PERFORMANCES OF DETECTION THE PILOT SIGNAL L1OCP OF SYSTEM GLONASS

The article presents the analysis results of global navigation satellite systems BOC(n, m) signals detection. The analytical ratios presenting statistical characteristics of navigation signals detection are given. Characteristics of L1Ocp GLONASS open pilot signals detection using the BPSK-like detector and the detector with subcarrier frequency removal at various coherent accumulation intervals are received. The capability of flexible time control of the coherent accumulation is shown if reception satellite L1Ocp GLONASS open pilot signals is needed various power. Losses at L1Ocp GLONASS open pilot signal detection depending on delay and frequency indeterminacy in a search cell are analyzed. The conclusion is made about the necessity of choosing search cell size taking into account the losses considered and detection characteristics required.

Keywords: global navigation satellite system, detection BOC(n, m) signals, detector with separate processing of each side band, detector with the removal of subcarrier frequency, loss detection.

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Introduction

Foreign global navigation satellite systems (GNSSs) use the signals with code demultiplexing and different types of BOC(n, m) (binary offset carrier) modulation [1, 2]. The use of similar signals is supposed in GLONASS (Global Navigation Satellite System), too [3]. BOC(n, m) signals have the following advantages in comparison with BPSK (binary phase shift keying) signals: the rational use of the frequency range; higher tracking accuracy and interference immunity; lower influence of multipathing. However, the advantages of new signals lead to the complication of signal processing algorithms, which is caused by the multimodality of autocorrelation functions (ACFs) and the considered signal spectrums. The features of GNSS BOC(n, m) signal detection are considered in the article. Whereby, the comparative analysis for detection methods has been implemented; the schemes of detecting devices have been given; the statistical characteristics of detection and the values of loss during the detection of the GLONASS L1Ocp signal have been determined and analyzed.

BOC(n, m) signal detection methods

The GLONASS L1Ocp signal is the two-component signal. One of the quadratures is supposed for the transmission of the pilot (L1Ocp) and information (L1Ocd) components with time multiplexing. The radiated power is shared equally between two components. The extraction of the L1Ocp signal into the component free of the information symbols is caused by the need for the increment of time for its coherent integration in the correlator during the weak-signal reception. The detection of the GLONASS L1Oc signal using its pilot component is the simplest method having the lowest computational complexity. Therewith, it is important to note that neglecting the information component during the satellite signal reception leads to the loss of half power.

The L1Ocp signal has the following characteristics: the modulation format – BOC(1, 1); the carrier frequency – 1600.995 MHz; the clock frequency of code – 0.5115 MHz; the subcarrier frequency – 2.046 MHz; the period of code – 8 msec; the receiver input power \(-157\approx \text{dBW} \) [3].

The normalized ACF and GLONASS L1Ocp pilot signal spectrum are presented in Fig. 1.

The presence of several spikes at ACF and side lobes at the spectrum does not allow using the previous algorithms for the detection of the considered BOC (1, 1) signal (the algorithms which have been used usually for BPSK signals detection) [4]. Let us consider the developed to date BOC(n, m) signal detection methods.

Let us present the BOC(n, m) signal at the navigation user equipment (NUE) after the transfer to the intermediate frequency and analog-to-digital conversion in the following form [5]
The normalized characteristics of the GLONASS L1OCp signal: a – the $R(\Delta t)$ ACF; b – $S(f)$ spectrum. The $R(\Delta t)$ depends on the $\Delta t$ units of symbols. The $S(f)$ is measured in dB and depends on the frequency $f$ (Hz).

$$r[\eta]=\Delta c[n-\tau_0]|S_C[n-\tau_0]|\cos[2\pi F_d,0n+\phi_0]+\eta[n],$$

where $\Delta$ is the signal amplitude; $c$ is the ranging code; $n$ is the number of count; $S_C$ is the $f_{sc}$ subcarrier frequency signal; $\tau_0=\tau/T_S$ is the signal delay time normalized to the $T_S$ sampling interval; $F_{d,0}=(F_{dp}+F_d)/f_S$ is the signal frequency normalized to the $f_S$ sampling rate; $F_{dp}$ is the intermediate frequency; $\phi_0$ is the Doppler frequency shift of the signal; $\eta$ is the random epoch angle of the signal; $\eta$ is the discrete white Gaussian noise with zero mean and dispersion $\sigma^2_\eta=N_0f_S/2$; $N_0$ is the spectral density of noise mean power.

A two-dimensional function of correlation in delay time and frequency with a single spike at the correlation interval should be generated for the detection of the BOC$(n, m)$ signal. The generation of such function during the BOC$(n, m)$ signal detection requires the additional processing at the GNSS receiver. There are two main BOC$(n, m)$ signal processing methods with different requirements to receiver hardware.

The first method includes the consideration of the received BOC$(n, m)$ signal as the sum of two BPSK$(m)$ signals with frequencies located symmetrically in relation to the carrier frequency and corresponding to every BOC$(n, m)$ signal spectrum component [6]. Each spectral lobe is processed separately as the BPSK$(m)$ signal. Initially, there was developed the method where the signal of each spectral lobe is filtered separately, is placed at the center of the receiver passband, and then the cross-correlation function (CCF) of the received signal with a copy of the BPSK$(m)$ signal is calculated. The receiver has two channels for CCF calculation: one channel for $e_y$ signal at the upper sideband and another at the lower sideband, respectively. Each channel provides the calculation of single-valued CCF. The outputs of two channels are multiplexed incoherently after the calculation of CCF. The sidebands of the BOC$(n, m)$ signal are separated using additional filters. The BOC$(n, m)$ signal detector scheme with separate processing at each sideband of each channel coincides with the BPSK$(m)$ signal detector scheme [4]. It should be noted that if the detector processes only one of the signals at the sideband, at least 3 dB incidental loss of signal power is inevitable. The loss will be 0.5 dB with incoherent multiplexing of correlation channels output data. This method should be used for BOC$(n, m)$ signals; their spectrum is distant sufficiently from the band center. Such signals are separated well into two components and do not require the channel filters with high steepness of amplitude-frequency characteristics. This method is complicated in use for the L1OCp pilot signal because its major lobes of the spectrum are located sufficiently closely to the carrier frequency.

The complexity for technical implementation of the considered method had been taken into account, and its modification called the BPSK-like method was proposed [6]. Whereby, the authors refused the separate filtering of each signal corresponding to the main lobes of the BOC$(n, m)$ signal spectrum. Instead of this, just one filter with passband width including two major lobes of the BOC$(n, m)$ signal spectrum and secondary lobes between them is used. The advantages of the BPSK-like method come to the simplification of implementation primarily due to the reduced amount of filters. Two channels for input signal CCF calculation with the BPSK$(m)$ signal are used at the correlator. The results for the operation of two channels are multiplexed as before.

The schematic diagram of the BOC$(n, m)$ signal digital detector based on the BPSK-like method is presented in Fig. 2.
The in-phase component at the output of one correlator channel for this detector can be presented as follows:

\[
R_{B1} = \frac{A}{2} R_{BH}(\Delta T_0) \text{sinc}(\pi \Delta f_{SC} T_S) \cos(\Delta \phi) + \eta_{IH}(n),
\]

where \( R_{BH}(\Delta T_0) \) is the CCF of the input signal and the copy of the ranging code generated at the receiver, modulated complex subcarrier frequency \( c(n - \tau_0) \text{exp}(j2\pi f_{SC} n T_S) \); \( \Delta T_0, \Delta f_{SC}, \Delta \phi \) are the mismatches by the delay time, frequency and phase, respectively.

The computations of CCF at three residual channels are expressed similarly:

\[
\begin{align*}
R_{B2} &= \frac{A}{2} R_{BH}(\Delta T_0) \text{sinc}(\pi \Delta f_{SC} T_S) \sin(\Delta \phi) + \eta_{QH} (n), \\
R_{B3} &= \frac{A}{2} R_{BL}(\Delta T_0) \text{sinc}(\pi \Delta f_{SC} T_S) \cos(\Delta \phi) + \eta_{IL} (n), \\
R_{B4} &= \frac{A}{2} R_{BL}(\Delta T_0) \text{sinc}(\pi \Delta f_{SC} T_S) \sin(\Delta \phi) + \eta_{QL} (m).
\end{align*}
\]

The \( I \) and \( Q \) indices in the presented formulas refer to the in-phase and quadrature branches of the carrier frequency, and the \( H \) and \( L \) indices refer to signal processing channels corresponding to the upper and lower major lobes in the BOC(\( n, m \)) signal spectrum. The \( \eta_{IH}(n), \eta_{QH}(n), \eta_{IL}(n) \) and \( \eta_{QL}(n) \) noises are the independent Gaussian random variables with equal dispersions [4]:

\[
\sigma_n^2 = \frac{N_0 \Delta f_{SC}^2}{2N} = \frac{\sigma^2_n}{2N}.
\]

The key feature of the second method consists in the recording of the subcarrier frequency signal during the detection of the navigation signal. In addition to the in-phase signal and quadrature signals of the carrier frequency, the in-phase and quadrature copies of the subcarrier frequency signal are generated at the receiver. The orthogonal subcarrier of the BOC(\( n, m \)) signal is determined in the following manner. If the \( SC(t) \) signal is the sine of subcarrier frequency, the \( SC(t) \) orthogonal subcarrier has the form of cosine. If the \( SC(t) \) signal is the cosine of subcarrier frequency, the \( SC(t) \) orthogonal subcarrier has the form of sine.

Two correlation channels are used additionally during the implementation, too. One of them is used for the calculation of CCF of the input signal with its copy at the phase of subcarrier frequency, and another – for similar calculation at the quadrature of subcarrier frequency. The CCF similar to CCF for the BPSK signal is obtained after the multiplexing of channel output data. This method is called the detection with deletion of subcarrier frequency [6]. The less complicated implementation of the correlator is the advantage of this method in comparison with the BPSK-like method. The
The schematic diagram for the digital detector of BOC\((n, m)\) signals based on the method with deletion of subcarrier frequency is presented in Fig. 3.

The following signals are generated at the correlator channel output:

\[
R_{31} = \frac{A}{2} R_{s1}(\Delta t) \text{sinc}(\pi \Delta f_d T_c) \cos(\Delta \varphi) + \eta_{H1}(n),
\]
\[
R_{32} = \frac{A}{2} R_{s1}(\Delta t) \text{sinc}(\pi \Delta f_d T_c) \sin(\Delta \varphi) + \eta_{Q1}(n),
\]
\[
R_{33} = \frac{A}{2} R_{s0}(\Delta t) \text{sinc}(\pi \Delta f_d T_c) \cos(\Delta \varphi) + \eta_{H0}(n),
\]
\[
R_{34} = \frac{A}{2} R_{s0}(\Delta t) \text{sinc}(\pi \Delta f_d T_c) \sin(\Delta \varphi) + \eta_{Q0}(n),
\]

where \(R_{s1}(\Delta t), R_{s0}(\Delta t)\) is the CCF of the input signal with in-phase and quadrature codes generated at the receiver; \(\eta_{H1}(n), \eta_{Q1}(n), \eta_{H0}(n), \eta_{Q0}(n)\) are the independent Gaussian noises with equal dispersions \(\sigma_{H1}^2 = \sigma_{Q1}^2 = \sigma_{H0}^2 - \sigma_{Q0}^2 = \sigma_n^2\).

The first indices \(I\) or \(Q\) in the above-mentioned formulas refer to the in-phase or quadrature branches of the carrier frequency, and the second indices – to the channel of subcarrier frequency.

The characteristics of BOC\((n, m)\) signal detection

The following signal is generated at the output of the correlator using both considered methods:

\[
S(\tau, f_d) = R_{31}^2 x_1 + R_{32}^2 x_2 + R_{33}^2 x_3 + R_{34}^2 x_4,
\]

where \(R_{3i}, i = 1, 2, 3, 4\) are the above-mentioned signals at the correlator channels outputs.

When the useful component of the signal is absent \((H_0\) hypothesis\), the values \(R_{3i}, i = 1, 2, 3, 4\) are the independent Gaussian noises with zero mean and equal dispersions \(\sigma_{H1}^2 = \sigma_n^2\). The \(S(\tau, f_d)\) value is subjected here to central \(\chi^2\) distribution with four degrees of freedom. The probability density of the signal accumulated by the correlator and normalized to the dispersion in this case is determined by the following formula:

\[
p_n(x | H_0) = \frac{1}{4\sigma_n^2} \exp \left( -\frac{x}{2\sigma_n^2} \right),
\]

where \(x\) is the \(S(\tau, f_d)\) signal.

The false-alarm probability will be determined by the formula [7]:

\[
P_{fa} = \int_{\hat{\beta}}^{\infty} p_n(x | H_0) dx = \exp \left( -\frac{\hat{\beta}}{2\sigma_n^2} \right) + \frac{\hat{\beta}}{2\sigma_n^2} + \frac{1}{2} \left( \frac{\hat{\beta}}{2\sigma_n^2} \right)^2,
\]

where the \(\hat{\beta}\) is the detection threshold.

The presented formula allows calculating the value of the \(\hat{\beta}\) threshold using the Neyman–Pearson criterion for detection taking into account the \(P_F\) specified false-alarm probability.

When the useful component is present in the signal \((H_1\) hypothesis\) \(R_{3i}, i = 1, 2, 3, 4\) values are the Gaussian random variables with equal dispersions \(\sigma_{H1}^2 = \sigma_n^2\) and mathematical expectations:

\[
\mu_{R_{31}/H1} = \frac{A}{2} R_{1}(\Delta t) \text{sinc}(\pi \Delta f_d T_c) \cos(\Delta \varphi), i = 1, 3,
\]
\[
\mu_{R_{32}/H1} = \frac{A}{2} R_{1}(\Delta t) \text{sinc}(\pi \Delta f_d T_c) \sin(\Delta \varphi), i = 2, 4.
\]

The \(R_{1}(\Delta t), i = 1, 2, 3, 4\) values in the presented formulas correspond to \(R_{R_{31}/H1}\) or \(R_{R_{32}/H1}\) for the BPSK-like method and \(R_{31}(\Delta t)\) or \(R_{32}(\Delta t)\) for the method with the deletion of subcarrier frequency. Then the \(S(\tau, f_d)\) is subjected to noncentral \(\chi^2\) distribution with four degrees of freedom. The noncentrality parameter is determined using the formula:
\[ \lambda = \sum_{i=1}^{4} \frac{A^2}{\beta} (R_{BH}^2(\Delta \tau) + R_{RL}^2(\Delta \tau)) \text{sinc}^2(\pi \Delta f_d T_C) \]

for BPSK-modulated method;

\[ \lambda = \frac{A^2}{\beta} (R_{CS}^2(\Delta \tau) + R_{SR}^2(\Delta \tau)) \text{sinc}^2(\pi \Delta f_d T_C) \]

d for method with shock absorber.

If \( \Delta \tau = 0 \) and \( \Delta f_d = 0 \), i.e., the delay and the frequency of the Doppler signal copy correspond to the input signal, the noncentrality parameter is equal to \( \lambda = A^2/2 \). In this case, the probability of correct detection is determined in accordance with the formula [5–7]:

\[ P_D = \int_{-\infty}^{\infty} P_2(x | H_1) dx = Q_2 \left( \frac{A^2}{2 \sigma_n^2}, \frac{\beta}{\sigma_n} \right), \]

where \( Q_2(a, b) \) is the generalized Marcum Q-function.

It should be noted that if the delay and the frequency of the Doppler signal copy do not correspond to the input signal, the \( \lambda \) noncentrality parameter would be reduced; therefore, the \( P_D \) probability of the correct detection value would be changed.

Therefore, the conducted analysis shows that the detection characteristics of the L1OCp pilot component of the GLONASS signal coincide for the considered methods with the absence of misalignment by the delay and frequency.

The detection characteristics of the L1OCp pilot GLONASS signal with different intervals of coherent integration are obtained in accordance with the presented formulas (Fig. 4).

The calculated were implemented under following conditions: the coherent integration interval was selected as the multiple of the ranging code period; the probability of false alarm was specified as equal to \( P_F = 10^{-3} \) and the passband of the analog path was matched with the L1OCp signal bandwidth. The obtained characteristics indicate the capability of adaptive management for storage time with the need for reception of satellite signals with different power levels.

The reason for the reduction of navigation signals detection quality is the uncertainty of signal location at the search cell. The received signal can be located in any area of the cell; herewith, the reference signal is calculated usually for the medium of the cell. The residual uncertainty of reference signal parameters does not exceed the \( \Delta \tau/2 \) for delay and \( \Delta f_d/2 \) for frequency.

One can determine the mean probability for correct signal detection at the search cell assuming the probability distribution \( \Delta \tau \) and \( \Delta f_d \) at the cell as equiprobable and using the above-mentioned formula for the noncentrality parameter of \( \chi^2 \) distribution. This article determines the values of loss at the search cell depending on the uncertainty by delay and frequency for the GLONASS L1OCp signal detected in one period of coherent integration \( T = 8 \) msec with the probability of false alarm \( P_F = 10^{-3} \) and the probability of correct detection at the cell center \( P_D = 0.95 \) (Fig. 5).

The considered conditions show that the probability of correct detection with the misalignment only by delay on the edges of the cell is reduced to \( P_{D_{\min}} = 0.57 \), and the mean probability for correct detection \( P_D \) is 0.79.

![Fig. 4. The characteristics of the L1OCp GLONASS signal. The probability of correct detection (Y-axis) depends on the signal-to-noise ratio \( q = P_s/N_0 \) (dB Hz). The light curve is for 8 msec; the dashed curve – for 16 msec; the dotted curve – for 40 msec; the dashed and dotted curve – for 120 msec; and the dark curve – for 200 msec, respectively.](image-url)
$P_{D_{\text{min}}} = 0.73$ and $P_D = 0.89$ are obtained for misalignment only by frequency. $P_{D_{\text{min}}} = 0.27$ and $P_D = 0.70$ are obtained during the simultaneous misalignment by the delay and frequency. The improvement of the received signal power by 2.17 dBW is required for the compensation of the received loss with the simultaneous uncertainty by $\Delta t$ and $\Delta f_d$.

**Results**

In accordance with the obtained results, one can conclude that the search cell dimensions during the reception of navigation signals should provide the mean probability of correct detection at the cell not worse than the specified one. On that basis, the number of search cells and, consequently, the total time for search should be determined.

It was demonstrated that during the detection of the GLONASS L1OCp signal, both the detectors with the separate processing at the sidebands and the detectors with the deletion of subcarrier frequency can be used. The obtained characteristics indicate the capability of adaptive management for storage time with the need for the reception of satellite signals with different power levels.

**Conclusion**

The loss analysis during the detection implemented in this article has demonstrated that the uncertainty by delay and frequency at the search cell can affect significantly the detection characteristics. The search cell dimensions should be selected taking into account the considered loss and the required characteristics of detection.

The mathematical apparatus for the calculation of the statistical characteristics of satellite navigation BOC($n, m$) signals detection can be used for the analysis of navigation user equipment capabilities during the detection of new signals.

**REFERENCES**

1. IS-GPS-800D. Navstar GPS Space Segment/ User Segment L1C Interface, 2014, p. 119.
2. European GNSS (Galileo) Open Service. SIS ICD, 2010.
3. KA GLONASS-K2. Struktura izluchaemykh navigatsionnykh radiosignalov s kodovym razdeleniem chastotnykh diapazonov L1, L2, L3 [KA GLONASS-K2. Structure of emitted navigation radio signals with code division of frequency bands L1, L2, L3]. 2nd ed. Moscow, AO «RKS» Publ., 2015. (In Russian).
4. Dobrikov V. A., Bakhholdin V. S., Gavrilov D. A., Ivanov V. F. Comparative analysis of methods and characteristics of detection of BPSK signals of global navigation satellite systems. In: Yu. V. Kuleshov, ed. Proc. VKA imeni A. F. Mozhaiskogo, 2016, vol. 654, pp. 26–33. (In Russian).
5. Borio D., O’Driscoll C., Lachapelle G. Coherent, noncoherent and differentially coherent combining techniques for acquisition of new composite GNSS signals. Aerospace and Electronic Systems, IEEE Transactions, 2009, vol. 45, pp. 1227–1240.
6. Heiries V., Roviras D., Ries L., Calmettes V. Analysis of non ambiguous BOC signal acquisition performance. Proceedings of ION GNSS 17th International Technical Meeting, 2004, pp. 2611–2622.
7. Yang Z., Huang Z., Geng S. Acquisition performance analysis of BOC signal considering the code search step size. Journal of Computers, 2011, vol. 6, no. 7, pp. 1386–1393.
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