http://dx.doi.org/10.35596/1729-7648-2022-20-8-51-58

Original paper
Оригинальная статья

UDC 621.396

SPOOFING'S SELECTION AND COMPENSATION IN THE GLOBAL NAVIGATION SATELLITE SYSTEM CONSUMER NAVIGATION EQUIPMENT WITH MULTI-CHANNEL ANTENNA SYSTEM

H. Kh. SAAD, M. A. LOBAN

Belarusian State University of Informatics and Radioelectronics (Minsk, Republic of Belarus)

Submitted 28.06.2022

Abstract. A method for selecting spoofing signals in consumer equipment with a multichannel antenna system is proposed. The method provides for consistent filtering of the received signals at the outputs of all antenna system elements and by ranging codes of all navigation satellites, detection and measurement of the time delay of the true and false navigation signals in each code channel by the output signal of one of the antenna system elements, measurement of the phase difference of the signals at the outputs of the antenna system elements and the selected reference element for the estimated time delay in each channel by code. Compensation of spoofing signals is carried out in the spatial domain by estimating the correlation matrix of processes at the outputs of the antenna system channels by the corresponding countdown of code channel signals after matched filtering and forming of a weight vector while minimizing the output power of spoofing signals by directly inverting the estimate of the correlation matrix and carrying out weight processing of the adopted implementation. The simulation results are presented, confirming the efficiency of the method.

Keywords: global navigation satellite system, spoofing, multichannel antenna system, statistical hypothesis testing, navigation signal, receiving channel, phase difference.

Conflict of interests. The authors declare no conflict of interests.

For citation. Saad H. Kh., Loban M. A. (2022) Spoofing's Selection and Compensation in the Global Navigation Satellite System Consumer Navigation Equipment with Multi-Channel Antenna System. *Doklady BGUIR.* 20 (8), 51–58. http://dx.doi.org/10.35596/1729-7648-2022-20-8-51-58.

СЕЛЕКЦИЯ И КОМПЕНСАЦИЯ СИГНАЛОВ СПУФИНГА В ГРАЖДАНСКОЙ АППАРАТУРЕ ПОТРЕБИТЕЛЯ ГЛОБАЛЬНОЙ НАВИГАЦИОННОЙ СПУТНИКОВОЙ СИСТЕМЫ С МНОГОКАНАЛЬНОЙ ПРИЕМНОЙ СИСТЕМОЙ

Х. Х. СААД, М. А. ЛОБАН

Белорусский государственный университет информатики и радиоэлектроники
(г. Минск, Республика Беларусь)

Поступила в редакцию 28.06.2022

Аннотация. Предложен метод селекции сигналов спуфинга (от англ. spoofing – подмена) в гражданской аппаратуре потребителя с многоканальной антенной системой. Метод предполагает согласованную фильтрацию принимаемых сигналов на выходах всех элементов антенной системы и по дальномерным кодам всех навигационных спутников, обнаружение и измерение времен задержки истинных и ложных навигационных сигналов в каждом кодовом канале по выходному сигналу одного из элементов антенной системы, измерение разности фаз сигналов на выходах элементов антенной системы и выбранного опорного элемента по расчетным временам задержки в каждом канале по коду. Компенсация сигналов спуфинга осуществляется в пространственной области путем оценивания корреляционной матрицы процессов на выходах каналов антенной системы по соответствующим отсчетам сигналов кодовых каналов после согласованной фильтрации, формирования весового вектора при минимизации выходной мощности сигналов спуфинга путем непосредственного обращения оценки корреляционной матрицы и проведения весовой обработки принятой реализации. Представлены результаты моделирования, подтверждающие эффективность метода.

Ключевые слова: глобальная навигационная спутниковая система, спуфинг, многоканальная антенная система, проверка статистических гипотез, навигационный сигнал, приемный канал, разность фаз.

Конфликт интересов. Авторы заявляют об отсутствии конфликта интересов.

Для цитирования. Саад, Х. Х. Селекция и компенсация сигналов спуфинга в гражданской аппаратуре потребителя глобальной навигационной спутниковой системы с многоканальной приемной системой / Х. Х. Саад, М. А. Лобан // Доклады БГУИР. 2022. Т. 20, № 8. С. 51–58. http://dx.doi.org/10.35596/1729-7648-2022-20-8-51-58.

Formulation of the problem

Nowadays, Global Positioning System (GPS) spoofing or Global Navigation Satellite System (GNSS) spoofing in general in addition to other types of either intentional or unintentional interference have been a main risk for the PVT solutions attained by the consumer navigation equipment. To clarify more what we are talking about, intentional interference such as jamming which is confined in emitting for example a low power signal similar to the GPS transmitted signal (L1 carrier frequency in our situation) is enough to mask the GPS navigation signal preventing the CNE from receiving the true navigation signal the way which will lead to the blockage of the receiver's functionality. Add to that, spoofing which is more dangerous than jamming is considered one of the main challenges dealing with the intentional interference facing the GPS receiver's accuracy; it can be defined as transmitting fake GNSS signals with the same navigation message's parameters (latitude, longitude, altitude, time, etc.), thus deceiving the user's segment, leading him/her to follow a different path than the intended one. Furthermore, unintentional interference such as the internal GPS receiver noise which is considered as a source of the navigation signal's distortion and the multipath (reflection of the desired navigation signals) is also classified as a pivotal base for errors affecting the accuracy of the receiver. On the other hand, and according to the previous explanation, and in order to get rid of such challenges (we will focus on the most harmful type _ spoofing), we propose in this article a methodology that should be able to detect the GPS spoofing signals from the true navigation satellites' signals with the ability for post processing attaining the compensation and the suppression of the false signals (spoofing signals) in addition to the jamming signals and other sources of interference. In order to achieve our goal, an adaptive array antenna or adaptive beamforming technique must be used, thus the use of multichannel array antenna (using multi-elements).

The aim of such process is keeping the receiving system antennas' radiation steered towards the desired signals [1–3] in addition to the nulling toward any other suspicious signal (jamming, spoofing, etc.); such procedure will be able at the end to save the receiver's accuracy stability giving the precise PVT solutions. Some of the results obtained previously make use of complex algorithms for adapting and suppression for the jamming and spoofing signals, using Spoofing and Jamming Suppression Method (SJSM), multiple signal classification (MUSIC), AntiJamming-AntiSpoofing (AJ-AS) algorithms, etc. One of the main problems in such results is the inability of spoofing suppression or the fair anti-spoofing results. Some of the results show that the some of these algorithms can only suppress jamming without the ability to suppress spoofing attack, and vice versa [4]. We can notice that the used algorithm for such results obtained can't lead to the integrity between jamming and spoofing prevention. At the end of this part, we can say that a brief description of the situation model and the receiving system (general geometry, number of channels, spoofing tool problem, etc.) is given highlighting the essential neediness to face such types of interference.

Preliminary signal processing

In this section, the main preprocessing operations will presented and mathematically formalized; such stages can be confined in the compression of signals at the outputs of antenna system elements in all receiving channels by code, detection of navigation signals (true and false) and estimation of their delay times, measurement of the phase difference of signals at the outputs of antenna system elements for estimated time points.

Assume $T = N_{T_0} T_0$; $m = \overline{1, M}$; $M = F_s T$; $M_1 = F_s T_0$, where N_{T_0} is the number of signal durations in the simulation interval and T_0 is the duration of the navigation signal; F_s is a sampling frequency, M is the number of the samples in the simulation interval, and M_1 is the number of samples in the duration of the navigation signal.

Note that the vector $\mathbf{Y} = (\mathbf{y}_1, \mathbf{y}_2, ..., \mathbf{y}_M)$ defines the multichannel implementation at the input of the processing system, which is composed up of vectors $\mathbf{y}_m = \left(\dot{Y}_{1,m}, \dot{Y}_{2,m}, ..., \dot{Y}_{L,m}\right)^{\mathrm{T}}$ of signal sampling $\dot{Y}_{l,m}$ of the l^{th} receiving channel of the array antenna system, $l = \overline{1, L}$, L is the number of receiving channels.

We will perform consistent filtering of the a**φμν**dapted multichannel implementation for all visible navigation satellites

$$\mathbf{s}_n(m) = MF_n(\mathbf{y}_m), \tag{1}$$

where $MF_n(\bullet)$ is the operator of matched filtering (convolution with the impulse response of the optimal filter) in the n^{th} receiving channel; $n = \overline{1, N}$; N is the number of the navigation satellites; $\mathbf{S}_n = (\mathbf{s}_n(1), ..., \mathbf{s}_n(M))$; $\mathbf{s}_n(m) = \left(\dot{S}_n(1,m), ..., \dot{S}_n(L,m)\right)^{\mathrm{T}}$ is a matrix of signals' samples in the output of the match filters; $\dot{S}_n(l,m)$ is the m^{th} sample of the signal in the output of l^{th} element array and match filter for n^{th} satellite.

For each navigation satellite (channel by code), we will find the index of the maximum of the signal module at the output of the first (or any other reference channel) at the interval of the duration of the navigation signal

$$i_n = \arg \max_{\substack{m \\ m=\overline{1, M_1}}} |\dot{S}_n(1,m)|, \tag{2}$$

and we estimate the phases' vectors $\boldsymbol{\varphi}_n^{(1)} = \left(\varphi_{1,n}^{(1)}, ..., \varphi_{L,n}^{(1)}\right)^{\mathrm{T}}$,
where

$$\varphi_{l,n}^{(1)} = \arg \dot{S}_n(l, i_n) \tag{3}$$

is the signal's phase at the output of the receiving channels for finding the maximum.

Let 's take the first receiving channel as a reference and recalculate the phase estimation according to the rule, knowing that it should be in the interval [0, 2π]

$$
\nu_{l,n} = \begin{cases} \Delta\varphi_{l,n}, \ \Delta\varphi_{l,n} < 2\pi; \\ \Delta\varphi_{l,n} - 2\pi\left[\dfrac{\Delta\varphi_{l,n}}{2\pi}\right], \ \Delta\varphi_{l,n} > 2\pi; \end{cases} \quad \begin{matrix} \Delta\varphi_{l,n} = \varphi_{l,n}^{(1)} - \varphi_{1,n}^{(1)}; \\ \Delta\varphi_{l,n} = \Delta\varphi_{l,n} + 2\pi, \ \text{if } \Delta\varphi_{l,n} < 0; \ l = \overline{2,L}, \end{matrix} \tag{4}
$$

and we form a vector of phase differences of signals at the outputs of the receiving channels

$$
\nu_n = \left(\nu_{2,n}, \ldots, \nu_{L,n}\right)^{\mathrm{T}}
$$

with dimension is $L-1$ for first maximum.

Similarly, we will find the second maximum and perform the same operations:

$$
k_n = \arg \max_{\substack{m \\ m=\overline{1,M_1}; \\ m \notin i_n \pm \Delta m}} |\dot{S}_n(1,m)|; \tag{5}
$$

where $\Delta m = \left[F_S / \Delta f_0\right]$ is the bandwidth of the compressed signal's samples, and we estimate the vectors $\varphi_n^{(2)} = \left(\varphi_{1,n}^{(2)}, \ldots, \varphi_{L,n}^{(2)}\right)^{\mathrm{T}}$;

$$
\varphi_{l,n}^{(2)} = \arg \dot{S}_n\left(l, k_n\right) \tag{6}
$$

of phases of the signals at the outputs of the receiving channels for the second maximum.

And recalculate the phase estimates according to the rule

$$
\mu_{l,n} = \begin{cases} \Delta\varphi_{l,n}, \ \Delta\varphi_{l,n} < 2\pi; \\ \Delta\varphi_{l,n} - 2\pi\left[\dfrac{\Delta\varphi_{l,n}}{2\pi}\right], \ \Delta\varphi_{l,n} > 2\pi; \end{cases} \quad \begin{matrix} \Delta\varphi_{l,n} = \varphi_{l,n}^{(2)} - \varphi_{1,n}^{(2)}; \\ \Delta\varphi_{l,n} = \Delta\varphi_{l,n} + 2\pi, \ \text{if } \Delta\varphi_{l,n} < 0; \ l = \overline{2,L} \end{matrix} \tag{7}
$$

and we form a vector of phase differences of signals at the outputs of the receiving channels

$$
\mu_n = \left(\mu_{2,n}, \ldots, \mu_{L,n}\right)^{\mathrm{T}}.
$$

Vectors ν_n and μ_n are the bases for the selection of spoofing signals and the result of preprocessing.

Selection of the spoofing signal

Taking into account the periodicity of the phase, we define the Euclidean distance between two phase values φ_1 and φ_2 as

$$
D_\varphi\left(\varphi_1, \varphi_2\right) = \arccos\left(\cos\varphi_1 \cos\varphi_2 + \sin\varphi_1 \sin\varphi_2\right), \ D\left(\varphi_1, \varphi_2\right) \geq 0 \tag{8}
$$

and the Euclidean distance between the two vectors of phase differences at the outputs of the receiving channels as

$$
D(\nu, \mu) = \sum_{l=2}^{L} D_\varphi\left(\nu_l, \mu_l\right), \ D \geq 0. \tag{9}
$$

Let's form an upper-triangular matrix of Euclidean distances between the measured vectors of phase differences at the outputs of the receiving channels with a dimension of $2N$ rows and columns

$$
\mathbf{D} = \left(\begin{array}{ccccc:cccccc}
0 & D(\nu_1,\nu_2) & D(\nu_1,\nu_3) & \ldots & D(\nu_1,\nu_N) & D(\nu_1,\mu_1) & D(\nu_1,\mu_2) & \cdots & \ldots & D(\nu_1,\mu_N) \\
 & 0 & D(\nu_2,\nu_3) & \ldots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
 & & 0 & \ddots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
 & & & 0 & D(\nu_{N-1},\nu_N) & D(\nu_{N-1},\mu_1) & D(\nu_{N-1},\mu_2) & \ldots & \cdots & D(\nu_{N-1},\mu_1) \\
 & & & & 0 & D(\nu_N,\mu_1) & D(\nu_N,\mu_2) & \ldots & \ldots & D(\nu_N,\mu_N) \\
\hdashline
 & & & & & 0 & D(\mu_1,\mu_2) & D(\mu_1,\mu_3) & \ldots & D(\mu_1,\mu_N) \\
 & & & & & & 0 & D(\mu_2,\mu_3) & \ldots & \vdots \\
 & & & & & & & \ddots & \ldots & \vdots \\
 & & & & & & & & \ddots & D(\mu_{N-1},\mu_N) \\
 & & & & & & & & & 0
\end{array}\right).
$$

The element $D_{q,p}$ of the matrix corresponds to: $n = q$ satellite and i_n samples if $q \le N$ and to $n = q - N$ satellite and k_n samples if $N < q \le 2N$; $n = p$ satellite and i_n samples if $p \le N$ and to $n = p - N$ satellite and k_n samples if $N < p \le 2N$.

Let's find the minimum element of the matrix **D** from above the main diagonal, the indices $q_{\min}$, $p_{\min}$ of this element

$$\left(q_{\min}, p_{\min}\right) = \arg \min_{\substack{q,p \\ p>q,\, D_{q,p} \ne 0}} D_{q,p}. \tag{10}$$

These indices determine the numbers of navigation satellites and corresponding maxima for which the Euclidean distance between the phase measurements is minimum.

When the following condition is met

$$\min D_{q,p} < h_D, \tag{11}$$

where h_D is the threshold for deciding that the signals are coming from a single source (spoofer), let's include $b_1 = q_{\min}, b_2 = p_{\min}$ indices; $q_{\min}, p_{\min}$ in the vector **b** indices of spoofing signals.

In addition to that, if the above condition isn't achieved, then there won't be a presence of spoofing signals. Let's add the **b** vector with the column indices of all elements in the $q_{\min}$ row and the indices of all elements in the $p_{\min}$ column whose values are less than the specified threshold:

$$\mathbf{b} \leftarrow \mathrm{Add}\begin{pmatrix} \forall p,\, D_{q_{\min},p} < h_D,\, p > q_{\min} \\ \forall q,\, D_{q,p_{\min}} < h_D,\, q < p_{\min} \end{pmatrix}. \tag{12}$$

As a result, vector **b** will contain indices of the corresponding signals received from one direction. This process can be considered as the process of dividing (clustering) the selected maxima into two regions containing signals from one direction and from different directions.

Spatial domain spoofing compensation procedure

The main operations for compensating spoofing signals in the spatial domain are presented and mathematically formalized: estimation of the correlation matrix, calculation of the weight vector, and weight processing. In a multichannel array antenna system, we can compensate for the source (or several sources) of interference, as well as the spoofing signal.

Using the obtained indices, we estimate the correlation matrix of signals coming from one direction (spoofing signals) as:

$$\widehat{\mathbf{R}} = \frac{1}{N_{T_0}\Theta(\mathbf{b})} \sum_{r=1}^{N_{T_0}} \sum_{q=1}^{\Theta(\mathbf{b})} \mathbf{s}_{n(b_q)}\left(m\left(b_q\right) + M_1 r\right) \mathbf{s}^H_{n(b_q)}\left(m\left(b_q\right) + M_1 r\right), \tag{13}$$

where H is the Hermitian conjugation (transpose and complex conjugation); $\Theta(\mathbf{b})$ is the length of vector **b**;

$$n\left(b_q\right) = \begin{cases} b_q,\, b_q \le N; \\ b_q - N,\, b_q > N; \end{cases} \quad m\left(b_q\right) = \begin{cases} i_n\left(b_q\right),\, b_q \le N; \\ k_n\left(b_q\right),\, b_q > N; \end{cases} \tag{14}$$

n, m represent the number of satellite and the number of samples respectively corresponding to the index b_q.

Since the correlation matrix is estimated by a relatively small number of samples (typically N_{T_0} = 4–5, $\Theta(\mathbf{b})$ = 4–8, $N_{T_0}\Theta(\mathbf{b})$ = 16–40) in accordance with [4, 7], it is recommended to regularize it in accordance with the expression

$$\widehat{\mathbf{R}}_r = \widehat{\mathbf{R}} + \mu_r \sigma_0^2 \mathbf{I}, \tag{15}$$

where μ_r is a regularization's coefficient; σ_0^2 is a power of internal noise in the output of the match filter; **I** is the unit matrix of the corresponding dimension.

Then we can calculate the weight vector as [4]

$$\mathbf{w} = \widehat{\mathbf{R}}_r^{-1}\mathbf{e}, \tag{16}$$

where $\mathrm{e} = (1, 0, \ldots, 0)^{\mathrm{T}}$, after normalization of the weight vector, we get

$$\mathbf{w} = \frac{\mathbf{w}}{|\mathbf{w}|}. \tag{17}$$

Weight vector can be used to weight processing signals **Y**, **S** to input of receiving channels or to the output of match filters according to expressions

$$\dot{Y}_m^{\text{wp}} = \mathbf{w}^H \mathbf{y}_m;\ \dot{S}_n^{\text{wp}}(m) = \mathbf{w}^H \mathbf{s}_n(m). \quad (18)$$

As a result, there is a rejection of spoofing signals. If there is masking interference from one or more directions in the received implementation, it will also be suppressed. The stages of algorithm shown are in Fig. 1.

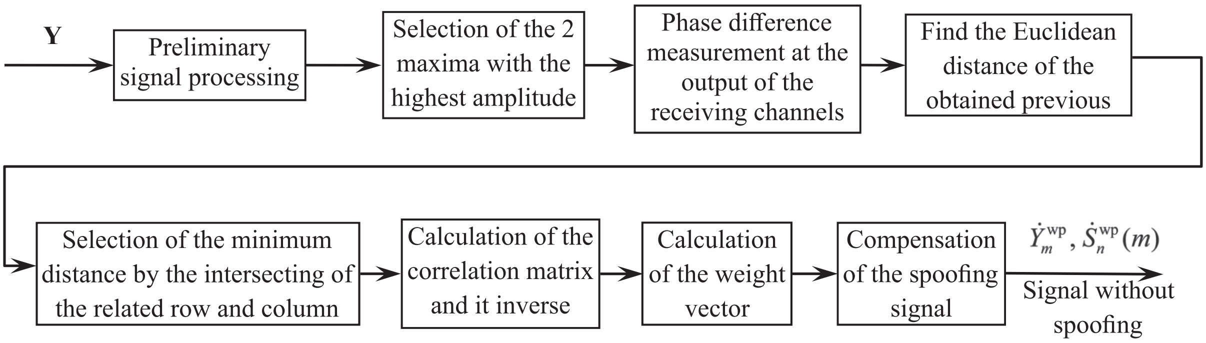

Fig. 1. The main stages of the processing algorithm for spoofing compensation

Knowing that if the radial velocity is negative, Doppler shift will be positive, they are inversely proportional to each other. Moreover, if the reflection is very high value, then the processing of spoofing suppression will decrease and the power of the output noise in the processing operation will decrease too. Also, and dealing with the power of noise, as the last at the output filter increases, then and accordingly to the time delay of the true navigation signals, the accuracy will be minimized.

Simulation results and discussion

The simulation of the model is done using Matlab software. In our mode, we set the positions of the array antenna elements, the directivity of these elements, the coordinates of the GPS navigation satellites, coordinates of the spoofer, jammer, false positioning coordinates; add to that all the parameters related to the GPS NSs, power transmitted by the GPS NS, power of the spoofer, jammer, azimuths and elevations for all the NSs, spoofer, jammer, etc… In our model, we calculate the signal at the input of the receiving channels and processing procedure is done according to the formulas (1)–(18). Then we detect the navigation signal, estimate the time delay, and measure the coordinates of the CNE. In the simulation process, we set the following parameters: the carrier frequency f_0 = 1575.42 MHz, $\lambda = c/f_0$, bandwidth of the receiving channels is 4 MHz, T_0 = 1 ms, F_s = 4 MHz, L = 4, N_{T_0} = 4, the distance between the elements of the array antenna system is $\lambda/2$, the spectral power density of the noise power is $N_0 = 10^{-20}$ W/Hz. Note that the power of the spoofer is 0.01 W. Moreover, the parameters of the GPS NS are standard [5, 6]. We assume that the coordinates of the spoofer and the false position are respectively the following: (–1500, –5000,20) and (7000,8000,0). Furthermore, the coordinates of the array antenna elements are (0,0,0). The gain in zenith for the array's elements is 3 dBi for each; the directivity of the array elements is represented as the cosine of the angle between the zenith and the source's direction (spoofer, NS, jammer, etc.).

The results of the simulation are shown in Fig. 2. In the first part of the figure, we can notice obviously that at the output of the filter the indices of maximum for the four true signals and the four spoofing signals, and after the operation of the processing algorithm, the compensation and the suppression of the spoofing signals while receiving only the navigation satellites' signals (true signals) with increasing in the amplitudes dealing mainly with the first and the second true signals.

Tabl. 1 shows the gain values for the adapted directional pattern towards the directions of the spoofer and the NSs in decible unit with reference to the isotropic antenna (dBi) for 10 iterations. Add to that, there are also the values for the NSs' signal to noise ratio (SNR) and the resulting error in estimating the coordinates of the navigation receiver. Note that the values of the signal-to-noise ratio exceeding 5–6 are not random.

The results in table 1 show that for all gain values of the adapted directivity towards the spoofer < –40 dBi; for 5–6 navigation satellites, the gain of the adapted antenna system is 1.0–1.5 with a typical SNR,

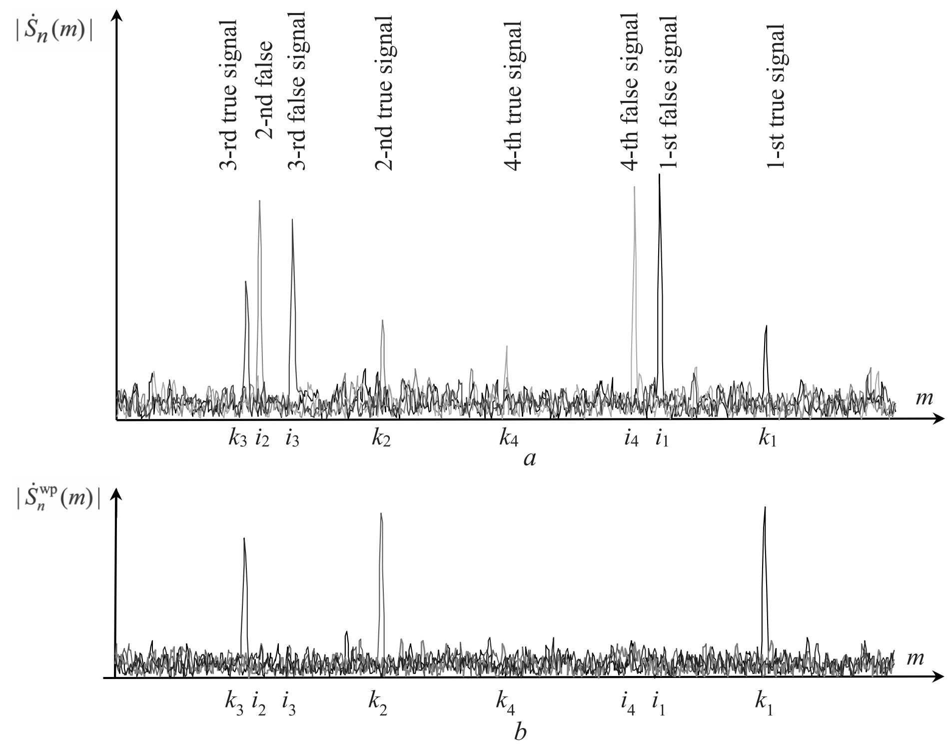

Fig. 2. The true and the spoofing signals at the output of the match filter for the 1st channel and after the processing algorithm: *a* – at the output of the match filter for 1st channel; *b* – after the processing algorithm

Table 1. The adaptive beamforming towards the spoofer and the NSs in addition to the NSs' SNR

№ of processing	Gain, dBi, to spoofer	Gain, dB / SNR, to NSs								Error, m
		1	2	3	4	5	6	7	8	
1	< –40	1.6 / 41	2.1 / 58	0.6 / 27	0.1 / 6	1.2 / 1,1	0.01 / 0,3	1.2 / 0,3	0.01 / 1.1	52
2	< –40	1.1 / 32	1.1 / 31	0.4 / 20	0.1 / 8	1.9 / 42	0.03 / 1,6	0.6 / 10	0.02 / 4.8	37
3	< –40	1 / 35	1.4 / 54	0.5 / 14	0.1 / 1	1.9 / 68	0.04 / 1.0	1.0 / 27	0.01 / 0.5	66
4	< –40	1.3 / 47	1.1 / 34	0.6 / 29	0.1 / 6	1.5 / 54	0.04 / 7.0	0.4 / 0.9	0.01 / 1.4	129
5	< –40	0.8 / 32	1.3 / 47.4	0.4 / 25	0.07 / 4	1.9 / 1.9	0.03 / 0.7	1.3 / 31	0.01 / 1.6	10
6	< –40	1.5 / 60	1.4/ 34.8	0.6 / 8	0.04 / 4	1.2 / 0.2	0.03 / 1.7	1.2 / 3.1	0.01 / 1.8	36
7	< –40	1.6 / 46	1.9/ 58.9	0.7 / 21	0.1 / 8	1.2 / 2.4	0.02 / 1,2	0.8 / 0.1	0.01 / 0.9	54
8	< –40	1.4 / 47	1.6/ 40.1	0.8 / 35	0.07 / 4	1.3 / 23	0.04 / 1,9	0.1 / 0.3	0.01 / 1.5	84
9	< –40	1.2 / 29	1.3/ 48.9	0.6 / 21	0.09 / 1	1.6 / 2.6	0.03 / 1,8	0.8 / 0.3	0.01 / 1.3	22
10	< –40	1.5 / 42	1.3/ 42	0.5 / 15	0.1 / 9	1.4 / 0.2	0.03 / 0,7	0.7 / 1.4	0.01 / 0.7	80

but there are 2 NSs in the direction of which the gain is close to zero. This may be due to their close location to the direction of the source of spoofing, or may be a random result in digital diagram formation. The error is typical for 1 repetition for the NS signal.

The variable parameters of the algorithm for a given geometry of a multichannel receiving system are: the threshold value h_D for the selection of measurements of the phases of signals related to one direction and the number N_{T_0} of repetition periods of the navigation signal used in the selection. The threshold value h_D can be determined based on the assumption that the matrix elements **D** representing the differences in the signals' phases estimation will have a normal distribution with zero mathematical expectation and variance determined by the formula of potential measurement accuracy. Therefore, the threshold can be determined based on the probability of a random variable falling into a given interval, or, in a particular case, according to the "three sigma" rule.

With an increase in the number N_{T_0} of the navigation signal's repetition periods, the accuracy of the estimation of the correlation matrix by spoofing signals increases. This leads to an increase in the degree of suppression of spoofing signals and an increase in the signal-to-noise ratio due to a decrease in the norm of the vector of weighting coefficients [7] and a decrease in the power of internal noise after weight processing.

The total number of independent samples used in the evaluation of the interference correlation matrix is $N_{T_0} N_{ns}$, where N_{ns} is the number of navigation satellites for which spoofing signals are present. If the condition $N_{T_0} N_{ns} \geq 2N_{ar}$ is met, where N_{ar} is the number of elements in the array antenna system, the signal-to-noise loss will be less than 3 dB [7]. With a further increase in the number of counts used, losses are reduced. Therefore, at N_{ns} = 5–6, it is enough to choose N_{T_0} = 2–4. With the specified parameters, the detection of the spoofing signal and the adjustment of the weighting coefficients in the multichannel receiving system can be carried out periodically with an interval of 50–100 ms. This will ensure timely detection of spoofing signals, including with the initial coincidence of true and false navigation signals by the delay time and a “smooth” change in the delay time and the Doppler shift of the false signal frequency [2, 3].

Conclusion

After showing the main steps of our implementation concerning the different interference sources mainly jamming and spoofing taking in consideration the various variables and parameters and their impact in the processing algorithm, we attained at the end the expected results with the compatibility and the stability of the proposed adaptation in the multichannel receiving system. Detection of the spoofing signals and selecting them is considered a successful technique in the way of protecting the consumer navigation equipment, but going beyond this and suppressing such fake signals is the most essential aim, and that’s what we have reached in this article.

References

1. Korotkevich A., Saad H. Kh., Stupin K. (2021) Models of GPS-Spoofing of Civil Navigation Equipment of Consumer. *News of Science and Technology*. 59 (4), 48–56.
2. Ali Jafarnia-Jahromi, Ali Broumandan, John Nielsen, Gйrard Lachapelle (2012) GPS Vulnerability to Spoofing Threats and a Review of Antispoofing Techniques. *International Journal of Navigation and Observatio.* 16. Doi: 10.1155/2012/127072.
3. Yang Gao, Hong Li, Mingquan Lu, Zhenming Feng (2013) Intermediate Spoofing Strategies and Countermeasures. *Tsinghua Science and Technology*. 18 (6), 599–605.
4. Robert A. Monzingo, Randy L. Haupt, Thomas W. Miller (2011) *Introduction to Adaptive Arrays, 2nd ed.* SciTech Publ. 686.
5. Spilker Jr. James J., Axelrad P., Parkinson Bradford W. (1996) *Global Positioning System: Theory and Application, Volume 1*. Washington, American Institute of Aeronautics and Astronautics. 1 Jan., 793.
6. IS-GPS-200: Interface Specification. Navstar GPS Space Segment. Navigation User Interfaces. *Navstar GPS*, 2004. 207.
7. Reed I. S., Mallett J. D., Brennan L. E. (1974) Rapid Convergence Rate in Adaptive Arrays. *IEEE Trans. Aerospace and Electronic Systems*. 10 (6), 853–863.

Authors’ contribution

Saad H. Kh. developed the statement of the problem, proposed the procedure for processing the accepted implementation, and developed the mathematical model of a multichannel receiving device, conducted modeling and the analysis of the results obtained.

Loban M. A. took part in modeling, discussing the results and prepared the manuscript of the article for publication.

Information about the authors

Saad H. Kh., Postgraduate at the Department of Information Radiotechnologies of the Belarusian State University of Informatics and Radioelectronics.

Loban M. A., Engineer at the Department of Information Radiotechnologies of the Belarusian State University of Informatics and Radioelectronics.

Address for correspondence

220013, Republic of Belarus,
Minsk, P. Brovka St., 6
Belarusian State University
of Informatics and Radioelectronics
Tel. +375 17 293-89-11
E-mail: m.loban@bsuir.by
Loban Maria Andreevna