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Повышение точности позиционирования системы ГЛОНАСС

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Точность определения координат в системах глобального позиционирования определяется количеством спутников, одновременно видимых навигационным оборудованием потребителя. На большей части поверхности земли над горизонтом находятся одновременно до 11 спутников ГЛОНАСС. Однако отношение сигнал/шум в канале связи, необходимое для безошибочного приема информации, часто обеспечивается только для 2–4 спутников. Для повышения точности позиционирования предложено использовать метод голографического помехоустойчивого кодирования, основанный на голографическом представлении цифрового сигнала. Процесс кодирования сообщения представляет собой математическое моделирование голограммы, создаваемой в виртуальном пространстве волной от источника входного сигнала. Показано, что голографическое представление сигнала обладает существенно большей помехоустойчивостью и позволяет восстановить исходную цифровую комбинацию при потере большей части кодового сообщения и при искажении кодированного сигнала шумом, в несколько раз превосходящим уровень сигнала. Проведенные исследования показали, что введение голографического кодирования в канале спутниковой связи системы ГЛОНАСС даст возможность навигационной аппаратуре потребителей получать информацию с большего количества спутников, что существенно повысит точность позиционирования. В часто встречающейся ситуации, когда требуемое отношение сигнал/шум выдерживается только для 4 спутников ГЛОНАСС, погрешность позиционирования превышает 10 м. При использовании голографического кодирования в такой же ситуации будет безошибочно декодироваться информация от 9 спутников и погрешность позиционирования составит около 2 м.

Ключевые слова: голографическое кодирование, исправление ошибок в канале связи, погрешность позиционирования.

Increasing the positioning accuracy of the GLONASS system

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The accuracy of determining coordinates in global positioning systems is determined by the number of satellites simultaneously visible to the consumer's navigation equipment. Over most of the earth's surface, there are up to 11 GLONASS satellites above the horizon at the same time, but the signal-to-noise ratio in *the communication channel required for error-free information reception is often ensured only for 2-4 satellites. To improve the positioning accuracy, it is proposed to use the holographic noise-immune coding method based on the holographic representation of the digital signal. The message coding process is a mathematical modeling of a hologram created in virtual space by a wave from the input signal source. It is shown that the holographic representation of the signal has significantly greater noise immunity and allows restoring the original digital combination when most of the code message is lost and when the coded signal is distorted by noise several times exceeding the signal level. The studies have shown that the introduction of holographic coding in the GLONASS satellite communication channel will enable consumer navigation equipment to receive information from a larger number of satellites, which will significantly improve the positioning accuracy. In a common situation where the required signal-to-noise ratio is maintained for only 4 GLONASS satellites, the positioning error exceeds 10 meters. Using holographic coding in the same situation, information from 9 satellites will be decoded without error, and the positioning error will be about 2 meters.*

Keywords: holographic coding, error correction in the communication channel, positioning error.

Introduction

One of the main characteristics of the global navigation satellite system GLONASS is the accuracy of coordinate and altitude estimates obtained in the navigation user equipment (NUE) only from satellite signals without using additional information [1]. Positioning accuracy is of particular importance for navigation systems of aircraft, including unmanned aircraft, in conditions of unintentional and intentional interference [2; 3]. However, insufficient positioning accuracy in many cases requires the development of other methods for solving this problem. In [4], it is proposed to use a high-precision ephemeris and time correction system for solving fundamental geodynemic and geodetic problems, collecting, storing and processing measurement and navigation information on GLONASS satellite navigation systems. In [5], calculation methods are proposed for reducing errors caused by signal passage in the ionosphere and troposphere; in [6], it is shown that the use of spatial selection methods using an antenna array can significantly increase the accuracy of navigation determinations by reducing the influence of multipath reception. The paper [7] describes the idea of digital recording of navigation signals and proposes a high-speed post-processing method to improve the accuracy of estimates. An approach to improving the noise immunity of navigation equipment by using a deep integration scheme for navigation equipment is proposed in [8; 9]. A method for improving the noise immunity of positioning systems by transmitting an additional time stamp is considered in [10]. The most complex and costly is the creation of a new navigation and information satellite system proposed in [11], which eliminates the problems in the development of the GLONASS system. The accuracy of positioning is greatly influenced by the characteristics of the NUE. Standard NUE samples do not provide the required level of noise immunity at the existing power level of received GLONASS signals of about minus 166–156 dBW [12; 13]. The GLONASS system uses Hamming code to improve noise immunity, which corrects single errors. The transmitted blocks of digital information are 85-bit codes, where the most significant 77 bits contain information symbols, and the least significant 8 bits contain check symbols [12].

Problem statement

The accuracy of coordinate measurements is determined by the number of satellites simultaneously visible to navigation equipment. GLONASS errors are 3–6 m when using 7–8 satellites. Up to 11 GLONASS satellites are simultaneously above the horizon on most of the earth's surface, but the signal-to-noise ratio in the communication channel, necessary for error-free reception of information, is often ensured only for 2–4 satellites. Fig. 1 shows an example of the visibility of satellites of different navigation systems in urban areas.

Fig. 2 shows the signal levels for visible.

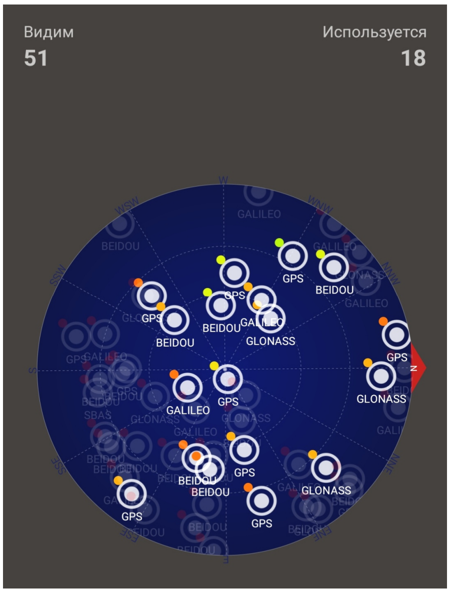

Рис. 1. Видимость спутников GPS, GLONASS, BEIDOU, GALILEO

Fig. 1. Visibility of GPS, GLONASS, BEIDOU, GALILEO satellites

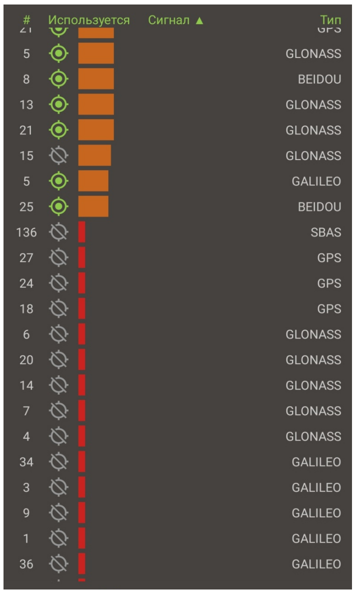

Рис. 2. Видимые и используемые спутники

Fig. 2. Visible and used satellites

The required signal-to-noise ratio is maintained for 4 GLONASS satellites, 5 GLONASS satellites are in the visibility zone, but are not used due to the low signal-to-noise ratio. Under these conditions, the positioning error exceeds 10 m. The positioning error can be reduced not only by increasing the number of satellites in the satellite constellation, but also by using coding that ensures the correction of a larger number of errors.

A large number of error-correcting codes of varying efficiency have been developed to date. However, their efficiency is insufficient to restore the original message when transmitting information over a satellite communication channel under conditions of a low signal-to-noise ratio, when large fragments of information can be lost. One of the ways to improve the stability of a communication channel is to use a form of signal representation that ensures the restoration of a message based on its fragment. The holographic method of error-correcting coding has such a feature [14; 15]. The holographic code can be used to solve a variety of problems, for example, to increase the reliability of onboard memory systems [16] or to increase the noise immunity of a radar channel [17]. Holographic coding can be used with the same success to increase the noise immunity of a satellite communication channel. The process of coding the transmitted information is a mathematical modeling of a digital hologram created in virtual space by a wave from the coded object [18; 19]. Holographic coding of arbitrary digital information differs from optical holography by the following factors:

– the object is one-dimensional;

– the object is not tied to spatial dimensions, the unit of measurement of the size of the object and the hologram is the wavelength of the radiation;

– the wave propagates without attenuation and is coherent at any length.

Holographic encoding/decoding algorithm

The input data block of the original digital message, which is an n-bit binary code, is transformed into a secondary block - a single position code with the number of positions $N = 2^n$. This transformation introduces redundancy into the message with a coefficient $q = 2^n/n$. The secondary block has (N–1) zeros and one unit in the position specified by the primary block. Thus, the block of the original digital message is used as the address of the position of the one in the sequence of zeros of the single position code of the secondary block.

The code combination is formed by geometric construction in the plane.

From the primary n-bit data block X, a secondary *block A,* a spatial one-dimensional object (hereinafter referred to as the object), consisting of points $A(i)$, $i = 1\ldots N$, the value of one of which is 1, the rest are zeros: $A(x) = A(i) = 1$, $i = X$, $A(i) = 0$ for $i \neq X$, is formed.

The distance between the points is d. The cell A(x) is the source of a spherical wave propagating in the plane of analysis and characterized by a wavelength $\lambda = d$.

Let us consider the values of the spherical wave front in the plane of the object on a line parallel to the object at a distance L, at N points with a step of d. The wave from the source propagates without attenuation and hits all the elements of the one-dimensional array $H(j)$, $j = 1\ldots N$ (Fig. 3). This set of points forms a section of the Fresnel zone plate (Fresnel zone ruler), which is the simplest hologram – a hologram of a point. Thus, a one-dimensional object $A(i)$ is assigned a one-dimensional hologram $H(j)$. The values of the resulting hologram are rounded to one bit, resulting in the formation of an N-bit one-dimensional array $H_O(j)$, which is a code combination of an n-bit input data block X.

The values of the wave front at the points under consideration $H(j)$, $j = 1\ldots N$ are determined by the phase of the incoming wave. The wave phase φ is a function of the spatial coordinates. The value of the wave from the element $A(i)$ at the point where the hologram element $H(j)$ is located equals to

$$H(j) = A(i)\sin\varphi(i, j), \tag{1}$$

where $\varphi(i, j)$ is the radiation phase of the element $A(i)$ at the point $H(j)$.

The distance $l(i, j)$ between points $A(i)$ и $H(j)$ is

$$l(i, j) = \sqrt{L^2 + d^2(i-j)^2},$$

then $\varphi(i, j)$ is the fractional part of the ratio of $l(i, j)$ to the wavelength:

$$\varphi(i, j) = \{l(i, j) / \lambda\}.$$

Thus, the code combination $H_O(j)$ is a point hologram, which is also a one-dimensional zone ruler carrying information from the input data block in the form of an N-bit code for the coordinate of the center of the Fresnel zones.

The code combination is transmitted over the communication channel and decoding is performed on the receiving side - the hologram is restored, the maximum is found and its coordinate is output as an n-bit output code.

The distorted hologram $H_R(j)$ received over the communication channel is considered as a one-dimensional array of points, the number of which may be less than N due to the loss of part of the information, and the values of the received elements are distorted by noise. Each of the points of the hologram $H_R(j)$ is a source of a spherical wave with the same wavelength λ as in encoding. The reconstructed object $A_R(i)$ is a one-dimensional array of points located with a step d on a straight line parallel to the hologram $H_R(j)$and located at a distance L from it.

The intensity of the wave from the hologram point $H_R(j)$ at the point of the reconstructed object $A_R(i)$ is calculated in the same way as in coding (1). Waves from each point of the hologram $H_R(j)$ (Fig. 3) arrive at each point of the object AR(i), and as a result of the interference of these waves, the values of the N-bit representation of the reconstructed object $A_R(i)$ are formed:

$$A_R(i) = \sum_{j=1}^{N} H_R(j),\ i = 1\ldots N.$$

Therefore, the reconstructed object $A_R(i)$ is a second-order hologram (a hologram of a hologram) of the original object.

To obtain the output data block in the form of an n-bit code, it is necessary to determine the position number Y, in which the maximum of the $A_R(i)$ array is located. This number is the value of the output data block.

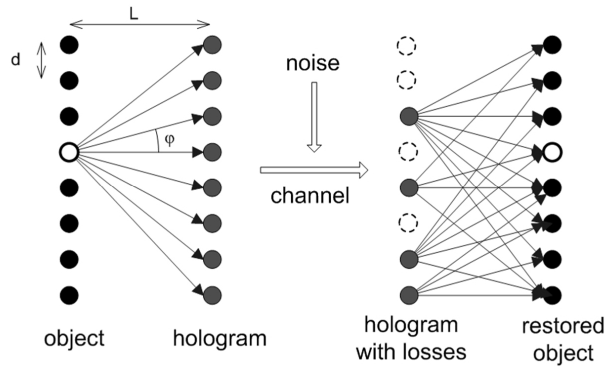

Рис. 3. Пространственная схема кодирования

Fig. 3. Spatial coding scheme

Sequence of operations of the encoding/decoding algorithm is the following:
1. Transformation of the primary data block X into the secondary block A.
2. Calculation of the wave front values at the hologram points H.
3. Transmission of the hologram.
4. Calculation of the reconstructed object A_R based on the received hologram H_R.
5. Search for the maximum in the A_R array.
6. Determination of the maximum value and formation of the output block Y.

Simulation results

The noise immunity of the considered holographic code was studied by simulating the coding-decoding processes in the Matlab environment when transmitting code messages over a noisy channel. A pseudo-random noise generator implemented by the Random function was used as a noise source.

Fig. 4 shows the result of reconstructing a signal carrying the value $Y = 100$. The reconstructed signal contains a small coding noise.

The level of coding noise, which determines the potential noise immunity of the code, depends on the length of the code combination. The shape of the reconstructed signal carrying the value $Y = 400$, with $N = 1024$ (redundancy coefficient $q = 128$) is shown in Fig. 5

Let us consider the code's resistance to errors caused by noise in the communication channel. The effect of noise is simulated by replacing part of the hologram with a binary random sequence. With a random fragment length in the signal of 70%, the reconstructed signal exceeds the maximum noise emission value by 11 dB (Fig. 6).

Increasing the length of the code combination leads to an increase in the noise immunity of the code. At $N = 1024$, the output signal is restored from a signal consisting of 80% random sequence. The signal-to-noise peak ratio at the decoder output is 6.3 dB (Fig. 7).

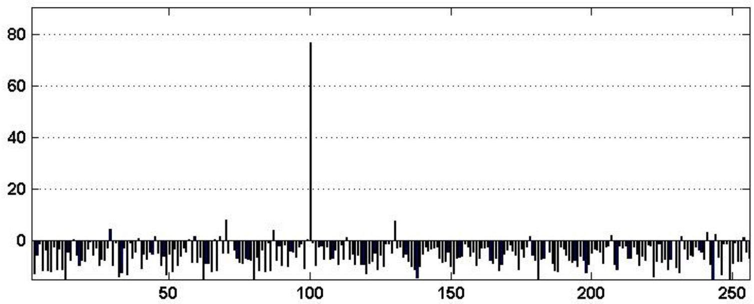

Рис. 4. Восстановленный сигнал при $N = 256$

Fig. 4. Reconstructed signal at $N = 256$

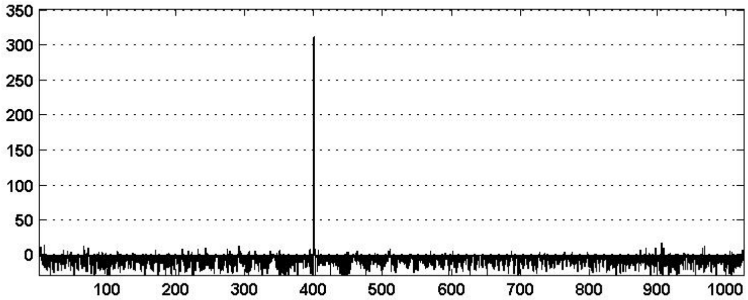

Рис. 5. Восстановленный сигнал при $N = 1024$

Fig. 5. Reconstructed signal at $N = 1024$

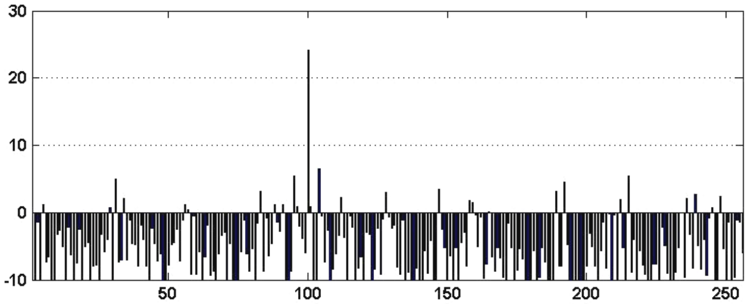

Рис. 6. Восстановленный сигнал при длине случайного фрагмента 70 %

Fig. 6. Reconstructed signal with a random fragment length of 70 %

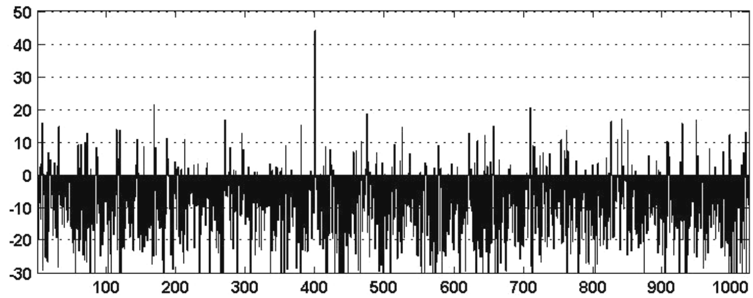

Рис. 7. Сигнал на выходе декодера при $N = 1024$. Длина случайного фрагмента 80 %

Fig. 7. Signal at the decoder output at $N = 1024$. Random fragment length 80 %

If the noise in the channel distorts 90% of the signal, it is necessary to increase the code combination length to $N = 4096$ to obtain a signal-to-noise ratio at the decoder output of 5 dB (Fig. 8).

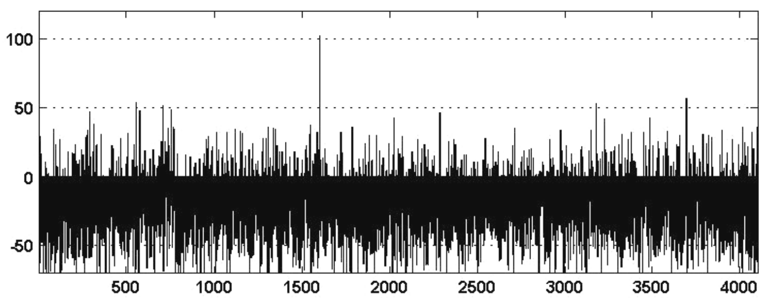

Рис. 8. Потери в канале 90 %. Восстановленный сигнал при $N = 4096$

Fig. 8. Channel losses 90 %. Reconstructed signal at $N = 4096$

A study of the dependence of the holographic code's error-correcting ability on the distance between the object and the hologram L, the hologram pitch d, and the wavelength λ showed that the best results are achieved with $L = nd$ and $\lambda = d$.

Let us consider the code's error-correcting capabilities.

The error-correcting capabilities of an error-correcting code with $n = 2^k$ symbols in a code combination, of which k symbols are information, are estimated by the maximum number of errors t that it can correct for a given degree of redundancy, for example, for the Reed–Muller code (RM code)) $t = 2^{k-2} - 1$ [20], which corresponds to the correction of errors of any type, constituting up to 25% of the code word length.

One of the most effective known error-correcting codes is the Reed–Solomon code (RS code), widely used in error-correcting coding, in data recovery systems from compact discs, and in creating archives with the ability to recover information in the event of damage [21]. The limit of the error-correcting ability (n, k) of the RS code is determined by the Singleton bound [22], according to which, to correct t errors, the code must have at least $n - k = 2t$ check symbols, i.e. two check symbols for one error. With a high degree of redundancy (n >> k), the number of correctable errors t approaches 50% of the code word length n. For example, the RS code (255.8) with a redundancy coefficient of 32 eliminates 123 errors, while the code word contains 132 correct symbols - errors occupy 48% of the code word. A feature of the RS code is that it demonstrates such a high correcting ability only for burst errors [21]. At the same time, random errors are typical for most digital channels described by the model of a binary symmetric channel without memory. If we switch from burst errors to random errors uniformly distributed over the code word, the maximum number of errors corrected by the RS code will be $t = n / 2k - 1$. It follows that the same version of the (n, k) RS code with $n = 256$, $k = 8$ corrects 15 random errors, which is 6% of the code word length.

To assess the noise immunity of the holographic code, a comparison of the reliability of information transmission over a channel with additive white Gaussian noise using several codes was performed. The dependence of the decoding error probability on the signal-to-noise ratio in the channel for the RS code, RM code, majority code and holographic code was considered. For this purpose, the above-considered maximum numbers of correctable errors for each code were taken and the dependence of the probability of occurrence of the number of errors no greater than the maximum on the signal-to-noise ratio was constructed. In all cases, the number of bits of the original word is 8, the length of the code word is 256 bits (code rate $R = 1/32$). The results are shown in Fig. 9.

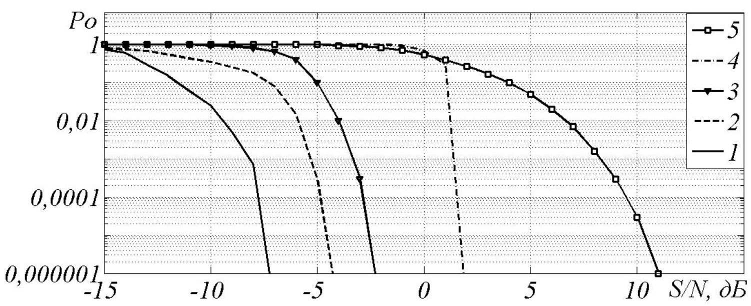

Рис. 9. Зависимость вероятности ошибки декодирования P_O от отношения сигнал / шум при скорости кода $R = 1/32$:
1 – голографический код; *2* – мажоритарный код; *3* – РМ-код; *4* – РС-код; *5* – без кодирования

Fig. 9. Dependence of the probability of decoding error P_O on the signal-to-noise ratio at code rate $R = 1/32$:
1 – holographic code; *2* – majority code; *3* – RM code; *4* – RS code; *5* – without coding

One of the most reliable methods of information transmission in highly noisy channels is averaging within the limits of the introduced redundancy with a majority method of choosing a solution. However, it turned out that the holographic code is more noise-resistant and provides a gain of 2 dB compared to the majority code, which makes it possible to obtain a decoding error probability of 10–6 with a signal-to-noise ratio $S/N = -7$ dB. The capabilities of the proposed holographic code are determined by the level of introduced redundancy: with a redundancy coefficient of $q = 32$, error-free decoding of the signal occurs when 70% of the signal is replaced by a random sequence, while the Hamming code used in GLONASS corrects one error in an 85-bit word.

All types of noise-immune coding, including holographic code, require the introduction of redundancy. The results of code comparison shown in Fig. 9 were obtained with the same code rate R = 1/32, i.e. with the same 32-fold redundancy. Other codes work with low redundancy, but with much lower efficiency. When using communication channels with a low signal-to-noise ratio, a holographic code can increase noise immunity by an order of magnitude, but this requires the introduction of at least 10-fold redundancy. This increases the volume of transmitted information and, when using the same communication channel, increases the transmission time and therefore the time for determining the coordinates. Therefore, the capabilities of holographic coding in terms of the duration of the time interval for determining the coordinates must be proportionate to the task at hand. This method is well suited for geodetic work, but will most likely be less in demand for measuring the coordinates of fast-moving objects.

Conclusion

The conducted studies have shown that the introduction of holographic coding in the GLONASS satellite communication channel will enable consumer navigation equipment to receive information from a larger number of satellites due to the code's ability to ensure the ability to correctly decode the signal with a signal/noise ratio in the satellite channel of up to -7 dB, which will significantly increase the positioning accuracy. The resulting problem of increasing the delay in issuing coordinates can be solved by two methods: increasing the speed of information transfer in the satellite channel or organizing an additional channel with holographic coding so that the modified navigation equipment can operate in two modes – fast with current accuracy and slow, but more accurate.

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