by using parallel calculation processes.

6. Discussion of results obtained in the study of the development of a direct penetrating signal compensator

The general structure of a compensator of direct penetrating signal in a diverted reception channel was developed (Fig. 2). If there are interferences from one source, it is sufficient to have one auxiliary antenna aimed at the source of interference and one auxiliary receiving channel. In the case under consideration, it is advisable to use the antenna and the receiver of the auxiliary channel of diverted reception as an auxiliary antenna and an auxiliary channel. To be able to suppress the penetrating signal in the band of the receiving device of the surveillance radar, the distance between the antennas should be up to 6 m. More generally, the penetrating signal compensator should contain an adder in which the signal received by the main channel is added to a signal received by the auxiliary channel and sent through the amplifier with a corresponding complex transmission factor $\hat{w}$ (expression (4)). The compensator of the direct penetrating signal features (expression (4), Fig. 2, *a*) a mandatory condition of adjusting the value of the complex transmission coefficient of the auxiliary channel of the signal amplifier.

Description of operation of the compensator of the direct penetrating signal in the diverted reception channel is given. The direct penetrating signal compensator was constructed digitally using the direct method of forming weighting coefficients without the use of feedback. The algorithm of operation of a digital compensator of a direct penetrating signal which uses direct methods of forming the weighting coefficients was represented by expressions (5), (6). Operation of the digital compensator of the direct penetrating signal which uses direct methods of forming the weighting coefficients is described as follows (Fig. 3). Digital codes from outputs of the CMPS of MCh and ACh enter the digital processor. The digital processor implements assessment of the CMPS at the software level performs its inversion and formation of complex weighting coefficients. Weighting coefficients are formed for each k-th count. The formed complex weighting coefficients enter the weight regulator where they are multiplied by digital codes of the auxiliary channel. The result of the multiplication is fed to the adder where the direct penetrating signal is suppressed in the main channel. To reduce the time of formation of weighting coefficients when using direct methods of calculating the correlation matrix, the technology of parallel computational processes was used (Fig. 4).

The quality of operation of the direct penetrating signal compensator in the diverted reception channel was assessed. The assessment was performed by the method of statistical modeling. The simulation model of statistical modeling is presented in Fig. 5. The results of statistical modeling of the process of suppression of the direct penetrating signal which were obtained using the model (Fig. 5) are shown in Fig. 6. Fig. 6 shows that without the use of suppression of the direct penetrating signal, its powerful response at the output of the matched filter masks a weak echo signal which makes detection impossible. When using a direct penetrating signal in the main channel of the compensator, its response at the output of the matched filter is significantly reduced (Fig. 6) which makes it possible to observe weak echoes against the background of a strong penetrating signal. The result of modeling the operation of the direct penetrating signal compensator during rotation of the surveillance radar antenna is shown in Fig. 7. It is seen from the analysis of Fig. 7 that the use of the developed compensator of the direct penetrating signal provides suppression of the direct penetrating signal from 57 dB to 70 dB.

Thus, the use of the direct penetrating signal from an external radiation source in the main receiving channel of the compensator enables the detection of weak echoes against the background of powerful direct penetrating signals. The structure of the compensator of the direct penetrating signal should be carried out in digital form using the direct method of forming weighting coefficients without the use of feedback. It is expedient to reduce the time of formation of the weighting coefficients through the use of parallel computation processes.

The study has the following limitations and assumptions:

– two-coordinate surveillance radars with mechanical rotation were considered;

– the possibility of realization of the mode of diverted reception in the surveillance radar was provided;

– the number of reception channels is two;

– synchronization of work of main and auxiliary reception channels of surveillance radars was provided;

– radio receiving devices with digital signal processing were considered;

– the type of interference components of the input signal was not taken into account.

Further studies should focus on the development of methods of suppressing the penetrating signal using several sources of external radiation.

7. Conclusions

1. General structure of the compensator of direct penetrating signals in the diverted reception channel was obtained. To be able to suppress the penetrating signals in the band of the receiving device of the surveillance radar, the distance between the antennas should be up to 6 m. In general, the penetrating signal compensator should contain an adder in which the signal received by the main channel is added to a corresponding complex transmission coefficient. The direct penetration signal compensator features an obligatory condition of adjusting the value of the complex coefficient of transmission of the amplifier of the auxiliary channel signal.

2. The direct penetrating signal compensator was constructed in a digital form using the direct method of forming weighting coefficients without the use of feedback. To reduce the time of formation of weighting coefficients when using direct methods of calculating the correlation matrix, the technology of parallel computational processes was used.

3. Quality of operation of the system of suppression of the direct penetrating signal in the diverted reception channel was assessed. It was established that without the use of suppression of direct penetrating signal, its powerful response at the output of the matched filter masks a weak echo signal making it impossible to detect. When using a direct penetrating signal compensator in the main channel, its response at the output of the matched filter is significantly reduced which makes it possible to observe weak echoes against the background of a strong penetrating signal. The use of the developed direct penetrating signal compensator provides suppression of the direct penetrating signal from 57 dB to 70 dB.

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