GNSS Receiver Interference Protection Increase for Small-Sized Equipment

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The research deals with a method of interference protection based on using the signal processing algorithms that improve interference immunity of the receiver in the case of non-Gaussian interferences. Interference immunity increase is achieved by using adaptive algorithms for nonlinear signal processing in the receiver. Evaluation of the protection effectiveness was obtained for the Rician interference.

***Index Terms*—Interference suppression, GNSS receiver, nonlinear processing, satellite navigation systems.**

I. Introduction

To solve the problem of interference immunity improvement for the GNSS user equipment (UE), the most attention is given to the development of adaptive antenna arrays and digital suppressors, which use spatial and frequency rejection [1]-[4]. Apparently, these devices are the most efficient means of interference suppression. They can be used, however, only in the cases when there are no substantial restrictions onto the UE dimensions and power consumption. The above-mentioned solutions are not suitable for small-sized hardware (with UE dimension less than 15 cm) not only because of the size of the equipment that does not allow implementing an adaptive antenna array, but, also, due to the restriction of power consumption in such devices. All solutions related to digital signal processing lead to a significant increase of power consumption.

The problem of interference protection of small-sized UE can be solved by using the signal processing algorithms for improving the interference immunity of the receiver in the case of non-Gaussian interferences [5]. In this case the asymptotically optimal algorithms are most attractive. They lead to a nonlinear signal processing. These algorithms can be implemented by analog means and their application does not need substantial increase in size and power consumption of the receiver.

Conditions of effective using the asymptotic optimal algorithms coincide with those of the GNSS UE functioning. These conditions are as follows: signal-to-interference ratio in the received signal is much less than unity, interferences substantially differ from the Gaussian noise, desired signal is not correlated with the interference, and signal processing in the receiver includes the coherent accumulation procedure to enable reliable capture and tracking the weak navigation signals.

The paper deals with the efficiency of using the nonlinear processing in the RF front end of the UE receiver for protecting it under external interferences. Interferences are represented by sinusoidal oscillations having an arbitrary angle modulation. Among these are: harmonic and similar to signal interferences and frequency-modulated continuous oscillations. Substantially, these interferences are non-Gaussian processes. A mixture of such interference and internal receiver Gaussian noise forms the stochastic process with the Rice distribution of envelope. That's why we call these processes as a Rician interference.

II. Interference Suppressor

The theory of signal detection against a background non-Gaussian interferences [5] considers algorithms for weak coherent signal detection. The optimal detection algorithms are based on the likelihood ratio. The asymptotic optimal algorithms are found under fixed energy by means of decreasing the signal level with simultaneous increasing the duration of signal accumulation.

The asymptotic optimal algorithms include a nonlinear signal processing implemented at the receiver RF front end. With some additional restrictions onto the interference properties, the nonlinear processing is defined as

$$f(x) = \int_0^x \frac{\frac{d}{dA}[Ag(A)]}{\sqrt{x^2 - A^2}} dA, x > 0, f(-x) = -f(x), f(0) = 0, \quad (1)$$

$$g(A) = \frac{d}{dA} ln \frac{W_A(A)}{A}. \quad (2)$$

In (1), $x(t)$ is the signal in the receiver linear part. It represents a mixture of the desired signal and interference (external interference and the internal receiver noise). This signal can be considered either at the receiver input or at an IF frequency. The function $W_A(A)$ is the amplitude probability density of the interference under which the desired signal is received.

Algorithm (1) is obtained at restrictions on the width of interference spectrum. Interference is a random process with a broad spectrum in relation to the desired signal. In spite of this, the algorithm (1) is efficient for protection against interference with a narrow spectrum relative to the desired signal [5]. This allows using algorithm (1) as the basis for determination of the interference protection device structure where the interference suppression results from nonlinear signal processing.

For Rician interferences representing a mixture of the external interference of the amplitude A_0 and the internal

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receiver noise having the power σ^2, the amplitude probability density $W_A(A)$ is given by

$$W_A(A) = \frac{A}{\sigma^2} exp\left(-\frac{A^2 + A_0^2}{2\sigma^2}\right) I_0\left(\frac{AA_0}{\sigma^2}\right).$$

Under this algorithm (1) is well approximated by the function [6]:

$$f(x) = x - \frac{A_0\pi}{4} sign(x). \tag{3}$$

The condition for well approximation is the ratio

$$\alpha = A_0^2 / 2\sigma^2 >> 1. \tag{4}$$

Under this condition the external interference represents the largest threat to the UE normal functioning.

The structural diagram of an interference suppression device corresponding to algorithm (3) is shown in Fig.1.

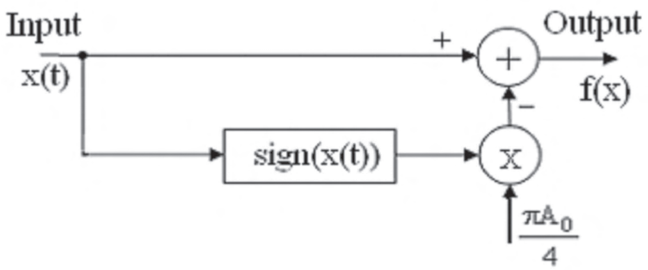

Fig. 1

The physical sense of processing shown in the diagram (Fig. 1) consists in compensation of the external interference. The compensating signal is formed on the basis of the input signal $x(t)$ as a component of the nonlinear conversion

$$A_0\pi \cdot sign[x(t)]/4 \tag{5}$$

on the carrier frequency of the signal $x(t)$. Higher harmonics of this conversion are placed beyond the receiver bandwidth, thus, having no impact onto the final result of the processing.

In real practice, the amplitude A_0 is unknown and subjected to change. That is why algorithm (3) has to be A_0 - adaptive.

The adaptation can be performed in different ways. For example, one can evaluate the parameter A_0 according to the signal $x(t)$. In this case, it is necessary to take into account that the external interference overpowers substantially both the desired signal and the internal receiver noise (condition (4)). So one can estimate the value $\hat{A}_0$ of the parameter A_0 as a mean value of the envelope A_x of the signal $x(t)$ at the previous time interval T_1:

$$\hat{A}_0(t) = \frac{1}{T_1} \int_{t-T_1}^{t} A_x(\tau) d\tau. \tag{6}$$

The estimated value obtained in such way is put in (3) (and in the diagram in Fig. 1) instead of A_0. The adaptation interval T_1 should be long enough to obtain a well-smoothed estimate of the parameter A_0.

The adaptive modification of algorithm (3) can also be built using correlation feedback as shown in Fig. 2. A low-pass filter is used to suppress the carrier frequency harmonics of the signal $x(t)$ that appear after the conversion $sign[x(t)]$.The compensating signal is formed as in the previous case, but its amplitude is established according to the minimal mean square of the residual compensation. The parameter γ affects the adaptation rate and accuracy.

The functions $g(A)$ and $f(x)$ included in (1) are joined up by the formula

$$g(A) = \frac{1}{\pi} \int_0^{2\pi} f(A\cos\varphi) \cos\varphi \, d\varphi.$$

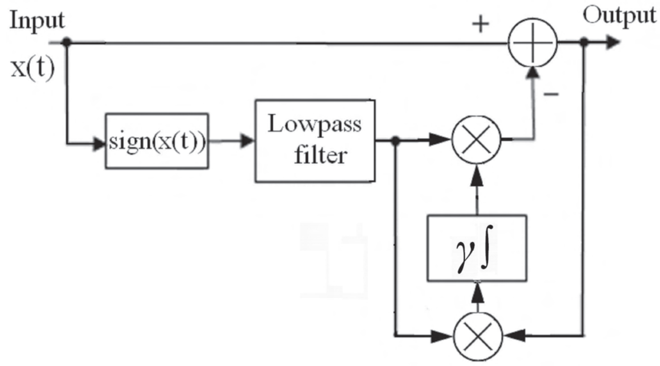

Fig. 2

It shows that $g(A)$ is the coefficient of the first harmonic Fourier series expansion of $f(A\cos\varphi)$.

Considering $x(t)$ as

$$x(t) = A_x(t)\cos[\omega_0 t - \varphi_x(t)],$$

the nonlinear processing result $f(x)$ on the frequency ω_0 may be presented in the form

$$f(x)_{\omega_0} = g[A_x(t)]\cos[\omega_0 t - \varphi_x(t)].$$

Given that only this component of the conversion $f(x)$ goes into the receiver, the nonlinear processing equivalent to (1) can be performed according to the diagram shown in Fig.3.

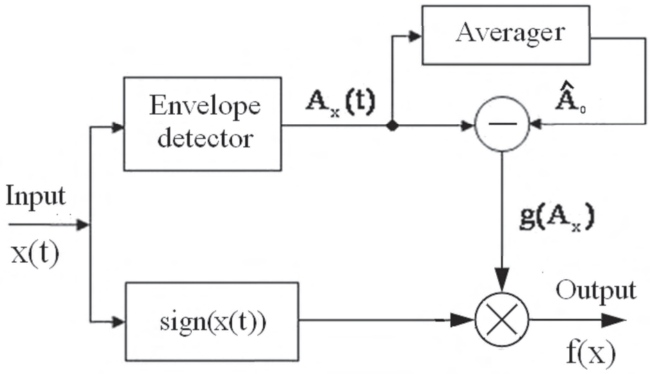

Fig. 3

For the case considered in this paper,

$$g(A_x) = A_x - A_0,$$

and with due account of the adaptation

$$g(A_x) = A_x - \hat{A}_0,$$

where the estimate $\hat{A}_0$ is defined by (6). The technical solution suggested in [7] is close to one in the diagram on Fig.3.

Thus, we suggest three variants of the interference suppression structure, which use nonlinear processing of the received signal at the RF front end. The first two variants involve interference compensation at radio frequency. In the third variant the compensation is performed at video frequency. All suggested variants require no digital processing and can be implemented by analog means. It allows improving the receiver interference immunity without substantial growth of its size and power consumption.

III. Analysis of Efficiency of Nonlinear Protection Devices

The efficiency of the nonlinear processing application to protect the navigation receiver against the Rician interferences was examined using the diagram shown in Fig. 4.

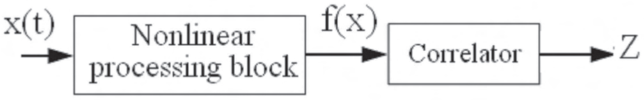

Fig. 4

The nonlinear processing block (NPB) is intended to increase signal-to-interference ratio at the correlator output. This ratio affects on the quality of detection and tracking of the navigation signals in the receiver. The correlator is a signal processing device in the navigation receiver. It is used to improve the signal-to-noise ratio.

NPB was considered in two variants shown in Fig. 2 and Fig. 3. The correlator accumulates signal during the time interval equal to the duration T of the GLONASS navigation signal ranging code

$$Z = \int_0^T f[x(t)]\,s(t)dt, \tag{7}$$

where $x(t)=A_x(t)cos[\omega_0 t-\varphi_x(t)]=s(t)+\xi(t)$ is the received signal, $s(t)=A_s(t)cos[\omega_0 t-\varphi_s(t)]$ and $\xi(t)=A_\xi(t)cos[\omega_0 t-\varphi_\xi(t)]$ are the useful and interfering components, correspondingly.

The effectiveness of the NPB application was estimated using the ρ value – increment of the signal-to-interference ratio at the correlator output:

$$\rho = q_{Z2} / q_{Z1}, \tag{8}$$

where q_{Z1} is the signal-to-interference ratio at the correlator output (7) in the absence of the nonlinear processing;

q_{Z2} is the same involving nonlinear processing.

The ratio $q_Z=P_S/P_\xi$ was defined at

$$P_S = M\left\{\left(Z_{S+\xi} - Z_\xi\right)^2\right\}, \tag{9}$$

$$P_\xi = M\left\{Z_\xi^{\ 2}\right\}. \tag{10}$$

In formulas (9) and (10)

$Z_{S+\xi}$ is the correlation integral value in the case when the received signal $x(t)$ contains useful and interference components;

Z_ξ is the same in the case when only the interference is present;

M is the symbol of assembly average.

The theoretical value of nonlinear processing effectiveness by (8) depends on the type of interference distribution $W_A(A)$ at the NPB input [5]. For the Rician interferences under condition (4), the theoretical value of NPB effectiveness is evaluated in [5] as follows:

$$\rho = \alpha / 2 \tag{11}$$

For broad-band interferences (relatively to the desired signal), this estimate is the limit value. For narrow-band interferences estimate (11) is approximate.

The real effectiveness of the NPB application was analyzed using MATLAB mathematical simulation software with the following simplifications:

– single channel correlator adjusting to the one GLONASS satellite signal is considered; the influence on this channel of others navigational signals is neglected;

– the desired signal was considered as the ranging code signal of the standard accuracy;

– the internal noise was simulated as the white Gaussian noise (WGN) of the given power within the desired signal bandwidth.

The first NPB variant (Fig. 2) was analyzed under the following conditions:

– navigation signal was simulated at the intermediate frequency f_c = 5 MHz;

– sampling frequency $f_s = 100 \cdot f_c$;

– ranging code length was T = 1 ms;

– duration of one ranging code element was 2 μs;

– external interferences were: harmonic without modulation, similar to signal, continuous with linear frequency modulation (LFM), and narrow-band Gaussian noise (NGN); all interferences were formed within the navigation signal bandwidth;

– interference-to-signal ratio at the NPB input for NGN was equal to 30 dB and 40 dB for other interferences;

– WGN power at the NPB input was 15 dB higher than the navigation signal power.

The simulation results are shown in Figs. 5 ÷ 7 as effectiveness dependences versus the parameter γ in the feedback loop. Figure 8 shows the effectiveness dependence on the interference-to-noise ratio. This dependence was obtained under a constant signal-to-noise ratio while changing the interference level at the NPB input.

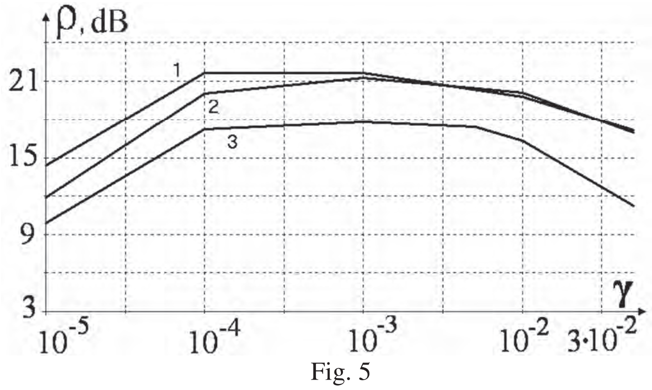

Fig. 5

1 – harmonic interference without modulation with carrier frequency 5.01 MHz; 2 – 5.02 MHz; 3 – 5.04 MHz.

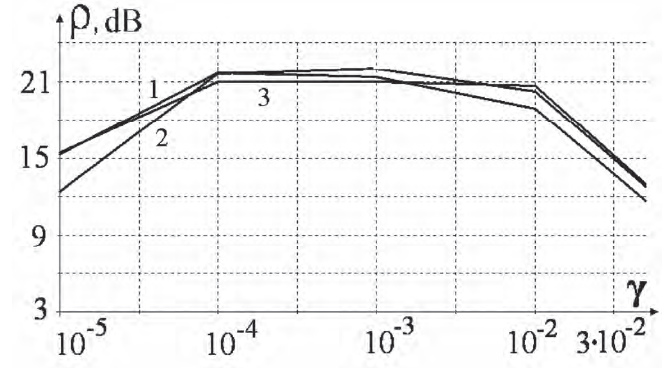

Fig. 6

1 – interference with periodic LFM with deviation 1 MHz and modulation period T_{M1} = 1 ms; 2 – T_{M2} = 0.25 ms; 3 – similar to signal interference with carrier frequency 5.01 MHz and 50 μs time shift.

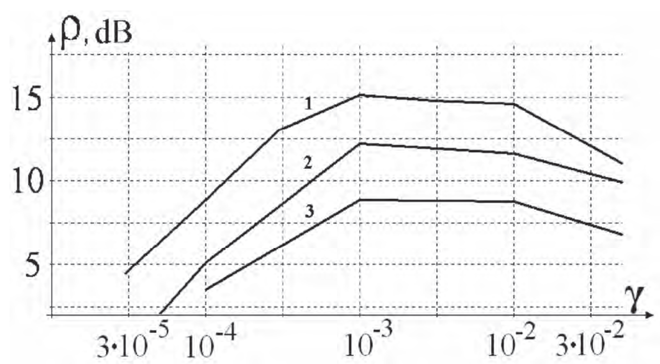

Fig. 7

1 – NGN spectrum bandwidth 4 kHz; 2 – 15 kHz; 3 – 30 kHz.

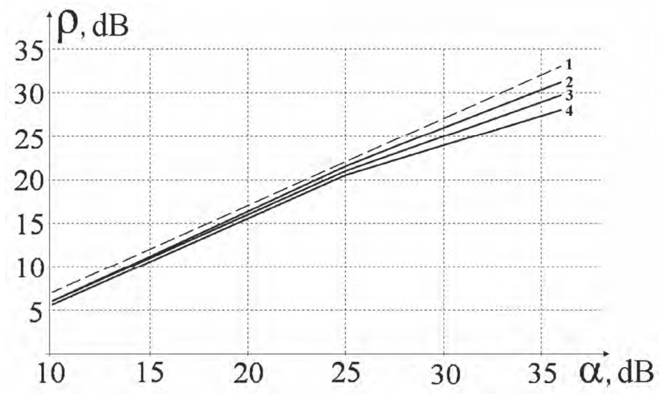

Fig. 8

1 – theoretical evaluation; 2 – similar to signal interference; 3 – harmonic interference without modulation with carrier frequency 5.01 MHz; 4 – periodic LFM with deviation 1 MHz and modulation period T_{M1} = 1 ms.

The results allow one to make the following conclusions:

– the effectiveness of nonlinear processing slowly depends on the type of angle modulation and the bandwidth of the active interference and is close to the theoretical estimate;

– the NPB can also be used for narrow-band Gaussian noise suppression, under this, the effectiveness of suppression depends on the NGN spectrum bandwidth; the larger is the NGN spectrum, the lower is the effectiveness of suppression;

– the effectiveness of nonlinear processing increases at higher interference-to-noise ratios.

Also NPB was analyzed in variant shown in Fig. 3. In this case, the simulation involved forming and processing the quadrature components of input signal at video frequency.

The investigation was mainly carried out under the same conditions as in the previous task, with the following differences:

– sinusoidal law was chosen for modulation of the FM interference;

– WGN power at the NPB input was 25 dB higher than the navigation signal power;

– the averaging interval T_1 was the adaptation parameter (see (6)).

The results of simulation are shown in Figs. 9÷10. Figure 9 shows the dependence of the NPB effectiveness under the sinusoidal FM interference on the modulation frequency f_{mod}. Figure 10 shows the same dependence under NGN on its bandwidth Δf_{NGN}.

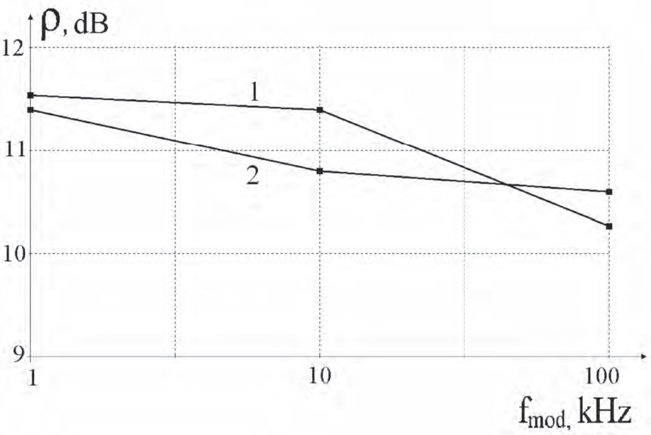

Fig. 9

1 – averaging interval $T_1 = 5$ μs; 2 – $T_1 = 10$ μs.

Fig. 10

1 – averaging interval $T_1 = 5$ μs; 2 – $T_1 = 10$ μs.

The results in Fig. 9 shows that the NPB structure as in Fig. 3 ensures the interference suppression effectiveness, which is close to the theoretical estimate ρ=12 dB. The effectiveness depends weakly on the rate of interference modulation and the averaging interval value T_1 if $T_1 \geq 5$ μs.

The results in Fig. 10 show the NPB can also be used for suppression of the narrow-band interferences described by NGN. In this case, the NPB effectiveness depends on the interference spectrum bandwidth and the selected averaging interval value T_1 used for current estimation of the NGN envelope. Since the NGN envelope is a fluctuation process, the selection of T_1 value has to be bound up with the process dynamics.

IV. Conclusion

In this paper, we present an effective method of navigation receiver protection under the Rician interferences: a special nonlinear processing of the signal at the receiver RF front end. This processing can be implemented by analog means. Its implementation does not lead to a substantial growth of the receiver size and power consumption. That is why the method considered above is of the high priority for application in small-sized equipments when the size and power consumption are substantially limited.

The obtained estimates of effectiveness for the nonlinear processing concern the use of this processing before correlator. In small-sized equipments the analog signal is converted by a one- or two-bit analog-digital converter (ADC) before correlator. The presence of a low-bit ADC before the correlator decreases the receiver interference immunity under the Rician interferences. Thus, the use of the above-mentioned protection against the Rician interferences becomes even more actual.

It should be recognized that research of the efficiency of nonlinear processing performed with a strong simplification of the GNSS signal and processing in the receiver. This may be a reason to doubt in the practical value of our results.

Additional research by seminatural simulation was carried out to reduce such doubts. In this study, the GPS signal and external interference were simulated by National Instruments software and hardware in full accordance with the actual conditions of observation. These signals were applied to the input of the real GPS receiver. Protection devices maquette was built in accordance with the recommendations in this paper. Maquette was applied at the receiver input. Results of seminatural simulation were confirmed the theoretical estimates of the mathematical modeling in this work.

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