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Математическое моделирование автокомпенсационных устройств

В. П. Каткова[1*], В. А. Вяхирев[2], А. Н. Кринталь[2]

[1]Войсковая часть 58133-5
Российская Федерация, 659300, Алтайский край, г. Бийск
[2]Сибирский федеральный университет, Военно-Инженерный институт
Российская Федерация, 660036, г. Красноярск, ул. Академгородок, 13а
[*]E-mail: Lesoedova.2011@mail.ru

Статья посвящена порядку разработки и описанию математических моделей автокомпенсационных устройств радиолокационных станций кругового обзора. Разработка алгоритмов пространственной обработки сигналов в радиолокационных системах с фазированными антенными решетками является важным этапом проектирования радиолокационных станций. В данной статье будет рассмотрен порядок создания математических моделей автокомпенсационных устройств, которые разнятся способами реализации, а именно: количеством компенсационных каналов, положением основного и компенсационных (дополнительных) каналов радиолокационной станции (стационарное или динамическое), амплитудно-фазовым распределением основной и дополнительных антенн, представлением фазированной антенной решётки, алгоритмами нахождения вектора весового коэффициента. Адекватность работы моделей проверена методом вычислительного эксперимента и результатами, сравнимыми с реализованными автокомпенсаторами в радиолокационных станциях. Результаты вычислительного эксперимента, представленные в виде графиков сигнала на выходе автокомпенсационного устройства, а также прохождения согласованного фильтра, показывают, насколько эффективен алгоритм вычисления вектора весового коэффициента, позволяют наглядно, быстро и экономично сравнить эффективность работы автокомпенсационных устройств в зависимости от способа их реализации. В статье рассматривается алгоритм непосредственного формирования вектора весового коэффициента и алгоритм формирования вектора весового коэффициента через обратную корреляционную переобеляющую матрицу. Математические модели автокомпенсационных устройств и результаты вычислительного эксперимента могут применяться для обучения будущих специалистов, разрабатывающих и эксплуатирующих радиолокационные станции.

Ключевые слова: математическая модель, активная шумовая помеха, корреляционный автокопенсатор, вектор весового коэффициента, быстродействие.

Mathematical modeling of autocompensation devices

V. P. Katkova[1*], V. A. Vyakhirev[2], A. N. Krintal[2]

[1]Military unit 58133-5
Altai Territory, Biysk, 659300, Russian Federation
[2]Siberian Federal University, Military Engineering Institute
13a, Academgorodok St., Krasnoyarsk, 660036, Russian Federation
[*]E-mail: Lesoedova.2011@mail.ru

The article studies the order of developing and describing mathematical models of automatic compensation devices of all-round radar stations. The development of algorithms for spatial processing of signals in radar systems with phased antenna arrays is an important stage in the design of radar stations. This article considers the procedure to create mathematical models of automatic compensation devices that differ in implementation methods, namely: the number of compensation channels, the position of the main and compensation (additional) channels of the radar station (stationary or dynamic), the amplitude-phase distribution of the main and additional antennas, the representation phased antenna array, algorithms for finding the weight vector. The method of computational experiment verifies the adequacy of the operation of the models and the results are comparable with the implemented automatic compensation devices in radar stations. Presented in the form of graphs of the signal at the output of the automatic compensation device as well as the passage of the matched filter, the results of the computational experiment show effectiveness of the algorithm to calculate the weight vector; they permit to visually, quickly and economically compare the efficiency of the automatic compensation devices, depending on the method of their implementation. The article discusses the algorithm for the direct formation of the weight vector and the algorithm for the formation of the weight vector through the inverse correlation whitening matrix. Mathematical models of automatic compensation devices and the results of a computational experiment can be used to train future specialists who develop and operate radar stations.

Keywords: mathematical model, active noise interference, correlation automatic compensation, weight coefficient vector, speed.

Introduction

The issue of detecting air objects and accurately determining their characteristics has been and remains significant [1]. Radar stations (RS) of all-round coverage, designed to deal with this issue, perform information tasks under the conditions of exposure to external interference. Interference sources conceal or imitate signals and make it difficult to extract useful information. A significant influence on the detection and correct determination of the plane coordinates of an airborne object is exerted by response pulse interference (RPI) and active noise interference (ANI) [2].

The impact on the operation of ANI RS is currently caused by the rapid development of methods and techniques of radio countermeasures, as well as a variety of types of intentional radio interference that reduce the efficiency of isolating useful signals [3]. RPI negatively affects the quality of reception of the useful signal, affecting the side lobes of the antenna pattern of the main channel. That is why one of the most important tasks in radar is the development of devices designed to compensate for various noise and interference when receiving a useful signal [4]. To solve this problem, radars use automatic compensation systems that implement algorithms for ANI compensation and RPI suppression along the side lobes of the main channel antenna radiation pattern.

Mathematical modeling is a powerful tool for studying complex technical systems, such as automatic interference compensation systems, which has got a number of advantages over other research methods [5]. The development of various mathematical models of algorithms and systems is currently an urgent task [6].

The purpose of this work is to consider the procedure for modeling the autocompensator and the response suppression algorithm adopted by the side lobes of the main channel antenna radiation pattern.

The automatic compensator (AC) is designed to reduce the influence of ANI affecting the receiving channel of the radar. The main idea of side-lobe ANI compensation is to add in antiphase the signals received by the antenna of the main channel with signals from additional channels, multiplied by a weighting factor. With an accurate and fast calculated weight coefficient, ANI is successfully suppressed without significantly weakening the useful signal [7]. To successfully suppress ANI, accurate and fast calculation of the weighting coefficient vector is necessary.

The algorithm for suppressing RPI based on the side lobes of the main channel radiation pattern consists of subtracting the signals received by the additional antenna from the signals of the main antenna. In this case, the level of signals received by the additional antenna in the direction of the side lobes of the antenna pattern of the main channel exceeds the signals received by the main antenna in the direction of the main lobe.

The procedure for creating a mathematical model of autocompensation devices

Fig. 1 presents the block diagram of the autocompensation system.

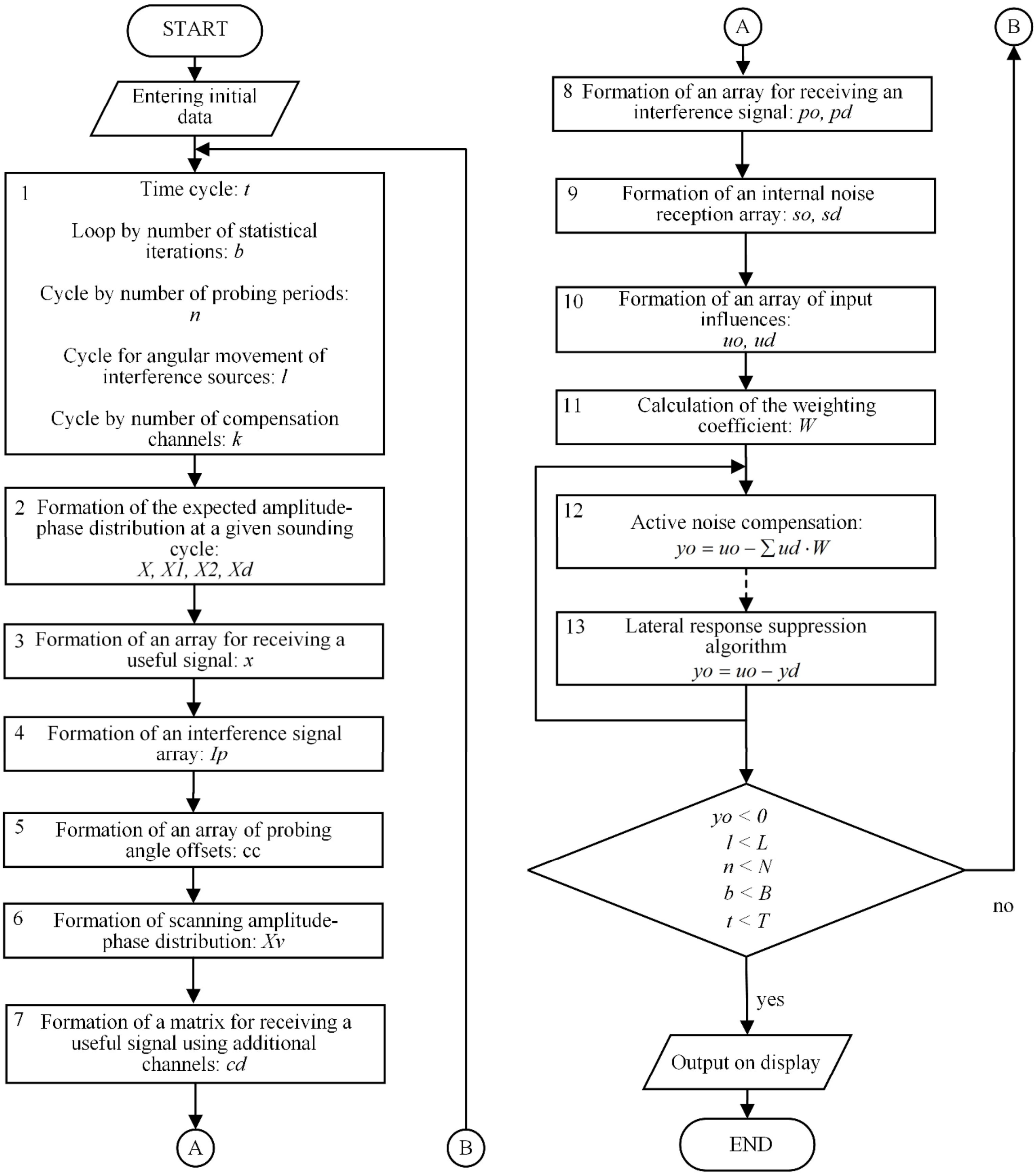


Рис. 1. Блок-схема системы автокомпенсации

Fig. 1. Block diagram of the autocompensation system

To start modeling auto-compensation systems, it is necessary to set the initial data, as well as the cycles indicated by block 1 in Fig. 1.

Modeling of the autocompensation system begins with the formation of amplitude-phase distributions of the antennae of the main and compensation channels (block 2 in Fig. 1). The amplitude-phase distribution of the main channel antenna, depending on the type of main channel antenna, is formed according to the expression [8]

$$X(m,l) = e^{-i\cdot\left(2\cdot(m+1)-\mathrm{M}-1\right)\cdot L(l)\cdot\frac{\pi}{M}} \cdot d(m), \tag{1}$$

where m – sequence number of the antenna element of the main channel array; M – quantity of non-directional antenna array elements; l– sequence number of the angular parameter of interference sources; L – reference number of the angular parameter; $d(m)$ – component of the amplitude-phase distribution of the antenna depending on the type of antenna.

The formation of an array of amplitude-phase distribution of compensation channels is carried out based on the expression

$$X1(m1,l) = e^{-i\cdot\left(2\cdot(m1+1)-\mathrm{M}1-1\right)\cdot L(l)\cdot\frac{\pi}{M1\cdot p}},$$

where $m1$ – sequence number of the antenna element of the compensation channel array, $M1$– quantity of of non-directional elements of the compensation channel antenna array, p – coefficient of normalization of the antenna radiation pattern by azimuth.

Further, an array of useful reception (*x*) is formed (block 3 in Fig. 1) [9]

$$x(m,t) = A\cdot e^{-i\cdot\left(2\cdot(m+1)-M-1\right)\cdot a\cdot\frac{\pi}{M\cdot p}} \cdot e^{-i\cdot\left(\omega\cdot t+\varphi_0+\varphi\right)},$$

where A – useful signal amplitude; a – direction of the useful signal arrival; ω – signal frequency; φ_0 – initial signal phase; φ – inter-period signal phase shift.

The amplitude of the useful signal can be constant, rapidly or slowly fluctuating due to one of the known laws [10].

Formation of an interference signal array (*Ip*) (block 4 in Fig. 1)

$$ap(n,t) = ip\cdot rnorm(1,0,1)_0,$$

$$fp(n,t) = rnd(2\pi),$$

$$Ip(n,t) = ap(n,t)\cdot(\cos(fp(n,t) + i\cdot\sin(fp(n,t)),$$

where ip – interference intensity; n – sequence number of the sounding period; t – sequence number of time reference.

Next, the rotation of the main antenna is simulated, that is, the displacement array is formed (block 5 in Fig 1),

$$cc(m,n) = e^{-i\cdot\left(2\cdot(m+1)-M-1\right)\cdot aa(n)\cdot\frac{\pi}{M\cdot p}}, \tag{2}$$

where *aa* – antenna rotation step during the sounding period.

Multiplying (1) and (2) gives the scanning result (*nc*).

Based on the scanning expression, an array of scanning amplitude-phase distribution (*Xv*) is formed (block 6 in Fig. 1)

$$Xv^{\langle l\rangle}{}_n = X^{\langle l\rangle}\cdot\left(nc^{\langle n\rangle}\right)_l.$$

The notation $\langle l\rangle$ indicates that the values of the matrix column vector are considered.

Modeling the rotation of antennas of additional channels depends on the radar stations. Their position can be stationary, or the compensation channels can rotate along with the main channel antenna. The formation of the amplitude-phase distribution (APD) for each compensation channel during their rotation (this article provides an example for two compensation channels) is carried out according to the expressions [11; 12]

$$X1(m1,l) = e^{-i\cdot\left(2\cdot(m1+1)-M1-1\right)\cdot\left(L(l)+a1\right)\cdot\frac{\pi}{M1\cdot p}},$$

$$X2(m1,l) = e^{-i\cdot\left(2\cdot(m1+1)-M1-1\right)\cdot\left(L(l)-a1\right)\cdot\frac{\pi}{M1\cdot p}},$$

where $a1$ – correction for the separation of antenna electrical centers.

Based on the obtained amplitude-phase distributions for each channel, the amplitude-phase distribution of the system of additional antennae is formed:

$$Xd = \left[X1 \; X2\right]^T.$$

where T – transposition operation.

Further, an array is formed for receiving the useful signal by compensation channels according to the expression (block 7 in Fig. 1)

$$cd(m1,t) = Yc(m1)\cdot A\cdot e^{-i\cdot\left(2\cdot(m1+1)-M1-1\right)\cdot(a\pm a1)\cdot\frac{\pi}{M1\cdot p}}\cdot e^{-i\cdot(\omega\cdot t+\varphi_0)}.$$

where Yc – amplitude-phase multiplier for the received useful signal by additional channels; k – sequence number of an additional channel.

Taking into account the errors in the amplitude-phase distribution of the antenna caused by various components and the movement of the antenna of the main channel, resulting in the formation of an interference matrix of the main and additional channels (*po, pd*) (block 8 in Fig. 1),

$$po(m,t) = Ip(n,t)\cdot e^{-1i\cdot\left(2\cdot(m+1)-M-1\right)\cdot np\cdot\frac{\pi}{M\cdot p}},$$

where np – direction of the interfering signal arrival.

$$pd(t,m1) = \left(YN^{(k)}\right)_{m1}\cdot Ip(n,t)\cdot e^{-1i\cdot\left(2\cdot(m1+1)-M1-1\right)\cdot(np\pm a1)\cdot\frac{\pi}{M1\cdot p}},$$

where $YN^{(k)}$ – amplitude-phase multiplier for the received interference signal of additional channels.

The internal noise matrix of the main channel *so* is formed according to the expression (block 9 in Fig. 1)

$$so(m,t) = as(m,t)\cdot\left(\cos\left(fs(m,t)\right) + i\cdot\sin\left(fs(m,t)\right)\right), \qquad (3)$$

where as and fs – random amplitude and phase of internal noise, respectively, are formed in a similar way to ap and fp. The noise matrix $sd(m1,t)$ of the additional channel is formed similarly (3).

From arrays of useful signal, interference and self-noise, an additive mixture of input influences arriving at the input of the antennae of the main and compensation channels (*uo, ud*) is formed (block 10 in Fig. 1), which is a mixture of noise recalculated to the input of the antenna array, useful signal and interference. In the case of rotation of the compensation channels, expression (4) will take a different form (5)

$$uo(n) = po(n) + so(n) + x(n),$$

$$ud(n,k) = pd(n,k) + sd(n,k) + cd(n,k), \qquad (4)$$

$$ud := \left[ud1 \; ud2\right]^T, \qquad (5)$$

where $ud1, ud2$ – additive mixture of input influences arriving at the input of the antennas of two compensation channels, formed similarly to ud.

When forming a flat antenna array, the number of array elements in the *a* (*M*1) plane, the number of array elements in the *b* (*M*2) plane, the direction of the useful signal source in the *a* (*a*) plane, the direction of the useful signal source in the *b* (*b*) plane will be added to the initial data; quantitative parameter reading in *a* (*LL*)plane, quantitative parameter reading in plane *b* (*KK*), as well as errors in the positions of elements in *a*, *b* (*r*1, *r*2) plane, random component to the amplitude of the useful signal (*AA*).

An array of errors is formed caused by the delay in the arrival of the useful signal due to the location of the elements normal to the antenna (*r3*).

Then an array of useful signal (*x*) is formed

$$x(m1, m2) = e^{-i\cdot(2\cdot(m1+1)-M1-1)\cdot a\cdot\frac{\pi}{M1}} \cdot e^{-i\cdot(2\cdot(m2+1)-M2-1)\cdot a\cdot\frac{\pi}{M2}} \cdot e^{-i\cdot(r3(n))_{m1,m2}}.$$

Next, an array of the random component of the signal amplitude (*An*) is formed.

Further, an array of signal distribution in the time domain is formed, taking into account the random amplitude component (*xt*)

$$xt(t, m1, m2) = e^{-i\cdot t\cdot\psi} \cdot An(n)\cdot(x(n))_{m1,m2},$$

where ψ – frequency multiplier; An – amplitude of a useful signal with a random component.

Expressions for the formation of the amplitude-phase distribution for each of the planes will take the following form in plane *a* (*X*1):

$$X1(m1, l) = e^{-i\cdot(2\cdot(m1+r1(n,m1)+1)-M1-1)\cdot L(l)\cdot\frac{\pi}{M1}}. \quad (6)$$

For plane *b*, expression (6) will take a similar form, with the exception of the components *M1, r1, L*, which will be replaced by *M*2, *r*2, *K* similar to them.

Then we set the direction of arrival of the interference signal in plane *a (N1)*, the direction of arrival of the useful signal in plane *b (N2)*, and the number of counts in the direction of arrival of the interference signal (*r*).

Based on *N1* and *N2*, a matrix of directions of interference sources is formed for two planes (*np*)

$$np(m1, m2) = e^{-i\cdot(2\cdot(m1+1)-M1-1)\cdot N1(r)\cdot\frac{\pi}{M1}} \cdot e^{-i\cdot(2\cdot(m2+1)-M2-1)\cdot N2(r)\cdot\frac{\pi}{M2}} \cdot e^{-i\cdot(r3(n))_{m1,m2}}.$$

There are many methods for finding the weight vector. We consider some of them, namely: the direct formation of a weight coefficient vector and the formation of a weight coefficient vector through an inverse correlation re-whitening matrix.

In practice, as a rule, the ANI parameters and spatial correlation matrix are unknown. Moreover, they change in time due to the movement of the noise sources and the radar space survey. Therefore, it is not possible to protect the main radar channel with pre-selected fixed parameters [13; 14].

That is why the ability to adapt to a constantly changing interference environment is of great importance for auto-compensation systems. The most important parameter of the quality of adaptive systems is their speed [14].

The performance of the auto-compensation system largely depends on the speed of calculating the weight coefficient vector. The additive mixture of useful signal and noise is multiplied by a vector of weighting coefficients and the summation of the signal coming from the main channel and the signals received by additional channels and multiplied by the vector of weighting coefficients occurs. At the output of the auto-compensator we receive a signal with compensated ANI. Based on this signal, the vector of weighting coefficients is calculated again, which ensures an increase in the signal/(noise + interference) ratio.

Direct formation of the weight coefficient vector is carried out due to the expression (block 11 in Fig. 1) [15]

$$W_k(n,k)=\frac{1}{T}\sum_{t=0}^{T-1}\left(\left(yo_{n-1}\right)_t\cdot\left(ud_{n-1,k}^{(t)}\cdot\overline{X1}\right)\right), \tag{7}$$

where yo_{n-1} – reaction coefficient; T – number of time counts; $\overline{}$ – complex conjugation operation.

Expression (7) is applicable for the case when the main channel antenna rotation is disabled. When rotation is enabled, expression (7) will take the following form:

$$W(n,k)=\frac{1}{T}\sum_{t=0}^{T-1}\left(\left(\frac{1}{1+yB_{n-1}}\right)_t\cdot\left(\left(\left(\left(\left(ud_b\right)_{n-1}\right)_k\right)^{(t)}\right)^T\cdot\overline{X1_n^{\langle k\rangle}}\right)\right),$$

where yB – the result of the difference between the signals of the main and compensation channels.

The algorithm for directly finding the weight coefficient vector (W) is in the summation over time of the product of the reaction coefficient in the previous sounding period by the additive mixture of input influences arriving at the input of the antennae of additional channels and the expected complex conjugate amplitude-phase distribution of additional channels.

Forming the weight coefficient vector through the inverse correlation whitening matrix is carried out according to the expression [10]:

$$W_k(n,k)=\frac{1}{T}\sum_{t=0}^{T-1}\left(\frac{1}{1+\left(yo_{n-1}\right)_t}\cdot\left(\left(ud_{n-1,k}^{(t)}\right)^T\cdot\overline{X1^{(Nc)}}\right)\right), \tag{8}$$

where Nc – quantitative counting of the direction of arrival of the useful signal.

When rotation is enabled, expression (8) will take the following form:

$$W_k(n,k)=\frac{1}{T}\sum_{t=0}^{T-1}\left(I-\frac{1}{1+\left(ud^{(t)}\right)^T\cdot\overline{ud^{(t)}}}\cdot ud^{(t)}\cdot\overline{ud^{(t)}}^T\right), \tag{9}$$

where I – identity matrix; $ud(k,t)=\left(\left(\left(ud_b\right)_{n-1}\right)_k\right)^{(T)}\cdot\overline{X1_{n-1}^{(k)}}$.

At the second and subsequent sounding periods, expression (9) will take the following form:

$$W_k(n)=\frac{1}{T}\sum_{t=0}^{T-1}\left(W_k(n-1)-\frac{1}{1+\left(ud^{(t)}\right)^T\cdot\overline{ud^{(t)}}}\cdot ud^{(t)}\cdot\overline{ud^{(t)}}^T\right).$$

Unlike the algorithm for directly finding the weight coefficient vector, the correlation matrix of noise is estimated.

After calculating the weight coefficient vector (W) at the zero iteration step, the array of input influences is multiplied by the weight coefficient vector (W), which is calculated depending on the algorithm used. It is calculated in such a way that after summing the signals coming from the compensation channels, ANI compensation occurs (block 12 in Fig. 1)

$$yo(n)=uo(n)\cdot Xv-\sum(ud\cdot Xd\cdot W).$$

Suppression of RPI occurs according to the algorithm (block 13 in Fig. 1)

$$yo(n)=\left|uo(n)\cdot Xv\right|-\sum\left|ud\cdot Xd\right|.$$

If the sum of the values of the signals arriving at the antennas of the compensation channels is greater than the signal arriving at the main channel, then we can assume that $yo(n)=0$. Therefore, RPI is suppressed.

Simulation results

The simulation results are presented in the form of graphs. Figure 2 demonstrates the simulation result with the autocompensator disabled. There is a lack of useful signal. It should be taken into account that Fig. 2 and 3 reflect the amplitude of the additive mixture of the useful signal, interference and intrinsic noise is normalized to the standard deviation of the noise.

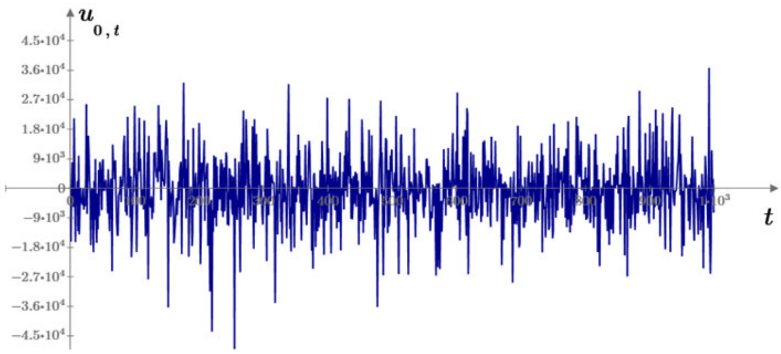
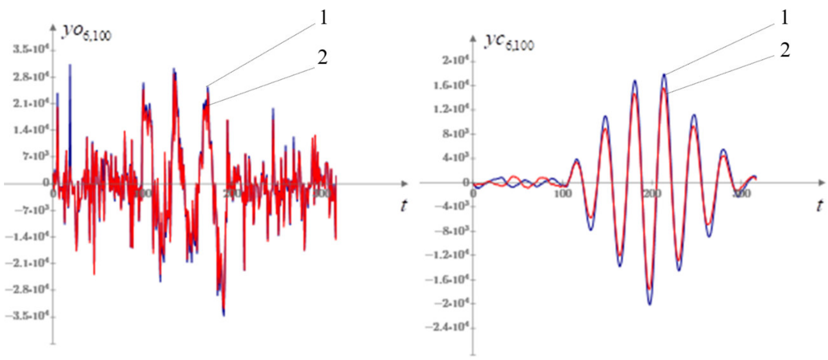


Рис. 2. Сигнал на выходе антенны основного канала
при выключенном автокомпенсаторе

Fig. 2. The signal at the output of the antenna of the main channel
when the automatic compensation devices is disabled

Figure 3 presents a graph of the signal at the output of the autocompensator and after passing through a matched filter for two algorithms for finding the weight coefficient vector. From the results of the computational experiment, we can conclude that the algorithm for finding the weight coefficient vector through the inverse correlation whitening matrix compensates for ANI faster.



а *б*

Рис. 3. График сигнала:
а – на выходе автокомпенсатора; *б* – после прохождения согласованного фильтра для двух алгоритмов.
1 – алгоритм непосредственного формирования вектора весового коэффициента; *2* – алгоритм вычисления вектора весового коэффициента через обратную корреляционную переобеляющую матрицу

Fig. 3. The graph of the signal:
a – at the output of the automatic compensation devices; *b* – the graph of the signal after passing the matched filter for two algorithms. In *1* – the algorithm for the direct formation of the vector of the weighting coefficient; *2* – the algorithm for calculating the vector of the weighting coefficient through the inverse correlation re-whitewashing matrix

Conclusion

The article discusses the mathematical model of the autocompensator and the algorithm for suppressing RPI along the side lobes. The results of computational experiments are presented in the form of graphs. The developed model makes it possible to conduct computational experiments depending on:

– from the selected adaptation algorithms to interference signals according to the criteria: maximum signal-to-noise ratio and speed of adaptation to interference;
– operation of the main antenna rotation system: rotation disabled or rotation enabled;
– position of compensation channels (dynamic or stationary);
– algorithm implemented in the radar for calculating the weight coefficient vector.

A mathematical model of an auto-compensator and an algorithm for suppressing RPI along the side lobes of the radiation pattern of the main channel antenna allows to better understand the principle of operation of auto-compensation devices and therefore can be used to train future specialists operating radars.

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Каткова Вера Павловна – инженер, войсковая часть 58133-5. E-mail: Lesoedova.2011@mail.ru.

Вяхирев Виктор Александрович – кандидат технических наук, доцент, профессор Военного учебного центра; Сибирский федеральный университет. E-mail: wyakhirev@yandex.ru.

Кринталь Андрей Николаевич – студент; Сибирский федеральный университет. E-mail: Andrey-krintal@yandex.ru.

Katkova Vera Pavlovna – engineer, military unit 58133-5. E-mail: Lesoedova.2011@mail.ru.

Vyakhirev Viktor Aleksandrovich – Cand. Sc., associate professor, professor of the Military Training Center; Siberian Federal University. E-mail: wyakhirev@yandex.ru.

Krintal Andrey Nikolaevich – student; Siberian Federal University. E-mail: Andrey-krintal@yandex.ru.