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PULSE CHARACTERISTICS OF NETWORK SATELLITE SYSTEMS ADAPTIVE ANTENNA FOR ASSESSING CORRELATION INTERFERENCE MATRIX

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Abstract

Purpose: *On the basis of spatial filtering, we propose a method for direct calculation of the inverse correlation interference matrix with unknown parameters of the input action for controlling the pattern of the adaptive antenna array using the impulse response of the spatial filter.* ***Methods:*** *the approach is based on the theory of random processes and adaptive signal processing.* ***Results:*** *the proposed method of direct calculation of the inverse correlation matrix has shown the possibility of carrying out such calculations without a prior knowledge of the interference direction, the correlation function of the interference, and also the spectral characteristics of the interference. The method allows to reduce the calculation time of the inverse correlation matrix and eliminate the errors caused by constructive inaccuracies of the radio channels of the adaptive antenna array, which in turn reduces the error in measuring the direction of the interference source****. Discussion:*** *the method is suggested in order to ensure availability and consistency of network satellite systems' navigation data.*

Keywords: network satellite systems; correlation matrix; impulse characteristics; adaptive antenna array; beam pattern.

1. Introduction

Network satellite systems (NSS), which are based on the coordinated motion and radiation signals of the artificial Earth satellites network (AES), act as continuous global systems with almost instantaneous navigational definitions. Increased over time level of technical solutions allowed the NSS to significantly improve the accuracy of determining the coordinates and parameters of the consumer's traffic. Therefore, the NSS is a qualitatively new stage in the development of radio navigation technology.

Network satellite systems provide high-precision navigation on a global scale and are able to solve the problems of navigational support of any mobile objects. Such systems can be assigned tasks of determining the coordinates and speed components of the sea vessels, aircraft (AC), spacecraft (SC) and land vehicles. This feature can also facilitate vehicle steering, managing air traffic and navigation, maintaining flight safety, preventing collisions, approach and landing of aircraft at aerodromes, conducting rescue operations, etc.

One of the NSS segments are global navigation satellite systems (GNSS) GPS, GLONASS, GALILEO. These GNSSs provide coordinate-time support, which is the basis for the efficient operation of many economy branches and is an important part of modern transport systems, digital telecommunications systems, command and control systems and precision weapons.

After the euphoria of the first years of mastering satellite navigation and temporal technologies, the use of GNSS as the only source of coordinate-time information (CTI) is now more scrupulously analyzed, creating a more realistic approach to the prospects of using GNSS. First of all, this is due to the vulnerability of GNSS in case of unintentional and deliberate interference. The vulnerability of GNSS civilian receivers has been known for a long time [1-4], but it is rarely taken into account by the manufacturers of receivers and their users. Only when the US Department of Defense intensified its activities related to the use of GPS in military conditions (NAVWAR), it became apparent that deliberate interference with civilian receivers should be considered as an important factor. The tests, which were conducted in the US in the New York area, [5] showed that a number of receivers installed on board of civil aircraft lost the ability to track GPS signals when approaching land at the international airport in Newark Liberty.

Several analyses of the transport systems vulnerability based on the use of GPS signals have been carried out [6-10]. One of the most important and timely reports on research in this area was the report of the Volpe Center [11] on GPS vulnerabilities, which concluded that the GPS system, like other radio navigation systems, is vulnerable to unintentional and deliberate interference, which is a threat to security and can have serious consequences for the economy and the environment. The report concludes that the growing use of GPS in civil infrastructure makes it an increasingly attractive target for the hostile actions of individuals and groups. At the same time, commercially available equipment for jamming has been identified [5].

Thus, the vulnerability of GNSS to the impact of unintentional and deliberate interference is now universally recognized. This vulnerability applies equally to GPS, GLONASS, GALILEO, since the principles of their construction and frequency bands are quite close.

2. Analysis of the research and publications

Since 2004 - 2007 scientists have been publishing in the open press works devoted to noise immunity improvement of GNSS consumer equipment (CE) based on [12-14], where it is proposed to use spatial filtering based on adaptive antenna arrays (AAA), in which the radiation pattern is defined as:

$$A(\theta,\varphi)=\sum_{i=1}^{N_x}\sum_{k=1}^{N_y} w_{i,k} e^{j(i-1)\psi_x} e^{j(k-1)\psi_y},$$

$$\psi_x = 2\pi\left(\frac{d_x}{\lambda}\right)\sin\theta\cos\varphi,$$

$$\psi_y = 2\pi\left(\frac{d_y}{\lambda}\right)\sin\theta\sin\varphi,$$

where d_x – the distance between AAA elements along x axis, $d_н$ – the distance between AAA elements along y axis, λ – the wavelength of the received electromagnetic wave, θ, φ – angles of arrival of the received electromagnetic fluctuation, $w_{i,k}$ – weight multipliers in elements (i, k) – AAA. Weight multipliers $w_{i,k}$ are defined with the help of the Wiener-Hopf equation.

$$\mathbf{w} = \mathbf{R}_п^{-1} \times \mathbf{s}, \quad (1)$$

where **w** – vector or weight multiplier, $\mathbf{R}_п^{-1}$ – inverse correlation matrix of interference, **s** – vector column characterizing the amplitude-phase distribution of the signal through the AAA reception channels.

However, papers [12-14] give recommendations concerning radiolocation, communication, and indicate difficulties in the direct calculation of the inverse correlation matrix of interference [14, 15].

According to the structure of signals and interference, GNSS differs from radar systems and radio communication systems. Therefore, when using adaptive methods for compensation of interference in GNSS channels, it is necessary to take into account a number of important features that often complicate the implementation of CE. So, unlike radar systems and radio communication systems, GNSS does not know the time-frequency structure of the useful signal in advance, thus excluding the possibility of using a number of widely used methods of adaptive interference compensation with the use of a reference signal. In [16], it was proposed to exclude the influence of the useful signal on the adaptation chains, but increasing the requirements for the accuracy of the coordinates determination requires new direct methods for determining the correlation interference matrices in AAA.

3. Research task

The task of the study is to propose on the basis of spatial filtration a direct calculation method of the inverse correlation matrix of interference with the unknown parameters of the input action for controlling the AAA pattern.

4. Results and Discussion

Let us suppose, that the source of the interference is a white noise of some power. Then the interference spectrum will form the following elements (Fig. 1), i.e. the filter F and the interference amplifier U, the propagation medium, A1, A2, A3, A4-antennas and the radio path of the adaptive antenna array. All these elements will constitute a spatial filter with a certain impulse characteristics.

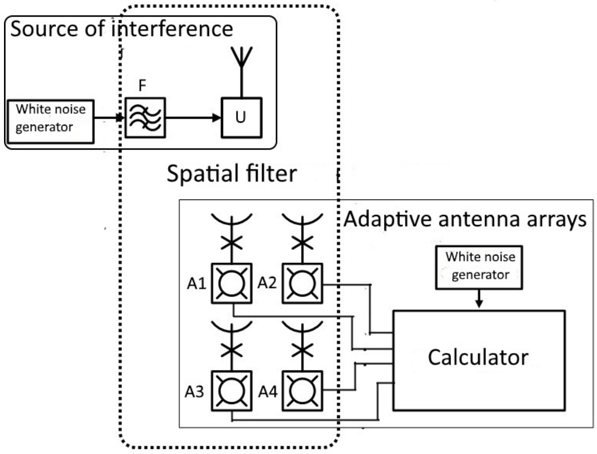

Fig. 1. Elements comprising a spatial filter

The spectral power of the interference density will be determined by expression:

$$G(\omega) = \int_{-\infty}^{\infty} R(\tau) e^{-j\omega\tau} d\tau, \quad (2)$$

where $R(\tau)$ – correlating interference function.

Usually spectral density $G(\omega)$ decreases if ω is big enough, and becomes negligible starting with certain frequency ω_c. Then the interference $\xi(t)$ can be rather accurately replaced with the process $\xi_0(t)$ with energy spectrum

$$G_0(\omega) = \begin{cases} G(\omega) & |\omega| \le \omega_c, \\ 0, & |\omega| > \omega_c. \end{cases} \quad (3)$$

We shall consider the random process $\xi_0(t)$ as a result of continuous white noise influence $x(t)$ with a limited by frequency ω_c spectrum on a continuous linear system which transfer function is determined by the relation

$$G_0 |K(j\omega)|^2 = G_0(\omega), \quad (4)$$

where G_0 is white noise spectral density (Fig. 2).

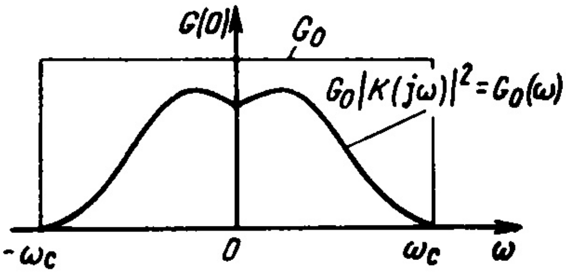

Fig. 2. Energy spectrum of white noise at the output of a linear system

Relation (4) expresses the fact known from the theory of random processes: the noise energy spectrum at the output of the linear system is equal to the product of the input noise power spectrum per square of the modulus of the system transfer function (complex frequency characteristics).

In order for the system transfer function to satisfy condition (4), it must look like

$$K_0(j\omega) = \left[\frac{1}{G_0} G_0(\omega) \right]^{\frac{1}{2}}. \quad (5)$$

The impulse characteristics corresponding to the transfer function (5) is

$$h(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} K_0(j\omega) e^{j\omega t} d\omega = \frac{1}{\pi} \int_{0}^{\omega_c} \left[\frac{1}{G_0} G_0(\omega) \right]^{\frac{1}{2}} \cos\omega t d\omega. \quad (6)$$

Let us substitute (2) in square brackets (6), then the impulse characteristics of the linear system (filter) can be expressed in terms of the interference correlation function

$$h(t) = \frac{1}{\pi} \int_{0}^{\omega_c} \left[\frac{1}{G_0} \int_{0}^{\tau} R(\tau) e^{-j\omega\tau} d\tau \right]^{\frac{1}{2}} e^{i\omega t} d\omega. \quad (7)$$

Expression (7) can be written in the matrix form for discrete signals

$$\mathbf{h} = \mathbf{W}^* [\mathbf{W}\mathbf{r}]^{\frac{1}{2}}, \quad (8)$$

where $\mathbf{W} = e^{-j\frac{2\pi kn}{N}}$ – matrix of turning factors of the discrete Fourier transform, $\mathbf{W}^*$ –complex conjugate matrix to $\mathbf{W}$, $\mathbf{r}$ – correlation function vector, $\mathbf{h}$ – impulse characteristics vector.

Proceeding from the fact that AAA is an element of a spatial filter, expression (8) can be written for a two-dimensional form of dimension $N \times N$

$$\mathbf{H} = \mathbf{W}^* [\mathbf{W}\mathbf{R}]^{\frac{1}{2}}, \quad (9)$$

where $\mathbf{R}$ – interference correlation matrix.

Let us find the inverse correlation matrix from (9). After taking the squaring of (9), we obtain

$$\mathbf{H}^2 = \mathbf{W}^{*2} \mathbf{W}\mathbf{R}. \quad (10)$$

Let us multiply both elements from the right side of (10) by $\mathbf{R}^{-1}$

$$\mathbf{H}^2 \mathbf{R}^{-1} = \mathbf{W}^{*2} \mathbf{W}\mathbf{R}\mathbf{R}^{-1} = \mathbf{W}^{*2} \mathbf{W}\mathbf{I} = \mathbf{W}^{*2} \mathbf{W}. \quad (11)$$

Let us multiply both elements from the left side of (11) by $(\mathbf{H}^2)^{-1}$

$$\left(\mathbf{H}^{2}\right)^{-1}\mathbf{H}^{2}\mathbf{R}^{-1}=\left(\mathbf{H}^{2}\right)^{-1}\mathbf{W}^{*2}\mathbf{W},$$
$$\mathbf{I}\mathbf{R}^{-1}=\left(\mathbf{H}^{2}\right)^{-1}\mathbf{W}^{*2}\mathbf{W}, \qquad (12)$$
$$\mathbf{R}^{-1}=\left(\mathbf{H}^{2}\right)^{-1}\mathbf{W}^{*2}\mathbf{W}.$$

where: $\mathbf{R}^{-1}$ — inverse correlation matrix of interference, **H** – impulse characteristics matrix of a spatial filter, **I** – unit matrix. Thus, (12) is an expression for determining the inverse correlation matrix of the interference.

In expression (12), the matrix **H**, like the matrix **R**, is unknown. In order to get the impulse characteristics of the filter we should use the *system identification* method. By the term *system identification* we mean the definition of the impulse response *h (n)* if it is not known.

The output of the system is connected with its input by the following relation (convolution)

$$y(n)=\sum_{m=0}^{n}h(m)x(n-m)=h(n)\otimes x(n), \qquad (13)$$

where: $y(n)$ – output sequence (interference with correlation function $\boldsymbol{r}$), $x(n)$ – input sequence (normal white noise), $h(n)$ – the desired impulse characteristics of the shaping filter.

Thus, having a white noise generator from the input sequence (i.e. from the outputs of the intermediate frequency amplifiers) embedded in AAA, the system identification method determines the impulse characteristics of the spatial filter necessary to calculate the inverse correlation matrix of the interference (See Fig. 1).

Fig. 3 shows the impulse characteristics of the four AAA channels obtained by the system identification method, since the phase front of the interference depends on the direction of its arrival (angles θ and φ), so the impulse characteristics of the AAA channels will differ and carry the information about the correlation function of the interference (7)

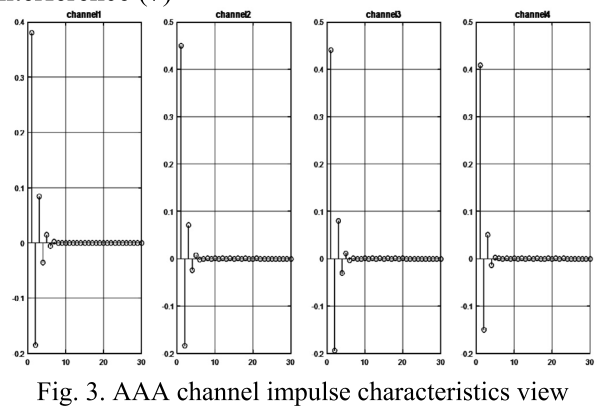

Fig. 3. AAA channel impulse characteristics view

Fig. 4 shows the AAA directivity pattern obtained while using expression (12).

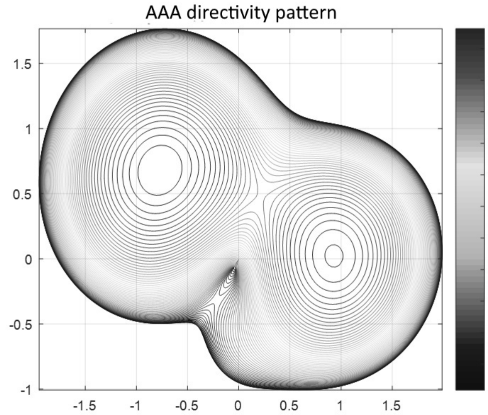

Fig. 4. AAA directivity pattern with generated "zero" gap to the source of interference

It can be seen from the figure above that in the directivity diagram a gap ("zero") is formed on the direction of the source of interference.

5. Conclusions

In order to increase the interference immunity of NSS while being a part of the GNSS equipment, it is possible to use AAAs, which allow to significantly reduce the signal reception coefficient from the direction where the source of interference is located.

To achieve the result it is proposed to use a qualitatively new method of direct calculation of the inverse correlation matrix based on the impulse response of the spatial filter (AAA). The proposed method makes it possible to reduce computational costs, due to the predetermined matrices of the turning multipliers of the Fourier transform. The matrix of the impulse characteristics is well-conditioned, so it is possible to calculate the inverse matrix of the impulse characteristics from it. Using the proposed method, it is possible to compensate for instrumental errors introduced by the design parameters of the AAA, which in turn reduces the error while measuring the direction of the source of interference.

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В. П. Харченко[1], В. А. Швець[2], **Імпульсна характеристика адаптивної антени мережевих супутникових систем для оцінки кореляційної матриці перешкоди**

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Мета: На основі просторової фільтрації запропонувати метод прямого обчислення зворотної кореляційної матриці перешкоди при невідомих параметрах вхідного впливу для управління діаграмою спрямованості адаптивної антенної решітки, використовуючи імпульсну характеристику просторового фільтра. **Методи**: підхід базується на теорії випадкових процесів і адаптивної обробки сигналів.

Результати: запропонований метод прямого обчислення зворотної кореляційної матриці показав можливість проводити такі обчислення без апріорних знань про направлення приходу перешкоди, про кореляційної функції перешкоди, а також про спектральні характеристики перешкоди. Метод дозволяє зменшити час обчислення зворотної кореляційної матриці і виключити похибки, які викликаються конструктивними розбіжностями радіоканалів адаптивної антенної решітки, що в свою чергу знижує помилку вимірювання напрямку на джерело перешкод.

Обговорення: метод пропонується для забезпечення доступності та цілісності (підвищення завадостійкості) навігаційних даних мережевих супутникових систем.

Ключові слова: мережеві супутникові системи; кореляційна матриця; імпульсна характеристика; адаптивна антенна решітка; діаграма спрямованості.

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Импульсная характеристика адаптивной антенны сетевых спутниковых систем для оценки корреляционной матрицы помехи

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Цель: На основе пространственной фильтрации предложить метод прямого вычисления обратной корреляционной матрицы помехи при неизвестных параметрах входного воздействия для управления диаграммой направленности адаптивной антенной решетки, используя импульсную характеристику пространственного фильтра. **Методы:** подход базируется на теории случайных процессов и адаптивной обработки сигналов. **Результати:** предложенный метод прямого вычисления обратной корреляционной матрицы показал возможность проводить такие вычисления без априорных знаний о направлении прихода помехи, о корреляционной функции помехи, а также о спектральных характеристиках помехи. Метод позволяет уменьшить время вычисления обратной корреляционной матрицы и исключить погрешности, которые вызываются конструктивными неточностями радиоканалов адаптивной антенной решетки, что в свою очередь снижает ошибку измерения направления на источник помех. **Обсуждение:** метод предлагается для обеспечения доступности и целостности (повышения помехоустойчивости) навигационных данных сетевых спутниковых систем.

Ключевые слова: сетевые спутниковые системы; корреляционная матрица; импульсная характеристика; адаптивная антенная решетка; диаграмма направленности.

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