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THE IMPACT OF GNSS SPATIAL SIGNAL PROCESSING ON POSITION AND TIME MEASUREMENTS

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One of the main research directions in global navigational satellite systems is increasing the intentional interferences resistance of modern navigation receiving equipment. The most effective method is supposed to be the use of spatial filtering techniques on the basis of adaptive antenna arrays (AAA). However, antenna array can bring about additional errors in the navigation and make it impossible to use it for applications requiring accurate positioning and time synchronization. We experimentally compared navigation solutions obtained based on signals from a single antenna and from the output of AAA. The results showed that the use of AAA as the part of navigation receiver might delay 1 pps (pulse per second) signal arrival on the value proportional to the summarized group delay in the digital signal processing block of AAA. Experimental results also showed that AAA could bring error to positioning of the receiver. A few methods were outlined to decrease the influence of AAA on navigation solution.

Keywords: global navigation satellite system, adaptive antenna array, 1 pps-signal, positioning, navigation receiver.

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ВЛИЯНИЕ ПРОСТРАНСТВЕННОЙ ОБРАБОТКИ СИГНАЛОВ ГНСС НА НАВИГАЦИОННО-ВРЕМЕННЫЕ ОПРЕДЕЛЕНИЯ

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Повышение помехозащищенности – важная задача, требующая решения в современной приёмной аппаратуре сигналов глобальных навигационных спутниковых систем. Одним из наиболее эффективных методов является пространственная фильтрация на основе адаптивных антенных решеток (ААР). Однако антенная решетка может приводить к появлению дополнительных ошибок в решении навигационной задачи, что делает невозможным использование ААР для приложений, требующих точного позиционирования и точной временной синхронизации. Проведено экспериментальное сравнение навигационных решений, полученных на основе сигналов с одиночной антенны и на основе сигнала на выходе ААР. Результаты показали, что использование ААР в составе приёмной навигационной аппаратуры может привести к задержке выдачи сигнала 1 pps на величину, пропорциональную времени задержки сигнала в цифровой части ААР. Результаты эксперимента также показали, что ААР может привести к появлению ошибки в позиционировании приёмника. Предложены варианты по уменьшению влияния ААР на решение навигационной задачи.

Ключевые слова: глобальная навигационная спутниковая система, адаптивная антенная решетка, 1 pps-сигнал, местоположение, навигационный приёмник.

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Introduction

Nowadays global navigation satellite systems (GNSS) find a wide range of applications in various fields of science and technology. GNSS allows determining position and speed of objects with high accuracy, to determine angular orientation and provide time synchronization of GNSS consumer equipment.

The main vulnerability of GNSS is caused by GNSS equipment susceptibility to intentional interference (jamming signals). One of the main research directions in GNSS is increasing the intentional interferences resistance of GNSS consumer equipment.

Reliable operation of GNSS receivers in the presence of jamming signals can be maintained by interference filtration techniques (time-frequency, polarization, spatial filtration), but the most effective and universal one is supposed to be spatial filtration on adaptive antenna arrays [1–5]. Spatial filtration technique is based on processing signals received on spaced antenna elements.

An adaptive antenna array (AAA) is a set of antenna elements whose channels gain can be controlled in amplitude and phase, that feature allows to shape desired radiation pattern of the AAA. To suppress interference, it is necessary to generate zeros of the radiation pattern at the interference arrival directions.

AAA research usually evaluates interference suppression performance and little attention is given to the impact of AAA on signals of interest, particularly on GNSS signals. In practice, the use of weighting processing, non-identical frequency characteristics of receiving channels, the use of antenna elements with non-identical radiation patterns can lead to the formation of additional amplitude-phase shift at the AAA output signal [6–8], the shift can introduce additional error in the solution of the navigation problem. Due to this additional error, the range of AAA applications as a part of navigation equipment (that requires high-precision positioning and/or accurate timing synchronization) can be reduced.

In papers [8–12] the influence of AAA on the operation of a GNSS receiver is shown by estimation of intermediate parameters of GNSS signal processing: pseudo-ranges and code or carrier phase biases. These papers do not describe how pseudo-ranges or phase biases could affect positioning or time synchronization pulse generating. In addition, the final result depends on the type of AAA algorithm used. In [13] the measured time delay is achieved in a few decimeters. In [14] after estimating the offset, the receiver offset errors could be compensated either in the navigation processor or in the tracking loop of the GNSS receiver. The simulation demonstrated centimeter-level bias correction accuracy.

The navigation solution can be produced on the basis of code or phase measurements [8–12], but in this work, we pay attention to code measurements.

The purpose of this research is to identify the impact of AAA on the navigation solution by comparing the accuracy of the navigation solution with and without using AAA. As the measure of AAA impact on navigation solution we used the deviation of coordinates in rectangular coordinate system relative to reference point and average time delay of synchronizing 1 pps pulses using AAA instead of a single antenna element for measurements.

Adaptive antenna array

Interference filtration by AAA is based on the principle of spatial selectivity. The main characteristic of AAA is the radiation pattern (RP) – dependence of the AAA gain on signal arrival direction. In order to suppress interference, it is necessary to shape the RP's zeros in the direction of the interference arrival.

Fig. 1 shows the structural diagram of AAA with N antenna elements. Interferences and signals of interest from satellites are received by antenna elements. Signals from each antenna element pass to the radionavigation receiving device, then analog-to-digital conversion (ADC) of the signals occurs, and the further processing is performed with digitized signals.

ADC-block forms $X(k)=\left[x_1(k)\ x_2(k)\ldots x_N(k)\right]^T$ samples of input signals for all AE, digitized input signals are further multiplied by complex-conjugated $W=[w_1, w_2, \ldots, w_N]$ weight coefficients and the obtained products are summed up. The sample of AAA output signal for the k^{th} moment of time is calculated as follows:

$$Y(k)=W^H X(k)=\sum_{n=1}^{N} w_n^* x_n(k),$$

the superscript H denotes Hermitian transpose, asterisk * denotes the complex conjugation.

Further, AAA weight coefficients are calculated on the basis of $X(k)$ and $Y(k)$ samples, AAA weights enable generating the AAA RP for interference suppression. There is a great variety of AAA algorithms based on following criteria: minimum mean square error, minimum output power, maximum SNR at the AAA output, etc. If navigation chips are used as GNSS consumer equipment, the AAA output signal is converted to analog form (DAC) (Fig. 1). The output signal of AAA is free of interference signals and used for calculation of navigation solution at the receiver.

Experimental setup

The purpose of the experiment is to determine AAA impact on navigation solution, evaluate the accuracy of the consumer's position and the accuracy of the moment 1 pps signal arrives from navigation receiver. The structural scheme used for measurements is shown in Fig. 2.

The list of the equipment:

navigation reception antenna L1 GPS/GLONASS Tallysman 33-7972-00-1500 (1 piece);

navigation receivers: u-blox LEA-M8T (2 pieces) (accuracy of positioning – 2.5 m, accuracy of 1 pps-signals delivery ≤ 20 ns);

a sample of a 4-element AAA for GNSS signals;

a two-channel device for recording moments of 1 pps signals arrival from navigation receivers;

PC with installed software for operation with navigation receivers and software to form1 pps-signals records.

A mixture of real satellite signals with AWGN is received on two antenna modules. A single antenna represents the first antenna module and the second is the sample of AAA. AAA is capable of operating in

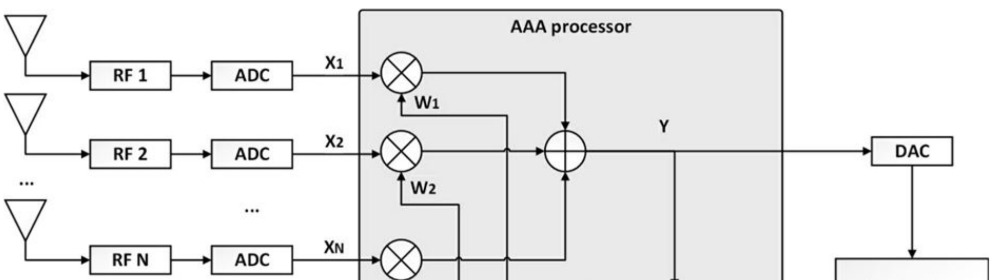

Fig. 1. Structural diagram of AAA with N antenna elements

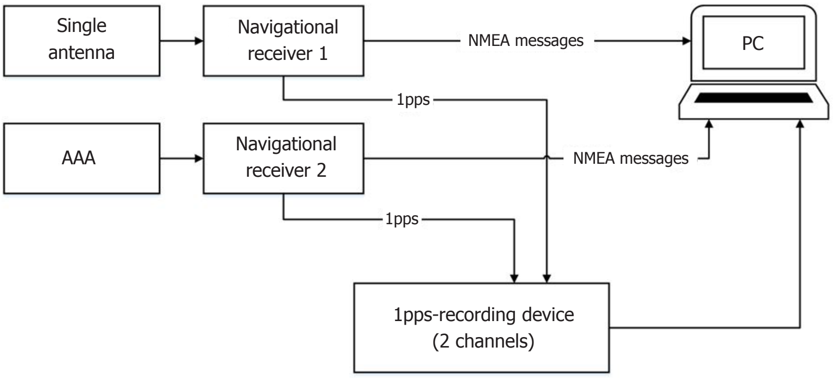

Fig. 2. Block diagram of the measuring equipment

the L1 frequency range of GNSS GPS and GLONASS. Signals from antenna modules are transmitted to inputs of corresponding navigation receivers, where the complete cycle of satellite signals processing is performed, as a result of which the solution of navigation task is evaluated, i.e. position and 1 pps-signal.

Both navigation receivers send NMEA messages to the PC via a serial port once per second and the PC writes them to a text file. Geographical coordinates (latitude, longitude, height) and their corresponding time are extracted from NMEA messages (GGA – Global positioning system fix data) and transformed into rectangular coordinates (x, y, z). Receivers also output a 1 pps signal at 1 Hz. The time of arrival of 1 pps signals is recorded by a two-channel 1 pps-recorder. The 1 pps-recorder contains a 240 MHz reference clock. There is also a counter incrementing every cycle of the reference clock. The second counter fixes moments of 1 pps arrival from a navigation receiver. The second counter increments after 1 pps tag is received and fixes the value until the next 1 pps tag is received. Obtained values of the second counter are recorded into a separate text file with a rate of 2 kHz. Recording is performed simultaneously via two channels from identical navigation receivers. As a result, two-channel record is formed containing arrival moments of the 1 pps signal samples relatively reference 240 MHz clock. Thus, the 1 pps edge is measured with 4 ns precision.

Experimental results

The purpose of the experiment is to compare navigation solution obtained based on signals received at a single antenna element; the measuring device is in the stationary state during measurements.

Comparison of delay of 1 pps signals with AAA relative to 1 pps signals from single antenna is carried out at generation of 1 pps signal on the basis of GPS satellites constellation. The experiment involves comparing the delay of 1 pps without an intentional interference and in the presence of one. However, in the presence of the interference, the navigational receiver is not able to get solution. Therefore, the following sets of records were made to make comparison of the operation navigation receivers with antenna and AAA possible in the presence of interference:

1. All receivers are configured to receive GPS signals. Records are made without intentional interference.
2. The receiver with the single antenna operates on GLONASS signals, the receiver with AAA operated on GPS signals. Records are made without intentional interference.
3. The receiver with the single antenna operates on GLONASS signals, the receiver with AAA operates on GPS signals. Records are made in the presence of 1 MHz wideband interference in the GPS signal band.

Each record set contains: records of NMEA messages from each navigation receiver; a two-channel record 1 pps signals from receivers. Measurements are made under conditions of direct reception of satellite signals during 20 minutes, the rate of navigation solution output – 1 Hz.

All coordinates are measured relatively (X_{ref}, Y_{ref}, Z_{ref}) – the reference point measured with centimeter-accuracy by the Trimble R7 GNSS Receiver. Based on the obtained records sets, we transformed the geodesic coordinates to rectangular and constructed histograms of rectangular coordinates (x, y, z) (Fig. 3–5). We also calculated sample mean and standard deviation of relative coordinates and tabulated the results (Table 1).

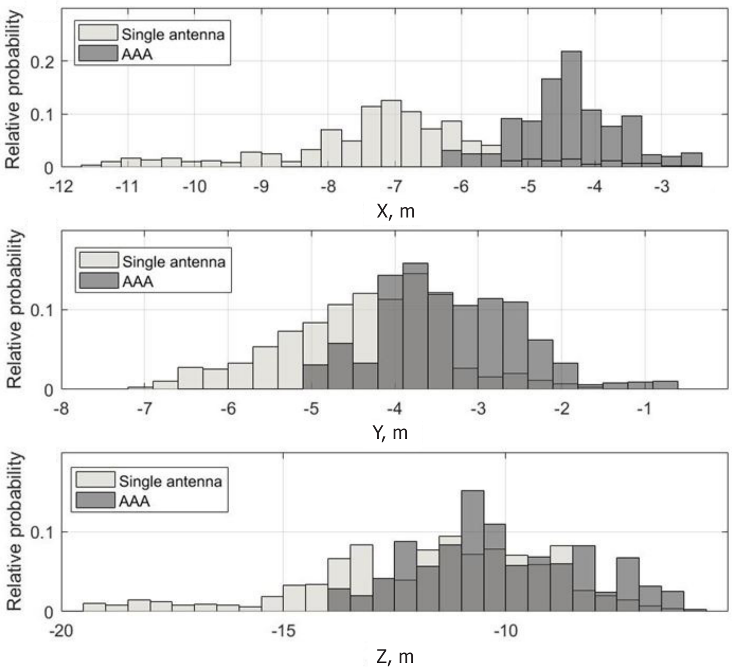

Fig. 3. Histograms of measured coordinates, both receivers operate on GPS, without interference

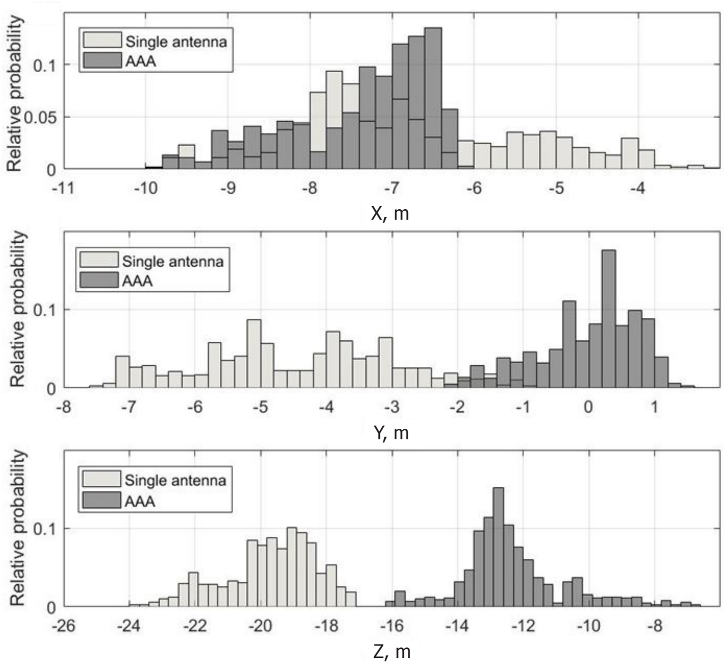

Fig. 4. Histograms of measured coordinates, receiver with single antenna operates on GLONASS, the other – on GPS, without interference

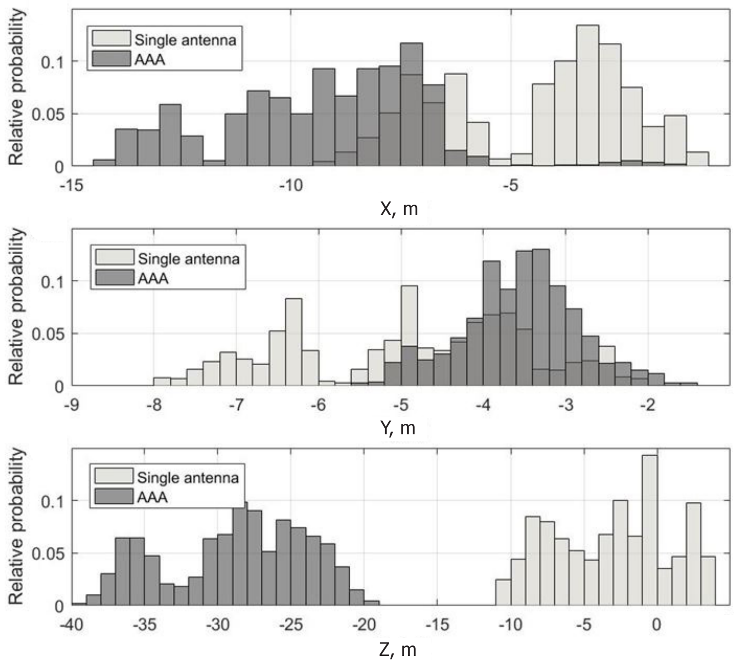

Fig. 5. Histograms of measured coordinates, receiver with single antenna operates on GLONASS, the other – on GPS, the presence of 1 MHz wideband interference for GPS

Table 1

Sample mean and standard deviations of measured coordinates in relation to the reference point

No. of the records set	Antenna module of receiver	Mean $(X–X_{ref})$, m	Mean $(Y–Y_{ref})$, m	Mean $(Z–Z_{ref})$, m	Std $(X–X_{ref})$, m	Std $(Y–Y_{ref})$, m	Std $(Z–Z_{ref})$, m
1	Single antenna	–7.13	–4.38	–11.73	1.59	0.97	2.63
	AAA	–4.39	–3.34	–10.09	0.79	0.84	1.88
2	Single antenna	–6.83	–4.44	–19.73	1.46	1.50	1.42
	AAA	–7.38	–0.01	–12.36	0.88	0.76	1.62
3	Single antenna	–4.49	–4.87	–3.05	2.15	1.42	4.00
	AAA	–9.26	–3.56	–28.76	2.34	0.72	4.83

We have estimated the delay of the 1 pps signals introduced by the AAA in relation to 1 pps signals generated from the receiver with the single antenna on the basis of two-channel 1 pps signal records. Estimated delays are summarized at Table 2 and are equivalent to the time delay introduced by the AAA.

Using the data from Table 2, we can estimate the delay Δt_{GPS} introduced by the AAA generating a 1 pps signal on GPS signals in the presence of interference based on the estimate of the 1 pps signal delay for the third set of records (during the third recording, a single antenna receiver generates a 1 pps signal via the constellation GLONASS):

$$\delta = \Delta t_1 - \Delta t_2,$$

$$\Delta t_{GPS} = \Delta t_3 + \delta,$$

where $\Delta t_{1,2,3}$ – estimates of 1 pps signal delay for the first, the second or the third set of records (from Table 2) determined for AAA; δ – difference of 1 pps signal delays caused by operation on different GNSS; Δt_{GPS} – the estimate of the 1 pps delay introduced by AAA signal using GPS constellation in the presence of intended interference. Table 3 contains AAA estimated delays for 1 pps signal without and with the interference effect. Without interference, the AAA sample introduces a delay of 22.2 µs. In the presence of wideband interference, the 1 pps signal is delayed by 22.145 µs.

Table 2

Estimated offset of the 1 pps signal when using AAA in relation to the 1 pps signal from a single antenna

Set of records	Initial conditions	Histogram with coordinates	Estimated AAA delay, µs
1	All receivers are configured to receive GPS signals. Records are made without intentional interference	Fig. 3	22.200
2	The receiver with the single antenna operates on GLONASS signals, the receiver with AAA operates on GPS signals. Records are made without intentional interference	Fig. 3	22.157
3	The receiver with the single antenna operates on GLONASS signals, the receiver with AAA operates on GPS signals. Records are made in the presence of 1 MHz wideband interference in the GPS signal band	Fig. 3	22.102

The delay introduced into the signal by AAA is supposed to be constant and can be attributed to the structure of analog and digital parts of AAA, i.e. signals received at AAA antenna elements are delayed within analog paths of RF-block. Fig. 6 shows a structure diagram of a digital signal processing block for one of the AAA channels. The main contribution to the delay of AAA signals (Table 3) is made by the group delays of digital filters used for signal resampling (down- and upsampling) and filters for correction of phase frequency characteristics of AAA receiving channels; the delay can also be formed by the AAA algorithm (the use of spatial-time processing additionally requires delay taps in each AAA channel).

Table 3

Comparison of 1 pps delay for AAA using GPS constellation

	Estimated AAA delay for GPS constellation, µs
no interference	22.200
1 MHz wideband interference	22.145

Conclusion

By comparing the accuracy of the evaluated navigation solution without and with the use of AAA, we found that the AAA sample delays the output of the 1 pps signal by 22.2 µs in relation to the 1 pps signal from a single antenna element.

The results of coordinate measurements (Table 1) show that without interference the sample mean and standard deviation of the measured coordinates with the single antenna and the AAA slightly differ from each other. In the presence of wideband interference (record set 3), the standard deviation of the vertical

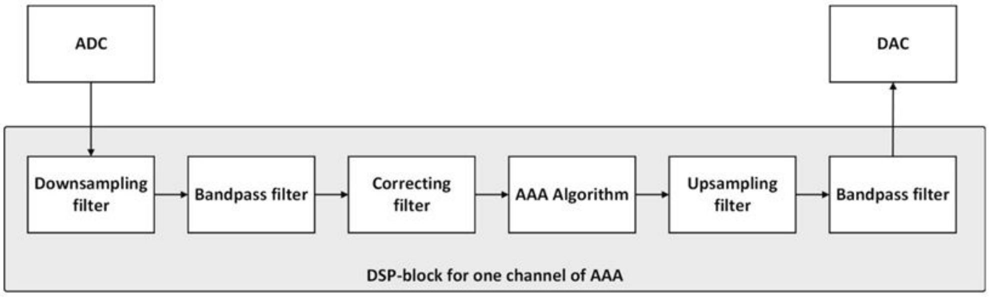

Fig. 6. Structure diagram of a digital signal processing block for one of the AAA channels

coordinate component $std(Z - Z_{on})$ increases by a factor of 2 compared with measurements without the interference. Sample mean coordinate $mean(Z - Z_{on})$ with the single antenna is – 3.05 m, and $mean(Z - Z_{on})$ with AAA is – 28.76 m. In case of interference effect, the use of AAA made the displacement of the measured Z coordinate, at the same time $std(Z - Z_{on})$ with single antenna and with AAA did not differ.

The results showed that the use of AAA as a part of GNSS receiving equipment made an impact on the navigation solution. The AAA influence on the time component can be compensated by the configuration of navigation receiver, the output 1 pps signal delays according to the measured delay value from Table 3. Influence of AAA on navigation parameters, such as, coordinates and speed, can be reduced only by reduction of AAA group delay or by taking into account AAA characteristics for navigation solution calculation.

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