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The Results of the Modeling and Estimate of the Characteristics of the Signals with Linear Frequency Modulation Reflected from the Spread Objects

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Abstract. The article contains the study of the algorithms of the weight pulse-type signal processing with linear frequency modulation in the radio engineering measurement system of parameters relative to the movement used for space vehicles docking. The aim of work is to increase the system working capacity through eliminating spurious signals reflected from the large-sized construction elements, for example, from the International Space Station. Such spurious signals are received in the same time interval together with the useful signal that contains the data on the relative movement parameters. This can reduce the measurement accuracy of these parameters. In order to eliminate this effect, there was selected a broadband pulse signal with linear frequency modulation and digital processing of the received signal. Deterioration of the measurement accuracy caused by the side lobes of the correlation function leads to the necessity to examine different ways of their reducing with the help of a so called "mismatched reception", which has a distinctive feature of losses caused by the discrepancy. This work contains the research on measuring these losses depending upon the relation FKV/FDEV = K. Moreover, the best value of K when using this filter was found.

Keywords: space vehicles docking, linear frequency modulation, multipath effect, mismatched filtering, deviation frequency, sampling frequency

Introduction

A combination of a useful signal, sum of the re-reflected signals and receiver noise is transmitted to the output of the filter for processing path to determine the position of large-size space objects (SO). As a result, a spurious signal consisting of a number of signals received from various paths owning to multipath radio waves propagation appears in the reception point. This signal significantly reduces the indicators of the system for mutual measurements and rendezvous-docking search (MMRDSS) in terms of measurement of the parameters accuracy of the rendezvous trajectory for SC and SO.

When developing MMRDSS, there appears a task to minimize the measurement errors due to the side lobes (SL) of the autocorrelation function of an emitted signal. In the literature, works on decreasing the SL response on the time axis are conducted in several directions:

1. Using weight processing methods [4, 5], when the main response lobe widens, and its value decreases in maximum.

2. Signals modification with linear frequency modulation (LFM) introducing a relatively small nonlinearity [1], which makes it possible to achieve the effects similar to weight processing.

3. Carrying out a disagreed processing based on the usage of the special reference function.

In [3], it is concluded that weight processing in the receiver is a more effective method than that of in the receiver, since control of the envelope on the output of power transmitters is considerably difficult.

When using mismatched filtering, there appears a problem to search optimal filter parameters. This task can be found in:

1. Evaluating the signals parameters received under the conditions of a white noise with related re-reflected interferences and multipath.

2. Tracking a great number of noncooperated objects.

3. Designing SAR (synthetic aperture radar).

4. Forming frequency-amplitude distribution according to the aperture of the active phase-array antennas (APAA) with areas of an increased suppression of the re-reflected signals.

The quantization frequency *Fq* is a filter characteristics under investigation. It allowes one to receive minimal loss because of disagreement for different values of the deviation frequency *Fdev* and the pulse duration τ. *Fq* to *Fdev* ratio is taken as $K=F_Q/F_{DEV}$.

Signal extraction principle of this method is based on the model of the received signal in the form of matrix, where the signals are as numeric vectors in a complex space and nonstatic processing methods by evaluating the functions of mutual correlation of the received spaced diversity signals. To search for an optimum solution of the set tasks, computer simulation and series of experiments in the *Matlab* was carried out.

The aim of the paper is to determine optimum parameters of the signal with LFM by computer simulation taking into account the peculiarities of the requirements on the operation of the SC docking system.

Properties of the LFM signal and description of the computer model

A signal with linear frequency modulation (LFM) was used during research. It was taken based on the fact that this signal is employed in the majority of the modern systems, since it has a number of useful properties, including simplicity of realization and opportunity to significantly compress a signal during the reception with increase in its amplitude under the interference level.

Determination of the best parameters of the signal with LFM such as pulse durability τ, deviation frequency F_{DEV}, quantization frequency F_{QUANT} and $F_{QUANT}/F_{DEV}= K$ ratio by means of simulation makes it possible to obtain necessary parameters in the response of the “mismatched” filter, such as:

1. The width of the main lobe (distance between 0 and crossing of the main lobe of the time axis – end point).

2. An integral level of the side lobes on the output of the supression filter.

3. “Mismatch” loss.

4. The maximum size of the peak suppression zone.

5. The minimum level of the side lobes out of the peak supression zone of the compression filter.

The detailed description of the computer model operation is given in [6]. To understand the system operation, further is given a short description of the functioning of the seacrh algorithm for the optimum filter parameters of the signal with LFM.

A model of the emitted signal with LFM: $S(t) = a\cos\left(\omega_0 t + \frac{\pi F_{DEV} t^2}{\tau_{PULSE}}\right)$;

An equivalent complex representation is the following:

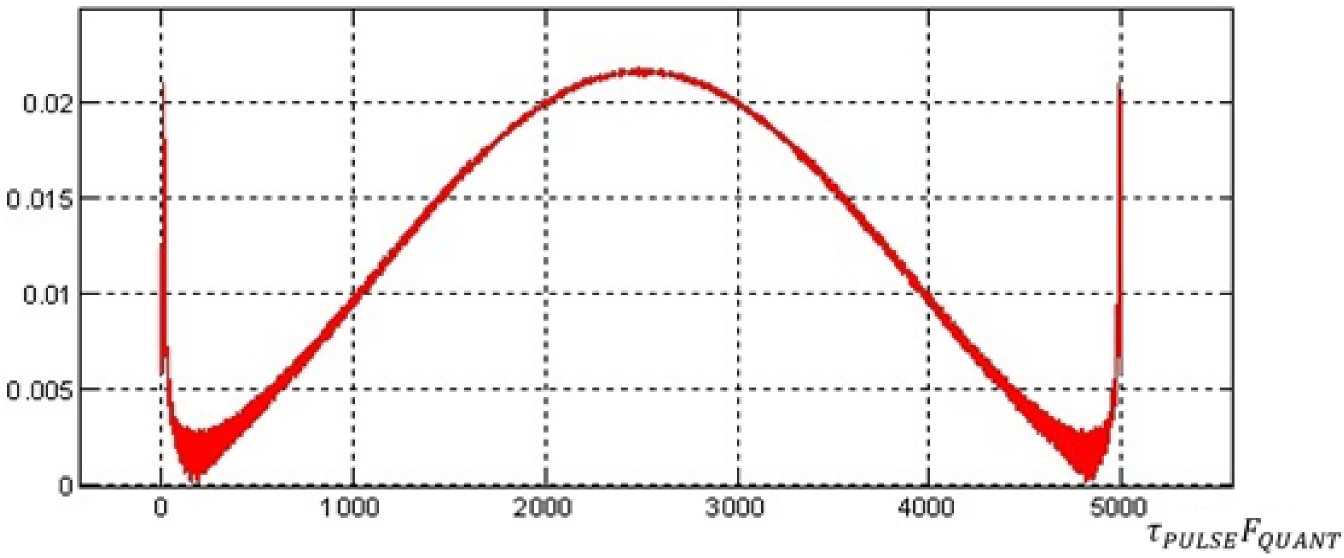

Fig. 1. Amplitude-frequency characteristics of the reference vector.

$$\dot{S}(t) = a\, exp\frac{j\pi F_{DEV}t^2}{\tau_{PULSE}}$$

Allowing for digital processing: $\bar{S}(i) = (z_{01}, z_{02}, \dots, z_{0n})$,where $i = 1,2 \dots n$, $\bar{S}(i)$ *is* a vector in the complex space.

A model of the reflected signal $\bar{S}_j = [(\alpha_{i1},\varphi_{i1}) (\alpha_{i2},\varphi_{i2}).....(\alpha_{in},\varphi_{in})]$ is a standard, centered emitted signal, where α_j is an unknown amplitude and φ_i is an unknown initial signal phase.

In this case a problem of the synthesis can be solved as a problem of the signal resolution $\bar{S}_k$ received together with *m*-other signals: to build an optimum filter (a supporting function) using an optimality criterion, i.e., obtain a response maximum on the signal under analysis when supressing interfering signals up to a some level *ε* (or zero).

A received signal

$$y_k(t_j) = \alpha_k \bar{S}_k + \sum_{i=1;i\neq k}^{m} \alpha_i \bar{S}_j + \bar{\omega}(t_j), \text{ where}$$

j=1,2,…2n, m=2n-1.

In the formula, the first summand can be considered as a useful signal, the second one – as an interfering signal, the third – as a noise.

The processing algorithm.

An optimum reference vector should be searched

$$\bar{P}_{0j} = (x_{01}, x_{02}, \dots x_{0n}), \text{ such that } \bar{S}_k, \bar{P}_{0j} = \max$$

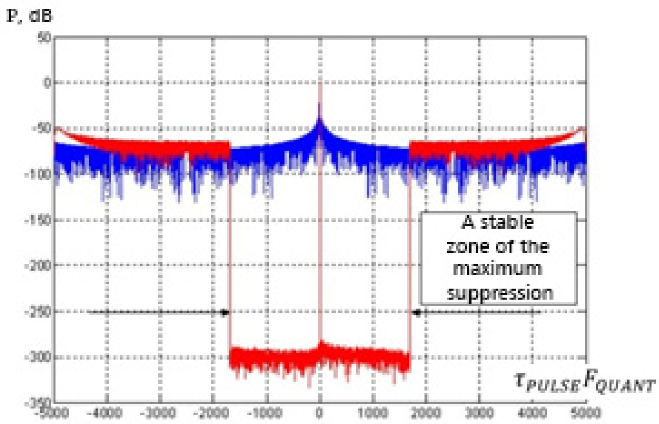

Fig. 2. The responses of the matched (blue) filters and filters under research (red).

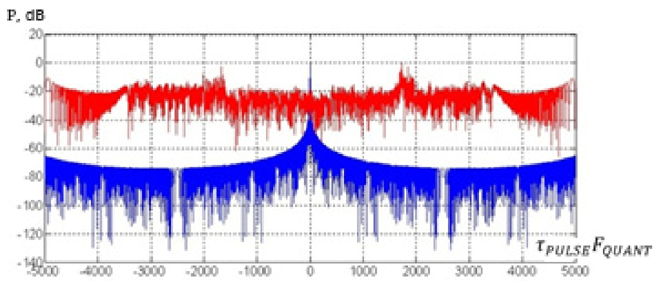

Fig. 3. The responses of the matched (blue) filters and filters under research (red) under the conditions of violating the algorithm for equations solution.

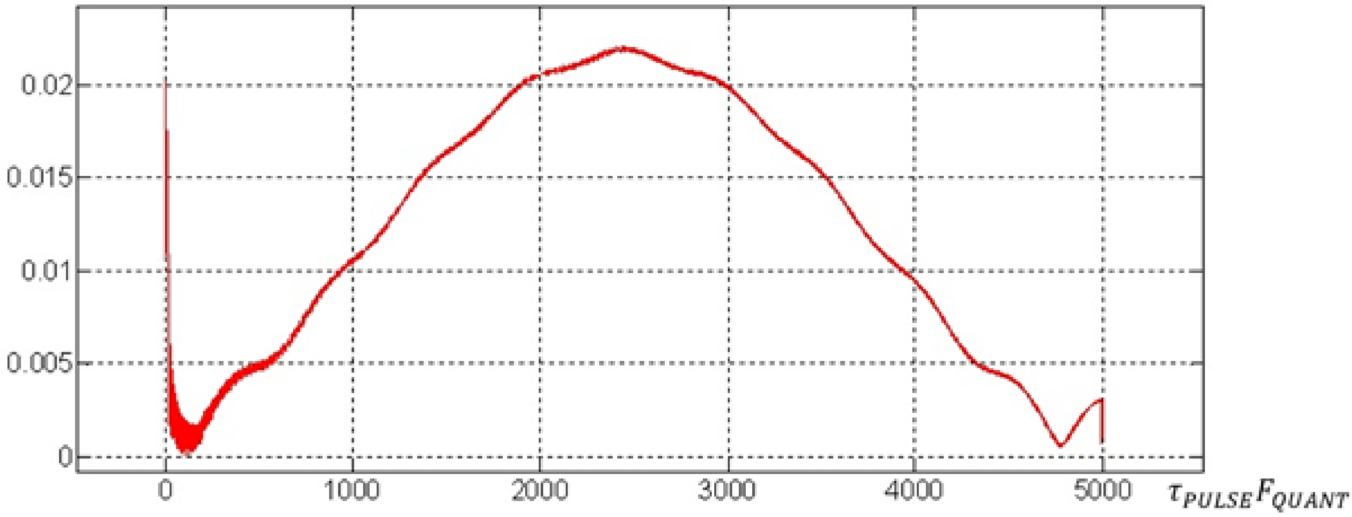

Fig. 4. Amplitude-frequency characteristics of the reference vector (physical simulating).

under the condition: $\left(\sum_{i=1;i\neq k}^{m}\alpha_i\bar{S}_{ij},\bar{P}_{0j}\right)\begin{cases}<\varepsilon\\ or\\ =0\end{cases}$

If to consider that a set of signals under research has a correlation interval $\sim\frac{1}{\Delta F}$, and $f_{quant.}>2\Delta F$ (ΔF is a signal band), so the matrix (S_{ij}) will have the dimension m x n, where $m<n$, the reference vector $\bar{P}_{0j}$ can be written as the following:

$$\bar{P}_{0j}=\left\{E-(S_{ij})^T_{-k}\left[(S_{ij})_{-k}(S_{ij})^T_{-k}\right]^{-1}\cdot (S_{ij})_{-k}\right\}\cdot\bar{S}^T_{kj} \qquad (1)$$

where $(S_{ij})_{-k}$ is the matrix (S_{ij}) without the k-th line.

The filter response built using (1) can be written as the following:

$$U(x/y)=\left(\alpha_k\bar{S}_{kj},\bar{P}_{0j}\right)+\left(\sum_{i=1 i\neq\kappa}^{m}\alpha_i\bar{S}_{ij},\bar{P}_{0j}\right)+ +\left(\overline{w}(t_j)\cdot\bar{P}_{0j}\right).$$

To obtain an analytic base of the research, a number of experiments with various values of the listed parameters of the signal with LFM was carried out. A programme of the experiment was the following: only one

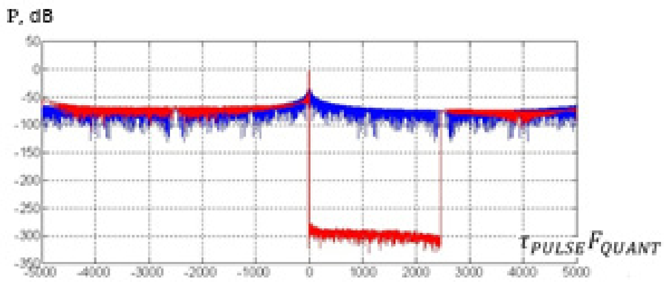

Fig. 5. The responses of the matched filter (blue colour) and the filter under research (red) for physical simulation.

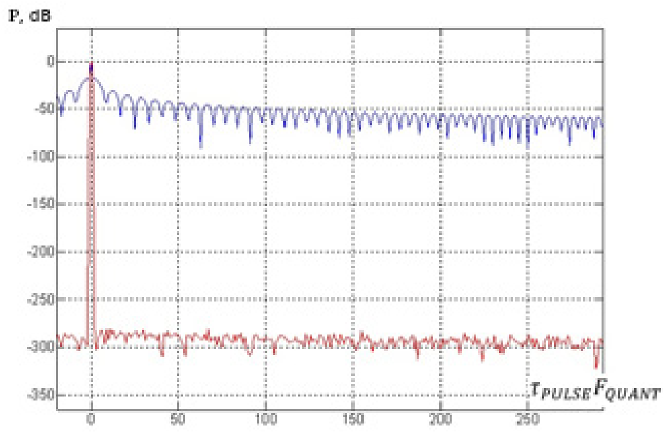

Fig. 6. The responses of the matched filter (blue colour) and the filter under research (red) for physical simulation.

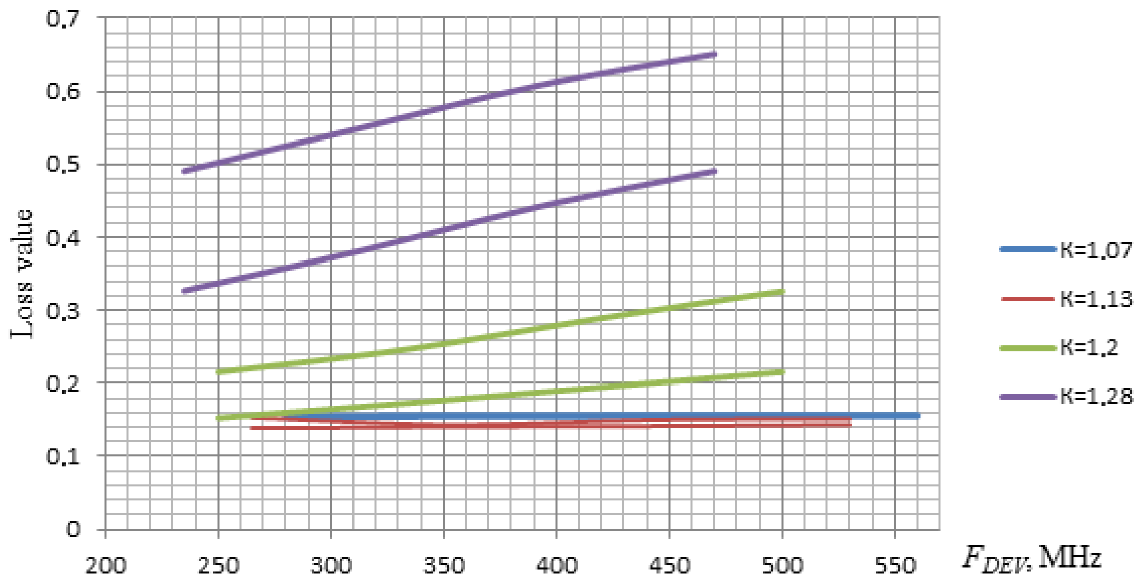

Fig. 7. Dependence of the loss level on deviation frequency for different K (a mathematical simulation).

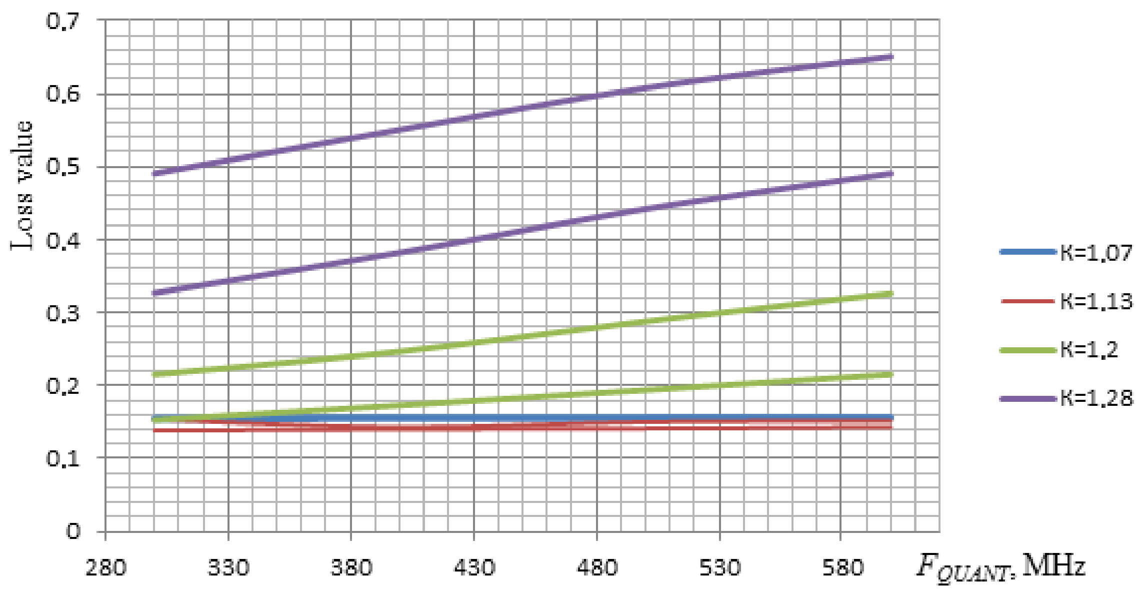

Fig. 8. Dependence of the loss level on quantitation frequency for different K (a mathematical simulation).

parameter varied on each stage, and others remained constant. It was performed to reveal a parameter among the others under investigation that determines to the full extent the result: to control the loss values and response function type. The corresponding analytical graphs were built for each experiment.

Simulation results

A model describes a received signal in the form of a matrix. Its lines are the reflected signals from the SC determined by the chosen correlation level between the neighbouring lines-signals of this matrix. Taking into

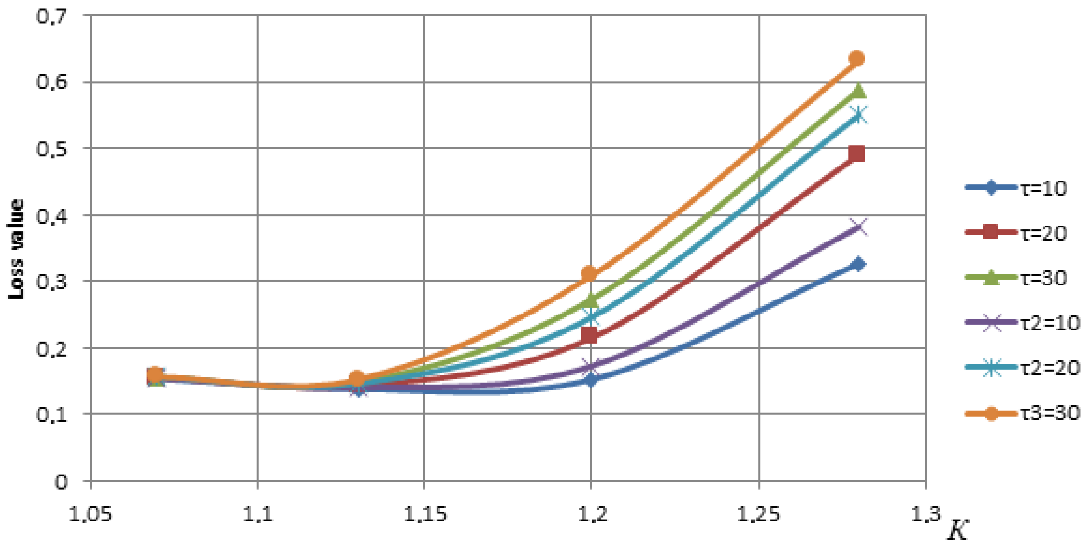

Fig. 9. Dependences for the quantization frequency 300 MHz (τ) and 400 MHz (τ2).

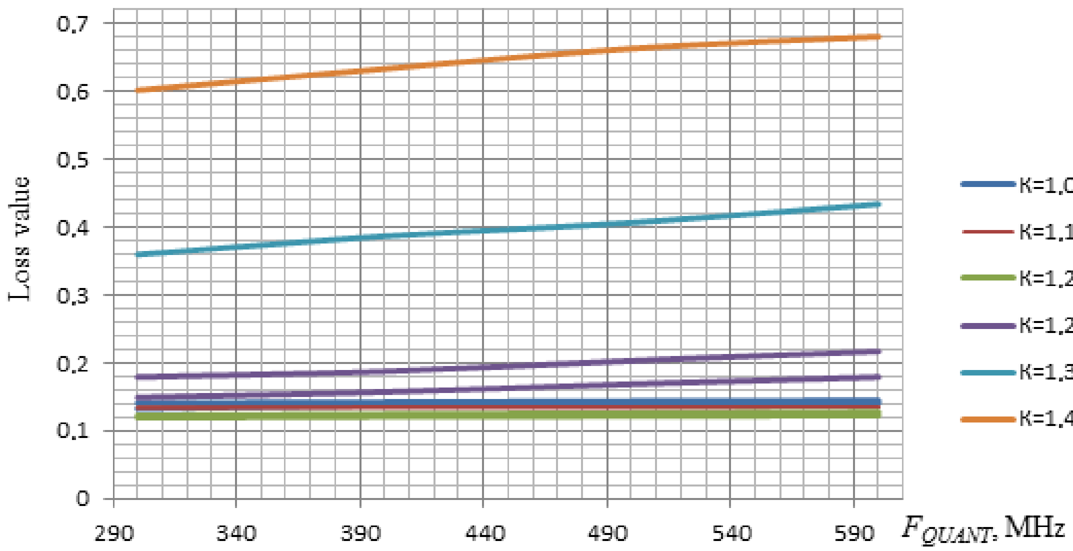

Fig. 10. Loss dependence on quantization frequency for different K during a physical simulation.

account a digital method for signal processing and presence of the quadrature mixers on the output of the receiver, signals of each line of this matrix can be given as numerical vectors in the complex space. The simulation task is determination of the technical parameter K depending on F_{DEV}, F_{QUANT} and τ_{PULSE} allowing one to obtain the minimum loss level of mismatching.

To get the character of the dependences and to reveal the parameters, which at the full extent influence, a number of experiments was conducted. Under these conditions, the varied parameters underwent "a net" of the values under analysis chosen a priori and built for deviation frequency, quantization frequency and pulse duration. The data varied in the range:

1. F_{QUANT} = 300–600 MHz.

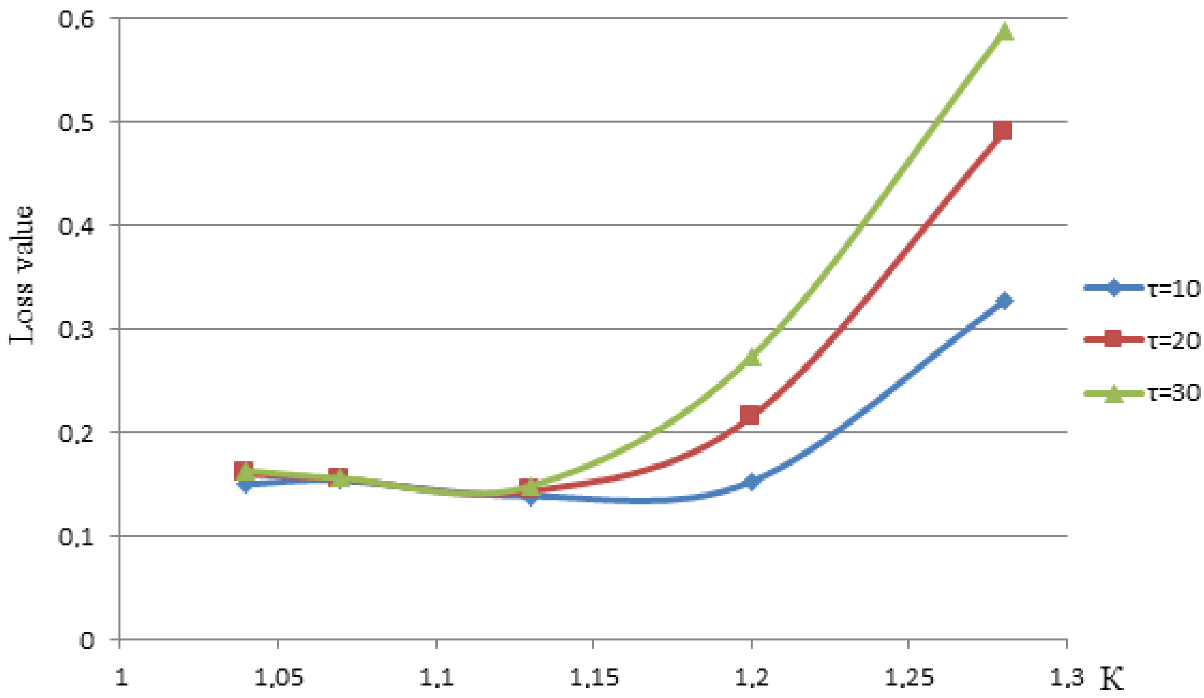

Fig. 11. A diagram of loss dependence on the ratio K=F_{QUANT}/f_{DEV}

2. F_{DEV} = 205–560 MHz (что соответствует значениям показателя K = 1.07–1.46).

3. τ = 10–40 µsec.

Further, the simulation results for a signal model with quantization frequency F_{QUANT}= 500 MHz, deviation frequcny F_{DEV} = 442 MHz (K=1.13) and pulse durability τ = 10 µsec.

Amplitude-frequency characteristics (Fig. 1) of the reference vector is distribution with the maximum in the area of the zero frequency and descending to the edges and tends to the maximum value in the area of the boundary points (the upper frequencies in the spectrum).

The response of the filter given in Fig. 2 is shown in comparison with the case of the matched filtration. The diagram shows that using the mismatched filtration (formula 1) it is possible to obtain a good area of the stable zone of the maximum suppression, about –300 dB.

A mathematical apparatus is the foundation of the algorithm for solution, which is used for solving a big (several thousands) system of linear equations. If an amount of equations in the system becomes more than a certain threshold, so the system turns into unstable, and suppression disappears. Fig. 3 shows with a red colour a response of the filter that is searched for under the amount of the equations in the system to be solved surpassing a third part from the value

The given diagrams show the character of the mathematical dependences when finding the signal symmetrically relative to zero on the time axis. In real conditions a signal exists in the time interval $t>0$, i.e., it is unsymmetrical relative to zero. The diagrams of the corresponding dependences are given below. Such simulating can be called physical.

It should be noted that for a physical simulating a condition of equations system solving is another: an amount of equations in the system should not exceed a half of the value . Fig. 5 shows a response of the filter, and Fig. 6. depicts its scaled area of the zone for the maximum suppression.

During each experiment, a level of a useful signal and loss level were registered.

The analysis of the data received

To obtain analytical data, a number of experiments for the values of the quantization frequencies lying in the range from 300 MHz to 600 MHz and deviation frequencies corresponding to them from 205 MHz to 560 MHz, the pulse duration τ varied from 10 µsec to 30 µsec.

The derived values were written in the summary table, the analysis of which was later given in the form of a diagram. The obtained distributions enable one to find out a frequency dependence of the results, determine the zones with the maximum signal level and the values of the parameters of the signal with LFM corresponding to them.

To demonstrate the results of the experiment, comparative diagrams for mathematical and physical simulation were built.

The results of a mathematical simulation

The diagrams of the loss dependences (in fractions, axis of coordinates) on the deviation frequency (axis of abscissas) (Fig. 7) and quantization frequency (Fig. 8) show the drop in signal amplitude with increasing the value of the K indicator. There is no frequency dependence for small values of the K indicator, while at K>1.2 with increase in frequency a level of the useful signal falls. In addition, there is a slight signal loss with increase in the duration τ.

Diagram 9 shows the dependence of the loss value on the K indicator. In case of a mathematical simulation, an area 1.07–1.15 is the smoothest and, consequently, recommended. Further, a significant drop in characteristics is seen that leads to the loss of a useful signal.

Analytical dependences for a physical distribution

A physical simulation permits one to obtain the same effect. The only difference is that an area of frequency independent results is at the indicator K≤1.2.

The results for the physical simulation is given in Figs. 10, 11.

The analysis of the diagrams received showed that at the small factor K (1.07–1.2) a loss value does not depend on the quantization frequency and is about 0.12–0.14%, while with increasing the K (K>1.2) loss of a useful signal increase by 20% with each increase of the K by 0.1. As the diagram above shows, at the value K=1.36, a loss value increased 3 times in comparison to the values obtained at small factors. At the K=1.46, the loss value increased 5 times. It can be concluded that the most useful, in terms of getting a useful information from the received signal, is an indicator of the quantization frequency-to-deviation frequency ratio equal to 1.07–1.2. With such indicator, the loss dependences on the quantization frequency in the recommended range are almost unobserved.

It should be concluded that the essential factor influencing the results is the indicator $K=F_{QUANT}/F_{DEV}$ (quantization frequency-to-deviation frequency ratio), optimum values of which lie is in the range 1.07–1.2. These results can be referred to the processing of the set of pulse signals with LFM. The results obtained in the foreign and domestic literature known to the authors were not found.

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