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IMPROVEMENT OF THE GPS SIGNAL RECEIVING RESISTANCE AGAINST ELECTROMAGNETIC INTERFERENCE, JAMMING, AND SPOOFING IS BASED ON THE USE OF THE ANTENNA ARRAY SYSTEM WITH DIGITAL BEAMFORMING AND NORAD TLE INFORMATION

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Background. Currently, in radio navigation systems of the various purposes, the urgent issue is stability increase of the GPS signal reception under such a jamming and spoofing types of the interference influence. In this article, the authors propose a new solution to the stability increase problem of the GPS signal reception against the jamming and spoofing interference based on the spatial selectivity of the receiver antenna. Spatial selectivity is provided through the integrated application of phased array digital beamforming technology and the use of the TLE NORAD information.

Objective. The research goal is to develop a methodology for the integrated identification of interference sources to the radio navigation system and to increase the noise immunity for receiving radio navigation signals via spatial selection through the digital beamforming technologies utilization.

Methods. For the research process, theoretical methods for the digital beamforming of receiving phased antenna system were used as well as the description of a two-line NORAD information element content, and calculation algorithms for the spacecraft current position**.**

Results. As a result of the research, the GPS signal reception model was formed using spatial selection of GPS signal sources and interference sources, the technique to increase the stability of GPS signal reception under the jamming and spoofing types of interference influence was developed, the block diagram was suggested for the receiving device that implements the developed technique through the integrated application of the digital beamforming technology of the phased array antenna and the TLE NORAD information utilization**.**

Conclusion. A conceptual idea of the method and a technical solution for the proposed method implementation were submitted. The method implementation will improve the stability of GPS signal reception under the influence of jamming and spoofing types of interference**.**

Keywords: *GPS signal reception; jamming and spoofing; digital beamforming; phased array antenna.*

Introduction

In today's post-industrial world Global Navigation Satellite Systems (GNSS) have become an element of a critical information infrastructure. The consumers of information of these systems are present in almost all sectors of human life, society, and the state: from transport systems, municipal infrastructure, and industrial facilities to healthcare facilities and systems. Separately, there are questions about the use of these systems for military purposes.

Considering the critical importance of the GNSS system performance for the life of society, the security of the state, and the country's economy, attackers with various goals are trying to introduce destructiveness into the correct operation of GNSS to complicate the use of these systems or disrupt the formed navigation field. Therefore, improving the resistance of GNSS systems from the influence of intentional electronic interference is becoming an important direction in their development. For this matter, various methods are used, which include the complication of the structure and increase in the noise immunity of signals, the use of cryptographic protection methods, etc. Methods of spatial selection of interference sources are actively used in the ground equipment of consumers.

One of the options for ensuring the spatial selection of GNSS signals is the use of antenna arrays with digital beamforming in combination with the integrated use of information from the NORAD space monitoring system and satellite ephemeris contained in the structure of the GPS navigation message.

1. Statement of the problem.

The Satellite Radio Navigation System NAVSTAR (GPS) is a space-based radio navigation system designed for navigation, positioning, and transmission of precise timing for consumers on the Earth. The system provides a high-accuracy measurement of the current coordinates and spatial location of an object in the WGC-84 coordinate system, measures the speed and direction of its movement, supporting of consumers with a time scale concerning UTC for all users who have the appropriate equipment, and are located at any point on the Earth's surface or near it [5]. The system consists of space and ground segments. The Space Segment currently consists of 31 satellites orbiting in MEO at approximately 20,200 km at an inclination of 55º. The satellites are situated in 6 orbital planes separated by 60º along the longitude of the ascending node. There are at least 4 satellites in each orbital plane.

GPS Satellites transmit navigation signals in three frequency bands, or frequency subbands, with nominal values of the carrier frequency: L1=1575.42 MHz, L2=1227.6 MHz, L5=1176.5 MHz [4,5]. The transmission of navigation message information in the GPS is carried out using code division of signals, formed based on pseudo-random sequences. The C/A code is the vehicle for the Standard Positioning Service, SPS, which is used for most civilian surveying applications. C/A code is available for all users of the GPS, which is transmitted on the L1 frequency. The precise P (or Y) codes are available to special users. A pseudo-random sequence of C/A codes is used to identify the GPS satellite number, has a duration of 1 ms, and is transmitted at a rate of 1023 kbps. The chip rate of the C/A code is 1023 kbps, and the bandwidth of the total combined signal is 30.69 MHz. Thus, the base [6] of the GPS C/A code signal is $B_{C/A}= 3{,}96 \cdot 10^4$.

To have a destructive impact on the functioning of the GPS, attackers make efforts to generate electronic interference that will either reduce the accuracy of measurement of the coordinate, determination of the current location and timing or even make it impossible to use GPS services [7]. For this matter there are three methods of GPS signals suppression used [8]:

- frequency and spectrum targeted noise process is used as interference (jamming);
- interference signal, which is transmitted at the operating frequency of the GPS signal, with a variable phase according to the law of the digital modulating function - a pseudo-imitating signal;
- re-transmitted interference signals simulating navigational messages with additional time delay (spoofing).

The most actively used methods are jamming and spoofing. Currently, to improve the noise immunity of GPS signal reception, methods are actively used, which are based on the spatial selection of GPS signals and on various methods of interference adapting receivers.

Methods Used

The GPS radio navigation system is the Classic Architecture Satellite System that uses the satellite constellation in Medium-Earth Orbit. The determination of the current consumers' coordinates on the Earth's surface is based on the Triangulation Method. GPS Satellites transmit their position coordinates in the Navigation Message Frame Structure [4,5]. The consumer's receiving equipment performs calculations using the indications of the onboard time scale and the ephemeris of navigation satellites to determine its current coordinates.

To improve the noise immunity and interference resistance of consumer receiving equipment at the C/A code level, it is proposed to consider the possibility of integrated use of antenna array with digital beamforming technology [1], NORAD system information [16] on the movement parameters of GPS satellites, and satellite ephemeris from the Navigation Message in combination with spatial selectivity of GPS satellite signals. Fig. 1 shows a block diagram of the proposed GPS signal-receiving device.

The Device consists of the following elements:

- Flat Antenna Array with Digital Beamforming;
- Spatial Frequency Array;
- Spatial Frequency Signals Switch;
- 12-channel GPS Signal Analyser;
- Output Register of GPS Signal Structures;
- Calculator of the GPS Satellite Current Coordinates, which uses TLE NORAD Information and Navigation Message Ephemeris;
- Match Matrix of GPS Signal Spatial Frequencies with GPS Satellite Current Coordinates.

The operation technology of the proposed method and device is as follows:

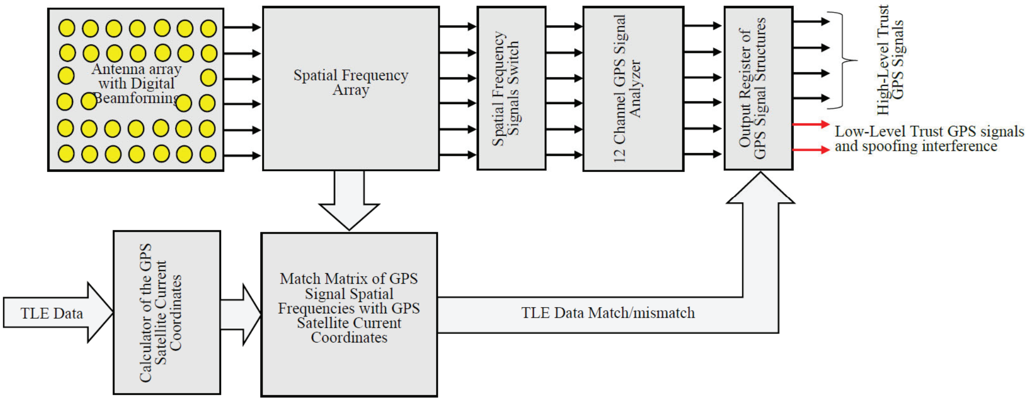

Fig. 1 The Block Diagram of the GPS signal-receiving device.

The current coordinates of the GPS Satellites that are observed from the Device's Location are calculated based on the NORAD TLE Data and the Navigation Message Ephemeris of these signals. Antenna Array with Digital Beamforming creates independent beams that provide GPS signals spatial selection. The calculation of the GPS Satellite Current Coordinates in the Topocentric Coordinate System for the location of the Receiving Device makes it possible to determine the Antenna Array Spatial Frequencies in which the GPS Satellites are observed.

Used technologies.

Antenna Array with Digital Beamforming

The Antenna Array with Digital Beamforming provides the formation of the Receiving Antenna Array Radiation Pattern by digital methods [1]. In the receiving system, as a result of the fallen wave-front *E* striking the array of elements of the receiving system, signals are formed at the output of the elements of the receiving array, which have the same amplitude $a(t)$, but the phases of the signals from neighbouring elements of the receiving array differ by

$$\varphi_n = \frac{2\pi n d \sin\alpha}{\lambda}$$

where n is the number of the element of the receiving linear antenna array; d is the spacing between antenna elements, or the step of the receiving array (distance between elements); α is the angle that determines the direction of the received signal (direction of the moving of wavefront) relative to the normal of the antenna array plane; λ is the wavelength of the received signal.

The flat N×N antenna array with digital beamforming forms a matrix of sample signals from the outputs of single elements $s_{n,m}$ of the antenna array. The matrix of samples of the flat N × N antenna array has the form

$$\dot{s}_{N\times N} = \begin{vmatrix} \dot{s}_{N/2-1,-(N/2-1)} & \cdots & \dot{s}_{N/2-1,-1} & \dot{s}_{N/2-1,0} & \dot{s}_{N/2-1,1} & \cdots & \dot{s}_{N/2-1,(N/2-1)} \\ \vdots & \ddots & \vdots & \vdots & \vdots & \iddots & \vdots \\ \dot{s}_{1,-(N/2-1)} & \cdots & \dot{s}_{1,-1} & \dot{s}_{1,0} & \dot{s}_{1,1} & \cdots & \dot{s}_{1,(N/2-1)} \\ \dot{s}_{0,-(N/2-1)} & \cdots & \dot{s}_{0,-1} & \dot{s}_{0,0} & \dot{s}_{0,1} & \cdots & \dot{s}_{0,(N/2-1)} \\ \dot{s}_{-1,-(N/2-1)} & \cdots & \dot{s}_{-1,-1} & \dot{s}_{-1,0} & \dot{s}_{-1,1} & \cdots & \dot{s}_{-1,(N/2-1)} \\ \vdots & \iddots & \vdots & \vdots & \vdots & \ddots & \vdots \\ \dot{s}_{-(N/2-1),-(N/2-1)} & \cdots & \dot{s}_{-(N/2-1),-1} & \dot{s}_{-(N/2-1),0} & \dot{s}_{-(N/2-1),1} & \cdots & \dot{s}_{-(N/2-1),(N/2-1)} \end{vmatrix}$$

As shown in [1], the flat N×N Antenna Array with a half-wave distance between elements provides the formation of responses of Spatial Frequencies, each of which is determined by the expression [1]

$$\dot{Y}_{r,s} = A(t) \sum_{n=-N/2}^{N/2-1} \sum_{m=-N/2}^{N/2-1} \dot{W}_{n,m} \dot{S}(n,m)\, e^{-j\left(\frac{2\pi}{N}\right)ms} e^{-j\left(\frac{2\pi}{N}\right)nr}$$

where *r*, *s* – beam number, *r, s*=0, 1, 2, …, *N*-1; $A(t)$ is the coefficient that contains information about the range and Doppler frequency shift; $\dot{W}_{n,m}$ - weight coefficient of the antenna element (*n*,*m*); $\dot{S}(n,m)$ is the factor depending on the angle of the signal arriving by element (*n*,*m*).

$$\dot{S}(n,m) = e^{j\pi m \cos\beta} e^{j\pi n \cos\alpha} = e^{j\pi m \sin\theta \sin\varphi} e^{j\pi n \sin\theta \cos\varphi}$$

where *α* and *β* are the arguments of the direction cosines *cosα* and *cosβ*, which determine the projection of the unit vector of the signal arriving direction on the antenna array plane axes *x* and *y*, respectively; *θ* and *φ* are the angles in the polar coordinate system with the center at the center of the antenna array plane, which determine the deviation of the signal arriving direction from the perpendicular to the antenna array plane and the azimuth of the projection of the signal reception vector onto the antenna array plane relative to the *x*-axis.

To calculate the responses of signals of spatial frequencies of the *N*×*N* Flat Antenna Array, the fast Two-dimensional Fourier Transform Algorithm is used. As a result, the square Spatial Frequencies Matrix is formed. For the *N*×*N* Flat Antenna Array, the Spatial Frequencies Matrix has the form

$$\dot{Y}_{N\times N}=\begin{vmatrix} \dot{Y}_{N/2-1,-(N/2-1)} & \cdots & \dot{Y}_{N/2-1,-1} & \dot{Y}_{N/2-1,0} & \dot{Y}_{N/2-1,1} & \cdots & \dot{Y}_{N/2-1,(N/2-1)} \\ \vdots & \ddots & \vdots & \vdots & \vdots & \iddots & \vdots \\ \dot{Y}_{1,-(N/2-1)} & \cdots & \dot{Y}_{1,-1} & \dot{Y}_{1,0} & \dot{Y}_{1,1} & \cdots & \dot{Y}_{1,(N/2-1)} \\ \dot{Y}_{0,-(N/2-1)} & \cdots & \dot{Y}_{0,-1} & \dot{Y}_{0,0} & \dot{Y}_{0,1} & \cdots & \dot{Y}_{0,(N/2-1)} \\ \dot{Y}_{-1,-(N/2-1)} & \cdots & \dot{Y}_{-1,-1} & \dot{Y}_{-1,0} & \dot{Y}_{-1,1} & \cdots & \dot{Y}_{-1,(N/2-1)} \\ \vdots & \iddots & \vdots & \vdots & \vdots & \ddots & \vdots \\ \dot{Y}_{-(N/2-1),-(N/2-1)} & \cdots & \dot{Y}_{-(N/2-1),-1} & \dot{Y}_{-(N/2-1),0} & \dot{Y}_{-(N/2-1),1} & \cdots & \dot{Y}_{-(N/2-1),(N/2-1)} \end{vmatrix}$$

The direction of the fixed beams in each plane perpendicular to the Antenna Array Plane and coinciding with the *x* and *y* axes, respectively, is determined by the expression [1]

$$\alpha_r=\arccos\frac{2r}{N}$$

where α_r is the direction of the r^{th} beam in the *x*-axis plane. The value of the angle β_s for the s^{th} beam in the *y*-axis plane is calculated similarly.

In a number of works on phased antenna arrays [2,3], it is shown that the flat *N*×*N* two-dimensional array, to which the flat antenna array with digital beamforming also belongs, creates beams in space, the cross-section of which is an ellipse. The axes of the ellipse are determined by the width of the radiation pattern of the linear array of dimension *N*, which correspond to the *x* and *y* axes of the flat antenna array. To determine the width of the antenna array beam pattern along the *x* and *y* axes, it's could use an approximate formula that is valid for phased antenna arrays of dimension $N\geq 8$ [2,3], and for antenna arrays with a spacing $d=\lambda/2$ takes the form

$$\theta_3(r)\cong\frac{1{,}7716}{N\cos\alpha_r}$$

$$\theta_3(s)\cong\frac{1{,}7716}{N\cos\beta_s}$$

A feature of the Antenna Array with Digital Beamforming is the fact that at the output of the Spatial Frequency Channel, a sequence of GPS signals samples is formed, which has the form

$$\dot{Y}_{r,s}=\sum_{l=0}^{N_{L1}-1}\dot{Y}_{r,s}(l\Delta t_{L1})$$

here N_{L1} is the number of the GPS signal discrete samples at the L1 frequency for the duration of one C/A-code sequence, the duration of which is 1 ms and which consists of 1023 symbols (chips); Δt_{L1} is the sampling interval of the signal at the output of the Spatial Frequency Channel. The sampling interval of the Antenna Array with Digital Beamforming signal is selected from the condition determined by the Kotelnikov theorem [1] and is

$$\Delta t_{L1}=\frac{1}{2(f_{L1}+\Delta f_{L1})}=\frac{1}{2(1575{,}42\ \text{МГц}+15{,}345\text{МГц})}=3{,}14\cdot 10^{-10}c$$

The number of signal samples at the output of the Spatial Frequency Channel (*r*,*s*) is

$$N_{L1}=\frac{1}{\Delta t_{L1}}=3{,}18153\cdot 10^{9}$$

Each signal sample $\dot{Y}_{r,s}(l\Delta t_{L1})$ is a mix of the GPS signal received in the Antenna Array Fixed Spatial Beam, noise and interference of natural and artificial origin

$$\dot{Y}_{r,s}(l\Delta t_{L1})=\dot{S}_i\left(l\Delta t_{L1}-\tau_{S_i}\right)+\dot{I}(l\Delta t_{L1})+n(l\Delta t_{L1})$$

here $\dot{S}_i(l\Delta t_{L1})$ is the signal sample of the i^{th} GPS satellite; τ_{S_i} is the propagation delay of the signal of the i^{th} GPS satellite to the place of reception; $\dot{I}(l\Delta t_{L1})$ is the interference component that is present in the Spatial Frequency Channel at the sampling instant; $n(l\Delta t_{L1})$ is the noise component.

The GPS Signal Sample of the i^{th} Satellite during the transmission of the C/A-code has the form

$$\dot{S}_i\left(l\Delta t_{L1}-\tau_{S_i}\right)=\sqrt{2P_i}\cdot C_i(l\Delta t_{L1}-\tau_{S_i})\cdot D_i(l\Delta t_{L1}-\tau_{S_i})\cdot e^{-j(2\pi f_{L1}(l\Delta t_{L1}-\tau_{S_i}))}$$

where P_i is the power of the received i^{th} GPS signal; C_i is the element of a pseudo-random sequence of C/A-code; D_i is the Navigation Message Element of the GPS Frame; f_{L1} is the frequency of the L1 GPS Signal Open Code.

Thus, on the interval of duration C/A-code, the signal at the output of the Spatial Frequency Channel (*r*, *s*) is determined by the sequence of discrete samples

$$\dot{Y}_{r,s} = \sum_{l=0}^{N_{L1}-1} [\sqrt{2P_i} \cdot C_i(l\Delta t_{L1} - \tau_{S_i}) \cdot D_i(l\Delta t_{L1} - \tau_{S_i}) \cdot e^{-j(2\pi f_{L1}(l\Delta t_{L1} - \tau_{S_i}))} + \dot{I}(l\Delta t_{L1}) + n(l\Delta t_{L1})]$$

$$= \sqrt{2P_i} \sum_{l=0}^{N_{L1}-1} C_i\left(l\Delta t_{L1} - \tau_{S_i}\right) \cdot D_i\left(l\Delta t_{L1} - \tau_{S_i}\right) \cdot e^{-j\left(2\pi f_{L1}\left(l\Delta t_{L1} - \tau_{S_i}\right)\right)} + \dot{I}_\Sigma + n_\Sigma$$

In the above expression, the first term determines the sequence of readings of the i^{th} GPS signal at the receiving point, obtained taking into account the spatial selection of the Flat Antenna Array with Digital Beamforming, and the second and third terms determine the interference and noise components present in the selected channel, respectively.

- *NORAD Information*

TLE information is a set of parameters describing the movement of a satellite in near-Earth orbit and measured by the NORAD system at a certain time. Table 1 lists the parameters contained in the first line of the TLE message. Table 2 lists the parameters contained in the second line of the TLE message.

Table 1. Parameters contained in the first line of the NORAD TLE message

Field	**Columns**	**Content**	**Example**
1	01-01	Line number	1
2	03-07	NORAD Satellite catalog number	25544
3	08-08	Classification (U: unclassified, C: classified, S: secret)	U
4	10-11	International Designator (last two digits of launch year)	98
5	12-14	International Designator (launch number of the year)	067
6	15-17	International Designator (a piece of the launch)	A
7	19-20	Epoch year (last two digits of the year)	08
8	21-32	Epoch (day of the year and fractional portion of the day)	264.51782528
9	34-43	The first derivative of mean motion; the ballistic coefficient	-.00002182
10	45-52	The second derivative of mean motion (decimal point assumed)	00000-0
11	54-61	*B*, the drag term, or radiation pressure coefficient (decimal point assumed)	-11606-4
12	63-63	Ephemeris type (always zero; only used in undistributed TLE data)	0
13	65-68	Element set number. Incremented when a new TLE is generated for this object.	292
14	69-69	Checksum (modulo 10)	7

Table 2. Parameters contained in the second line of the NORAD TLE message

Field	**Columns**	**Content**	**Example**
1	01-01	Line number	2
2	03-07	NORAD Satellite Catalog number	25544
3	09-16	Inclination (degrees)	51.6416
4	18-25	The right ascension of the ascending node (degrees)	247.4627
5	27-33	Eccentricity (decimal point assumed)	0006703
6	35-42	The argument of perigee (degrees)	130.5360
7	44-51	Mean anomaly (degrees)	325.0288
8	53-63	Mean motion (revolutions per day)	15.72125391
9	64-68	Revolution number at epoch (revolutions)	56353
10	69-69	Checksum (modulo 10)	7

It is possible to calculate the coordinates of the GPS Satellite based on the NORAD TLE data at a given in time in a topocentric coordinate system, the center of which is a point on the Earth's surface where the GPS Receivers with the flat antenna array are located: x'_S, y'_S, z'_S. The antenna array plane coincides with the $x'y'$ lane of the topocentric rectangular coordinate system.

The calculated coordinates allow us to determine the direction of cosines $\cos\alpha_S$ and $\cos\beta_S$ for the antenna array beam, as well as the deflection angles of the antenna array beam: the angle θ, which is measured relative to the z' axis, the angle φ, which is the azimuth. Since the direction cosines determine the deflection angles of the antenna array beam in the plane of the x' and y' axes, it is more convenient to calculate the values of these quantities.

$$\cos\alpha_S = \frac{x'_S}{\sqrt{{x'_S}^2 + {z'_S}^2}}$$

$$\cos\beta_S = \frac{y'_S}{\sqrt{{y'_S}^2 + {z'_S}^2}}$$

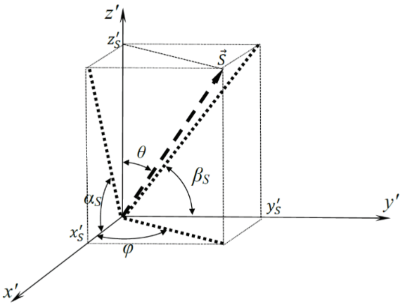

Fig.2. Determining the orientation of the fixed antenna array beam in the topocentric coordinate system using the angles of deflection and azimuth of the beam, and direction cosines.

If the direction of signal reception from the radiation source is known and is determined by the angles θ and φ, or using the direction cosines, it is possible to determine the number of the fixed antenna array beam in which the signal is received from a particular GPS Satellite. The beam number *r, s* along *x, y* axis is determined by the expression

$$r = \frac{1}{2}\lfloor N\sin\theta\cos\varphi\rfloor = \frac{1}{2}\lfloor\cos\alpha_S\rfloor$$
$$s = \frac{1}{2}\lfloor N\sin\theta\sin\varphi\rfloor = \frac{1}{2}\lfloor\cos\beta_S\rfloor$$

here $\lfloor\cdot\rfloor$ defines the action of limiting from below to the nearest integer.

The above expressions make it possible to determine the number of the fixed beam of a flat *N*×*N* antenna array, in which a signal is received from a source with known angular coordinates in a topocentric coordinate system.

2. Jamming resistance

Signals C/A-code of the GPS belong to the class of wideband spread-spectrum signals (SSS) with a noise-like structure. To analyse the effect of jamming interference on the reception of GPS signals using an antenna array with digital beamforming, it's used a digital signal model at the output of the Spatial Frequency Channel (r, s) given above.

$$\dot{Y}_{r,s} = \sqrt{2P_i}\sum_{l=0}^{N_{L1}-1} C_i\left(l\Delta t_{L1} - \tau_{S_i}\right)\cdot D_i\left(l\Delta t_{L1} - \tau_{S_i}\right) \cdot e^{-j\left(2\pi f_{L1}\left(l\Delta t_{L1}-\tau_{S_i}\right)\right)} + \dot{I}_\Sigma + n_\Sigma$$

Fig. 3 shows a situational diagram of the impact of jamming interference on the reception of GPS signals using an antenna array with digital beamforming.

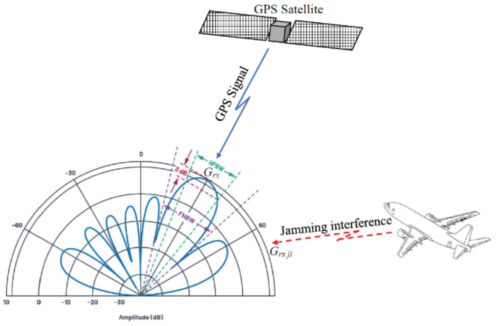

Fig.3 A situational diagram of the impact of jamming interference on the reception of GPS signals using an antenna array *N*=8 with digital beamforming.

Correlators or Matched Filters are used to receive GPS Signals [4]. When a Matched Filter or Correlator receives a sequence of GPS Signal Instant Samples and a mixture of Jamming Interference and noise at the input, the output signal could be present by the next equation.

$$\begin{aligned}\dot{S}_{r,s}(k) = {} & 2P_i \sum_{l=0}^{N_{L1}-1} C_i\left(l\Delta t_{L1} - \tau_{S_i}\right)\cdot D_i\left(l\Delta t_{L1} - \tau_{S_i}\right)\cdot e^{-j\left(2\pi f_{L1}\left(l\Delta t_{L1}-\tau_{S_i}\right)\right)}\cdot C_i^*\left((l+k)\Delta t_{L1}\right) \\ & \cdot D_i^*\left((l+k)\Delta t_{L1}\right)e^{j\left(2\pi f_{L1}\left((l+k)\Delta t_{L1}\right)\right)} + P_{jam}\sum_{l=0}^{N_{L1}-1} \dot{I}_\Sigma \cdot C_i^*\left((l+k)\Delta t_{L1}\right) \\ & \cdot D_i^*\left((l+k)\Delta t_{L1}\right)e^{j\left(2\pi f_{L1}\left((l+k)\Delta t_{L1}\right)\right)} \\ & + P_n \sum_{l=0}^{N_{L1}-1} n_\Sigma \cdot C_i^*\left((l+k)\Delta t_{L1}\right)\cdot D_i^*\left((l+k)\Delta t_{L1}\right)e^{j\left(2\pi f_{L1}\left((l+k)\Delta t_{L1}\right)\right)} \\ & = 2P_i\dot{R}_i(k) + P_{jam}\dot{R}_{iI_\Sigma}(k) + P_n\dot{R}_{in}(k)\end{aligned}$$

As can be seen from the above expression, the signal at the output of the Correlator or Matched Filter is the sum of the response of the autocorrelation function $\dot{R}_i(k)$ of the received GPS Signal of the i^{th} Satellite with the amplitude coefficient $2P_i$ corresponding to the signal received power, the component of the mutual convolution of the GPS Signal and interference $P_{jam}\dot{R}_{iI_\Sigma}(k)$, and the convolution component of the GPS Signal and noise $P_n\dot{R}_{in}(k)$. Quite a lot of publications [4,7,8] are devoted to the analysis of noise immunity and noise resistance of GPS Signal reception under the influence of white noise and jamming broadband interference, which affect the entire frequency band of GPS Signal reception. Taking into account the nature of GPS signals as SSS, the analysis of the resistance of GPS signals to the effects of jamming is carried out based on the approaches described in [6]. In particular, it was shown in [6] that the error probability or error rate for coherent reception of binary signals is determined by the expression

$$P_0 = 1 - F(\alpha h_2)$$

where F(x) is the probability integral,

$$F(x) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{x} e^{-z^2/2} dz$$

h_2 – the ratio of signal energy to the spectral density of the total interference

$$h_2^2 = \frac{E_2}{N_0}$$

E_2 – the energy of signals which are used for binary information transmission, $E_2 = P_S T_2$

P_S – signal received power;

T_2 – the signal duration when transmitting binary information;

N_0 – interference power spectral density, $N_0 = P_I/\Delta F$

P_I – interference power;

ΔF – signal spectrum width;

α — manipulation type factor, $\alpha = \sqrt{2}$ when PM-2 is used;

The ratio of signal energy to the spectral interference power density ratio is dependent on the signal base as shown in [6]

$$h_2^2 = \frac{P_S T_2}{N_0} = B\rho^2$$

where B is the base of signals which are used for binary information transmission, $B = \Delta F T_2$.

ρ^2 - the ratio of signal power to noise power at the receiver input, $\rho^2 = P_S/P_I$.

Under the influence of jamming interference, the signal-to-noise ratio at the input of the GPS receiver can be represented as follows

$$\rho^2 = \frac{P_S}{P_I} = \frac{W_{GPS} G_{rx}}{W_I G_{rx\,I}} \frac{L_{A\,I}}{L_{A\,GPS}}$$

where W_{GPS} is the GPS Signal power flux-densities at the receiving point;

G_{rx} – GPS Receiver Antenna Gain in the direction of the GPS Satellite;

W_I – interference power flux-density at the receiving point;

$G_{rx\,I}$ – GPS Receiver Antenna Gain in the direction of interference source;

$L_{A\,GPS}$ – additional losses for the propagation of the GPS signal through the atmosphere of Earth;

$L_{A\,I}$ – additional losses for the interference propagation through the atmosphere of Earth.

With a fixed value of the GPS signal power flux-density to the interference power flux-density ratio at the GPS signal reception point, it is possible to increase the signal-to-noise ratio ρ^2 at the receiver input by the increasing the Gain of the GPS Receiver Antenna in the direction of the GPS Satellite relative to the Gain in the direction Interference Source. The Antenna Array with Digital Beamforming technology makes it possible to realize this task by digital methods.

Fig. 3 shows an example of receiving the GPS signal and interference by the device with an antenna array with digital beamforming. As can be seen from their figure, the pattern with fixed beams of the antenna array with digital beamforming makes it possible to implement the principle of spatial selectivity for isolating the GPS Signal. The gain of the antenna array in the direction of receiving the GPS signal is G_{rx}, and the gain in the direction of the interference is $G_{rx\,I}$. Fig. 3 illustrates the case for the single Spatial Frequency of the Antenna Array with Digital Beamforming. When the signal of the given Spatial Frequency is received, interference appears in the following cases:

- the source of interference appears in the Main Lobe of the Spatial Frequency Beam in which the GPS signal is received;
- the interferer source is located outside the main lobe of the given spatial frequency beam and acts through the side lobes of the spatial frequency beam radiation pattern.

Considering that Antenna Arrays with Digital Beamforming form rather narrow Spatial Frequencies Beams, the probability of an interference source appearing in the Main Lobe of the Beam Pattern is quite small. For the equiprobability of the appearance of an interference source at any point in the celestial hemisphere, the probability of the appearance of interference in the main lobe of the given beam of spatial frequency is

$$p_I = 1 - \cos\frac{\theta_3}{2}$$

where θ_3 is the half-power beam width.

This probability is not zero, therefore, in each spatial frequency channel, which is used for processing, taking into account the current coordinates of the GPS satellite, the method of controlling the spectral power density level of interference is applied. In the case of detecting the impact on the spatial frequency channel of the jamming, this channel is excluded from the GPS information processing.

When the Interference Source is outside the Main Lobe of the Spatial Frequency Beam, the influence of Jamming is possible through the Side Lobes of the Antenna Array Radiation Pattern. The peculiarity of the Antenna Array Radiation Pattern is that the level of the first side lobe is lower by 13.5 dB relative to the Main Lobe. The use of an Antenna Array with Digital Beamforming in GPS receiving devices makes it possible to increase the noise immunity of reception by at least 13.5 dB. For a rough estimate of the arriving interference level at the input of the Spatial Frequency Channel, it is used the expression that determines the gain decrease of the p^{th} Side Lobe $G_{SL\,p}$ relative to the gain G_{ML} of the Main Lobe [3]

$$\frac{G_{SL\,p}}{G_{ML}} = \frac{1}{N \sin\left(\frac{2p+1}{2N}\pi\right)}$$

where $p = 1, 2, 3, \ldots$

To increase the level of protection of the array factor, it is possible to use the weighting technology using plots such as Hanning (-30 dB), Hamming (-42 dB), or Blackman (-57 dB) [1,2].

3. Resistance to the effects of spoofing interference

Quite a lot of publications [9,10,11,12] are devoted to the issue of analysing the influence of spoofing interference and developing methods to counteract these interferences. Spoofing Interference is a signal that repeats by the form and structure of the GPS signal, and which is retransmitted with a delay relative to the time of arrival of the original GPS Signal.

Fig. 4 shows a situational diagram of the impact of spoofing interference on the reception of GPS signals using an antenna array with digital beamforming.

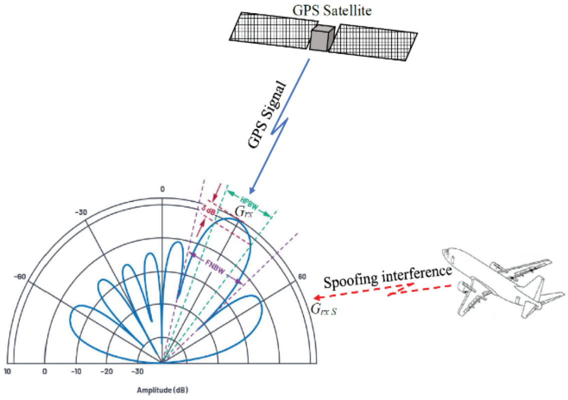

Fig.4 A situational diagram of the impact of spoofing interference on the reception of GPS signals using an antenna array N=8 with digital beamforming.

When the GPS receiver is affected by spoofing interference, there is a mix of the GPS signal instant samples, spoofing interference, and additive white noise at the receiver input.

$$\begin{aligned}\dot{Y}_{r,s} &= \sum_{l=0}^{N_{L1}-1} [\sqrt{2P_i} \cdot C_i(l\Delta t_{L1} - \tau_{S_i}) \cdot D_i(l\Delta t_{L1} - \tau_{S_i}) \cdot e^{-j(2\pi f_{L1}(l\Delta t_{L1} - \tau_{S_i}))} + \dot{I}(l\Delta t_{L1}) + n(l\Delta t_{L1})] \\ &= \sqrt{2P_i} \sum_{l=0}^{N_{L1}-1} C_i\left(l\Delta t_{L1} - \tau_{S_i}\right) \cdot D_i\left(l\Delta t_{L1} - \tau_{S_i}\right) \cdot e^{-j\left(2\pi f_{L1}\left(l\Delta t_{L1} - \tau_{S_i}\right)\right)} \\ &+ \sqrt{2P_{Si}} \sum_{l=0}^{N_{L1}-1} C_{Si}\left(l\Delta t_{L1} - k\Delta t_{L1} - \tau_{S_i}\right) \cdot D_{Si}\left(l\Delta t_{L1} k\Delta t_{L1} - \tau_{S_i}\right) \\ &\cdot e^{-j\left(2\pi f_{L1}\left(l\Delta t_{L1} - k\Delta t_{L1} - \tau_{S_i}\right)\right)} + n_{\Sigma}\end{aligned}$$

where P_{Si} is the received power of the i^{th} GPS signal used as spoofing interference; k is the number of signal sampling intervals at the output of the Spatial Frequency Channel (r,s), which corresponds to the delay of the spoofing interference relative to the original i^{th} GPS signal; C_{Si} is the element of the C/A-code of the spoofing interference; D_{Si} is the navigation message element of the GPS signal frame used as spoofing interference.

When coherent reception is implemented using Correlator or Matched Filters, the signal at the output of the GPS Receiver Device is determined by the following relationship [12]

$$\begin{aligned}\dot{S}_{r,s}(k) = 2P_i & \sum_{l=0}^{N_{L1}-1} C_i\left(l\Delta t_{L1} - \tau_{S_i}\right) \cdot D_i\left(l\Delta t_{L1} - \tau_{S_i}\right) \cdot e^{-j\left(2\pi f_{L1}\left(l\Delta t_{L1} - \tau_{S_i}\right)\right)} \cdot C_i^*\left((l+m)\Delta t_{L1}\right) \\ & \cdot D_i^*\left((l+m)\Delta t_{L1}\right) e^{j\left(2\pi f_{L1}\left((l+m)\Delta t_{L1}\right)\right)} \\ & + 2P_{Si} \sum_{l=0}^{N_{L1}-1} C_{Si}\left(l\Delta t_{L1} - k\Delta t_{L1}\tau_{S_i}\right) \cdot D_{Si}\left(l\Delta t_{L1} - k\Delta t_{L1}\tau_{S_i}\right) \cdot e^{-j\left(2\pi f_{L1}\left(l\Delta t_{L1} - k\Delta t_{L1} - \tau_{S_i}\right)\right)} \\ & \cdot C_i^*\left((l+m)\Delta t_{L1}\right) \cdot D_i^*\left((l+m)\Delta t_{L1}\right) e^{j\left(2\pi f_{L1}\left((l+m)\Delta t_{L1}\right)\right)} \\ & + P_n \sum_{l=0}^{N_{L1}-1} n_\Sigma \cdot C_i^*\left((l+m)\Delta t_{L1}\right) \cdot D_i^*\left((l+m)\Delta t_{L1}\right) e^{j\left(2\pi f_{L1}\left((l+m)\Delta t_{L1}\right)\right)} \\ & = 2P_i \dot{R}_i(m) + 2P_{Si}\dot{R}_{Si}(k+m) + P_n \dot{R}_{in}(m)\end{aligned}$$

As it could be seen from the above expression, the signal at the output there Correlator or Matched Filter is the sum of the response of the autocorrelation function $\dot{R}_i(k)$ of the i^{th} received GPS signal with the amplitude coefficient $2P_i$ corresponding to the GPS signal received power, the component of the autocorrelation function of the i^{th} GPS signal $\dot{R}_{Si}(k+m)$, shifted by m sampling intervals and used as spoofing interference, with an amplitude coefficient depending on the received power of the reradiated signal $2P_{Si}$, mutual convolution of the i^{th} GPS signal and noise $P_n\dot{R}_{in}(k)$. When the i^{th} GPS signal and its reradiated copy, which is used as spoofing interference, are processed by the receiver, the signal at the output of the Matched Filter or Correlator contains two components that depend on the GPS Signal Autocorrelation Function. The autocorrelation properties of sequences used to generate C/A-code of the GPS Signals are well studied and summarized in [13].

The influence of spoofing interference is that the Decision Unit at the output of the Correlator and Matched Filter takes a wrong decision on the choice of the instant time of arrival of the GPS signal. The decision of the Decision Unit is based on the comparison of the response levels of the GPS Signals $S_i(t)$ and spoofing interference $S_{Si}(t)$. The decision is made whether to use the C/A-code signal $s_i(t)$ coming directly from the GPS Satellite or the spoofing signal relayed with a delay $\Delta\tau_{si}$.

$$\begin{aligned} S_i(t,\tau) > S_{S_i}(t,\tau) &\;\Rightarrow\; s_i\left(l\Delta t_{L_1}\right) \\ S_i(t,\tau) < S_{S_i}(t,\tau) &\;\Rightarrow\; s_{S_i}\left((l+k)\Delta t_{L_1}\right) \end{aligned}$$

Taking into account that the magnitude of the response at the output of the Matched Filter or Correlator depends on the product of the amplitude coefficient and the unnormalized autocorrelation function, the above condition could be converted to the form

$$\begin{aligned} P_i > P_{Si} &\;\Rightarrow\; s_i\left(l\Delta t_{L_1}\right) \\ P_i < P_{Si} &\;\Rightarrow\; s_{S_i}\left((l+k)\Delta t_{L_1}\right) \end{aligned}$$

The received power of the signal is related to the power flux density by the following relation, which follows from the definition of the power flux density [14]

$$P_{rx} = \frac{W G_{rx} \lambda^2}{4\pi}$$

here W is the power flux density; G_{rx} is the gain of the receiving antenna array in the direction of the radiation source; λ is the wavelength of the GPS Signal. Taking into account the above relation, the condition for receiving GPS Signals under the influence of spoofing interference takes the form

$$\begin{aligned} W_i G_{rx}(\theta_i) > W_{Si} G_{rx}(\theta_{Si}) &\;\Rightarrow\; s_i\left(l\Delta t_{L_1}\right) \\ W_i G_{rx}(\theta_i) < W_{Si} G_{rx}(\theta_{Si}) &\;\Rightarrow\; s_{S_i}\left((l+k)\Delta t_{L_1}\right) \end{aligned}$$

As could be seen from the above expression, the reception condition is determined by the power flux-density of the signal at the point of receiving GPS signals and the gain of the receiving antenna in the direction of the radiation source.

The use of the antenna array with digital beamforming allows for minimizing the effect of spoofing interference by the spatial selection of spatial frequency signals, which is accompanied by a change in the values of the amplitude coefficients P_i and P_{si}. As could be seen from Fig. 4, spoofing interference can penetrate the spatial frequency signal processing channel in two cases:

- when the spoofing interference transmitter is in the solid angle, the angular size of which is determined by the width of the directional pattern of the fixed beam which is formed by an antenna array with digital beamforming;
- when the direction to the interference transmitter coincides with the direction of orientation of the side lobes of the antenna array beam pattern.

Detection of the fact that the spoofing interference appears in the antenna array spatial frequency channel allows refusing to process the C/A-code signal used as spoofing interference, and not to use this signal when calculating the current position of the GPS unit.

A distinctive feature of spoofing interference is the stability of the position of its transmitter. At the same time, the average motion of the GPS satellite is around $1.45 \cdot 10^{-4}$ rad/s. Depending on the width of the Antenna Array Fixed Beam patterns, the GPS satellite moves from one spatial frequency beam to another, which is accompanied by the reception of the GPS satellite signal in different spatial frequency channels. For spatial frequency beams with an elevation angle of more than 45º, the time spent by the satellite and, accordingly, receiving the signal in the spatial frequency channel is from 5.5 min. for the antenna array 32×32 dimension up to 20 min for the antenna array 8×8 dimension. When a GPS satellite is moving to the antenna array beams with a lower elevation angle, the time spent by the GPS satellite within one fixed beam increases to 10÷17 min for a 32×32 antenna array and up to 25÷35 minutes for an 8×8 antenna array. Thus, the blocking of the Spatial Frequency Channels in which the spoofing interference with detected C/A-code appears can be carried out for a limited time, after which the use of the signal of this C/A-code structure can be resumed, provided that the reception of signals in the Spatial Frequency Channel with identified spoofing interference is present is blocked.

Similarly, the reception of GPS satellite signals under the influence of jamming interference can be optimized [15]. The use of the antenna array with digital beamforming allows, based on the analysis of signals in the spatial frequency channels, carrying out a spatial selection of fixed beams affected by this type of interference, and to exclude these spatial frequency channels from the processing algorithm.

Conclusion

1. Until now, the issue of increasing the noise immunity and resistance of GPS signal reception based on the spatial selection of interference sources and various methods of adapting receivers to the effects of interference remains relevant.
2. The use of antenna arrays with digital beamforming makes it possible to implement a spatial selection of GPS signals, to identify and exclude sources of jamming and spoofing interference from further processing. The use of antenna arrays with digital beamforming allows you to increase the noise immunity of reception by at least 13.5 dB. Further increase in noise immunity is possible through the use of digital masks to reduce the level of side lobes to the level of -30 ÷ -40 dB.
3. The use of TLE NORAD information and satellite ephemeris from the GPS navigation message makes it possible to reduce the field of view of the celestial sphere by excluding from the processing of information the channels of spatial frequencies of the antenna array with digital beamforming, in which GPS signals should not be received, and to localize areas of the celestial sphere in which there are sources of spoofing interference. This leads to a reduction in the number of calculations and an increase in the noise immunity and resistance of GPS signal reception.
4. Taking into account the predicted movement of GPS satellites in the visible hemisphere allows you to optimize the number of C/A-code signals used to solve navigation problems and obtain accurate time, locate sources of jamming and spoofing interference, and dynamically correct the list of C/A code signals used depending on the current GPS satellite positions.

References

1. Hrigor'ev L.N. Cifrovoe formirovanie diagrammy napravlennosti v fazirovannyh antennyh reshetkah. / Digital beamforming in phased antenna array / M.: Radiotehnika, 2010. – 144 p.
2. Phased Array Antennas. Second edition / R.C. Hansen / © 2009 by John Wiley & Sons, Inc. All rights reserved.
3. Ustrojstva SVCh i antenny. Proektirovanie fazirovannyh antennyh reshetok: Uchebn. posobie dlja vuzov / Microwave devices and antennas. Phased array design: / Pod. red. D.I. Voskresenskogo. Izd. 4-e, pererab. i dop. – M.: Radiotehnika, 2012. – 744 p.
4. Konin V.V., Harchenko V.P. Sistemy sputnikovoj radionavigacii / Satellite radio navigation systems / V.V. Konin, V.P. Harchenko; Nacional'nyj aviacionnyj universitet. - K.: Holteh, 2010. – 520 p.
5. Recommendation ITU-R M.1787-4 (01/2022) Description of systems and networks in the radio navigation-satellite service (space-to-Earth and space-to-space) and technical characteristics of transmitting space stations operating in the bands 1164-1215 MHz, 1215-1300 MHz. M Series. Mobile, radiodetermination, amateur, and related satellite services
6. Varakin L.E. Sistemy svjazi s shumopodobnymi signalami. / Communication systems with noise-like signals. / M.: Radio i svjaz', 1985. – 384 p.
7. Djatlov A.P., Djatlov P.A., Kul'bikajan B.H. Radiojelektronnaja bor'ba so sputnikovymi radionavigacionnymi sistemami. / Electronic warfare with satellite radio navigation systems / M.: Radio i svjaz', 2004. – 226 p.
8. Mihajlov R. L. Radiojelektronnaja bor'ba v Vooruzhennyh silah SShA: voenno-teoreticheskij trud. / Electronic warfare in the US Armed Forces: military-theoretical work / SPb.: Naukoemkie tehnologii, 2018. – 131 p.
9. On GPS spoofing of aerial platforms: a review of threats, challenges, methodologies, and future

research directions / Shah Zahid Khan, Mujahid Mohsin and Waseem Iqbal / PeerJ Computer Science, 6 May 2021 / DOI 10.7717/peerj-cs.507

10. Detection and Mitigation of GPS Spoofing Based on Antenna Array Processing / J. Magiera and R. Katulski / Journal of Applied Research and Technology, Vol. 13, February 2015, pp.45-57

11. NLOS Multipath Classification of GNSS Signal Correlation Output Using Machine Learning / Taro Suzuki and Yoshiharu Amano / Sensors 2021, 21, 2503. https://doi.org/10.3390/s21072503

12. Detection of Spoofing Attack using Machine Learning based on Multi-Layer Neural Network in Single-Frequency GPS Receivers / E. Shafiee, M. R. Mosavi and M. Moazedi / The Journal of Navigation, Volume 71, Issue 1, January 2018, pp. 169 – 188 / DOI: https://doi.org/10.1017/S0373463317000558

13. Study of correlation characteristics of spreading signal sequences with code division of channels of satellite radio navigation systems / D.V. Odel, A.P. Beetle / Reshetnev readings. Control systems, space navigation, and communications. 2009. pp. 154-156.

14. Satellite Communication Systems. Systems, Techniques, and Technology. Fifth Edition / Gerald Maral, Michel Bousquet / © 2009 John Wiley & Sons Ltd.

15. Morales-Ferre, R. A Survey on Coping with Intentional Interference in Satellite Navigation for Manned and Unmanned Aircraft / R. Morales-Ferre, P. Richter, E. Falletti, A. de la Fuente and E. S. Lohan / *IEEE Communications Surveys & Tutorials*, vol. 22, no. 1, pp. 249-291, Firstquarter 2020, DOI: 10.1109/COMST.2019.2949178. Retrieved from https://ieeexplore.ieee.org/document/8882350/references#references

16. Where and how to get the orbital parameters (Two-Line Element) of a satellite over a period of time? -NORAD tutorial- / Joséphine Picot / Retrieved from https://josephinepicot.medium.com/where-and-how-to-get-the-orbital-parameters-two-line-element-of-a-satellite-over-a-period-of-time-f955f65b6cb

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Підвищення стійкості прийому сигналу GPS до електромагнітних змін, jamming та spoofing, основане на використанні системи антенних решіток з цифровим формуванням променю та інформацією NORAD TLE

Проблематика. У цій статті автори пропонують нове рішення проблеми підвищення стабільності прийому GPS-сигналу від перешкод і перешкод на основі просторової вибірковості антени приймача. Просторова вибірковість забезпечується інтегрованим застосуванням технології цифрового формування променя з фазованою решіткою та використанням інформації TLE NORAD.

Мета досліджень. Метою дослідження є розробка методології комплексної ідентифікації джерел перешкод радіонавігаційній системі та підвищення завадостійкості прийому радіонавігаційних сигналів шляхом просторової селекції шляхом використання технологій цифрового формування променя.

Методика реалізації. У процесі дослідження були використані теоретичні методи цифрового формування променя приймально-фазованої антенної системи, опис вмісту дворядкового інформаційного елемента NORAD та алгоритми розрахунку поточного положення космічного корабля.

Результати досліджень. В результаті проведених досліджень сформовано модель прийому GPS-сигналу з використанням просторової селекції джерел GPS-сигналу та джерел перешкод, розроблено методику підвищення стійкості прийому GPS-сигналу впливом різних типів завад, структурну схему. Запропоновано приймальний пристрій, що реалізує розроблену методику шляхом інтегрованого застосування технології цифрового формування променя фазованої антенної решітки та використання інформації TLE NORAD.

Висновки. Подано концептуальну ідею методу та технічне рішення щодо реалізації запропонованого методу. Реалізація способу дозволить підвищити стабільність прийому сигналу GPS під впливом перешкод типу jamming та spoofing.

Ключові слова: *прийом сигналу GPS; цифрове формування променя; фазована антенна решітка.*