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A PROPOSED GPS ANTI-SPOOFING ALGORITHM USING MULTI-CHANNEL ANTENNA RECEIVING CNE

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Аннотация. Предложен метод селекции сигналов от GPS спуфинга в гражданской навигационной аппаратуре (CNE) с многоканальной антенной системой. Способ обеспечивает последовательную фильтрацию принимаемых сигналов на выходе всех элементов антенной системы и по дальномерным кодам всех навигационных спутников, обнаруживает и измеряет время задержки истинных и ложных навигационных сигналов в каждом кодовом канале по выходному сигналу одного из элементов антенной системы, измеряет разность фаз сигналов на выходе элементов антенной системы и по коду выбранного опорного элемента рассчитывает время задержки в каждом канале. Компенсация спуфинговых сигналов осуществляется путем оценки корреляционной матрицы процессов на выходе каналов антенной системы по соответствующим отсчетам сигналов кодовых каналов после согласованной фильтрации, формирования весового вектора при минимизации выходной мощности спуфинга сигналов путем прямого обращения оценки корреляционной матрицы и проведения весовой обработки приемной реализации.

Abstract. A method for selecting GPS spoofing signals in consumer navigation equipment (CNE) with a multichannel antenna system is proposed. The method provides for consistent filtering of received signals at the outputs of all elements of the antenna system and by ranging codes of all navigation satellites, detection and measurement of the delay times of true and false navigation signals in each code channel by the output signal of one of the elements of the antenna system, measurement of the phase difference of the signals at the outputs of the elements antenna system and the selected reference element for the estimated delay times 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 channels of the antenna system according to the corresponding samples of code channel signals after matched filtering, forming 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.

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 [1,2] 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 [3]. 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 $\mathrm{Y}=(\mathrm{y}_1,\mathrm{y}_2,...,\mathrm{y}_\mathrm{M})$ defines the multichannel implementation at the input of the processing system, which is composed up of vectors $\mathrm{y}_m = (\dot{Y}_{1,m}, \dot{Y}_{2,m}, ..., \dot{Y}_{L,m})^{\mathrm{T}}$ of signal sampling $\dot{Y}_{\ell,m}$ of the ℓ-th receiving channel of the array antenna system, $\ell = \overline{1, L}$, L is the number of receiving channels.

We will perform consistent filtering of the adapted 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, where $n = \overline{1, N}$, N is the number of the navigation satellites; $\mathbf{S}_n = (\mathbf{s}_n(1), ..., \mathbf{s}_n(M))$; $\mathbf{s}_n(m) = (\dot{S}_n(1,m), ..., \dot{S}_n(L,m))^{\mathrm{T}}$ is a matrix of signals' samples in the output of the match filters; $\dot{S}_n(\ell, m)$ 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 $\boldsymbol{\varphi}_n^{(1)} = (\varphi_{1,n}^{(1)}, ..., \varphi_{L,n}^{(1)})^{\mathrm{T}}$ where

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

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]

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

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

$$\boldsymbol{\nu}_n = (\nu_{2,n}, ..., \nu_{L,n})^{\mathrm{T}}$$

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

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

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

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

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

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

Vectors $\mathbf{v}_n$ and $\boldsymbol{\mu}_n$ 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

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

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

$$D(\nu, \mu) = \sum_{\ell=2}^{L} D_\varphi(\nu_\ell, \mu_\ell), \; D \ge 0. \tag{9}$$

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

$$\mathbf{D} = \left(\begin{array}{ccccc|ccccc}
0 & D(\mathbf{v}_1, \mathbf{v}_2) & D(\mathbf{v}_1, \mathbf{v}_3) & ... & D(\mathbf{v}_1, \mathbf{v}_N) & D(\mathbf{v}_1, \mu_1) & D(\mathbf{v}_1, \mu_2) & \cdots & \ldots & D(\mathbf{v}_1, \mu_N) \\
 & 0 & D(\mathbf{v}_2, \mathbf{v}_3) & ... & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
 & & 0 & \ddots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
 & & & 0 & D(\mathbf{v}_{N-1}, \mathbf{v}_N) & D(\mathbf{v}_{N-1}, \mu_1) & D(\mathbf{v}_{N-1}, \mu_2) & \ldots & \cdots & D(\mathbf{v}_{N-1}, \mu_1) \\
 & & & & 0 & D(\mathbf{v}_N, \mu_1) & D(\mathbf{v}_N, \mu_2) & \ldots & \ldots & D(\mathbf{v}_N, \mu_N) \\
\hline
 & & & & & 0 & D(\mu_1, \mu_2) & D(\mu_1, \mu_3) & \ldots & D(\mu_1, \mu_N) \\
 & & & & & & 0 & D(\mu_2, \mu_3) & \ldots & \vdots \\
 & & & & & & & \ddots & \ldots & \vdots \\
 & & & & & & & & \ddots & D(\mu_{N-1}, \mu_N) \\
 & & & & & & & & & 0
\end{array}\right)$$

.

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

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

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:

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

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:

$$\hat{\mathrm{R}} = \frac{1}{N_{T_0}\Theta(\mathrm{b})} \sum_{r=1}^{N_{T_0}} \sum_{q=1}^{\Theta(\mathrm{b})} \mathrm{s}_{n(b_q)}(m(b_q) + M_1 r)\mathrm{s}_{n(b_q)}^{H}(m(b_q) + M_1 r), \tag{13}$$

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

$$n(b_q) = \begin{cases} b_q,\ b_q \le N; \\ b_q - N,\ b_q > N, \end{cases} \quad m(b_q) = \begin{cases} i_{n(b_q)},\ b_q \le N; \\ k_{n(b_q)},\ b_q > N, \end{cases} \tag{14}$$

where n and 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, $\Theta(\mathrm{b})$ =4…8, $N_{T_0}\Theta(\mathrm{b}) = 16...40$) in accordance with [3,4], it is recommended to regularize it in accordance with the expression

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

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 [3]

$$\mathrm{w} = \hat{\mathrm{R}}_r^{-1}\mathrm{e}, \tag{16}$$

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

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

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

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

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 main stages of the processing algorithm for spoofing compensation show if figure 1.

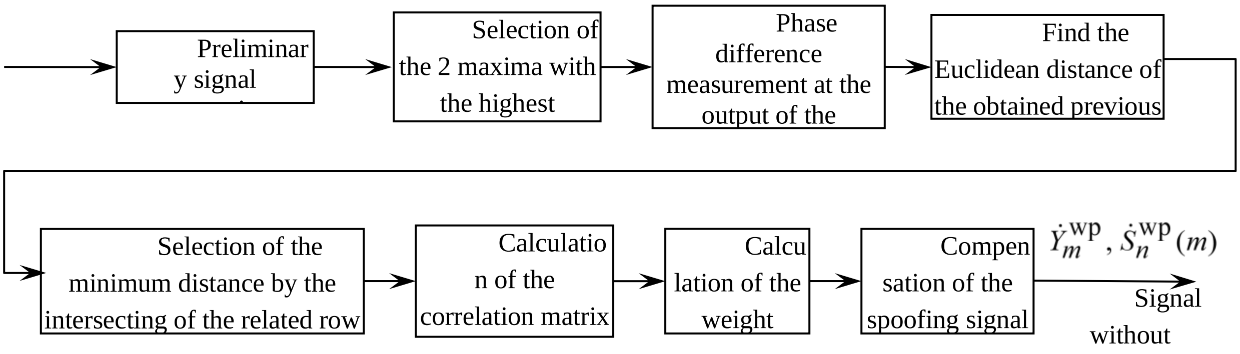

Fig. 1. The main stages of the processing algorithm for spoofing compensation

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.

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.

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