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Variant of Technical Realization of Non-Linear Multiplexing GLONASS FDMA and CDMA Navigation Signals

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Abstract. Due to modernization of the GLONASS system, a problem of non-linear multiplexing of GLONASS FDMA and CDMA navigation signals has become of interest. The multiplexing allows transmitting these signals through a common space vehicle (SV) antenna. Development of an apparatus for generating composite (group) L1 and L2 signals each formed by non-linear multiplexing of GLONASS FDMA and CDMA navigation signals may reduce mass-dimensional characteristics of SV with a simultaneous improvement of accuracy characteristics of the signals. However, the difficulty of such multiplexing is that clock frequencies and central frequencies of the multiplexed GLONASS navigation signals have an unacceptably great value of lowest common multiple, as opposed to the value for known methods of non-linear multiplexing, such as AltBOC modulation.

The article proposes an algorithm for computing model values of a composite signal. The algorithm considerably simplifies technical realization of the non-linear multiplexer (NMUX) to form GLONASS signals. A method of computing energy loss is proposed. Spectrum of a composite signal in radio astronomy band is estimated.

Keywords: global navigation satellite system (GNSS), GLONASS, non-linear multiplexing, energy loss, AltBOC

Introduction

In the course of modernization of the GLONASS system, in addition to frequency signals (signals with frequency division), code signals are introduced (signals with code division). Spectra of frequency and code signals are blocked in the radio-frequency ranges L1 and L2 GLONASS. In this regard, the problem of consolidation (multiplexing) of these signals for their radiation via the general antenna is of interest.

The structure of the mentioned GLONASS signals is such that the problem of their consolidation in each of the ranges L1 and L2 comes down to consolidation of two quadrature pairs of signals. In the world practice, AltBOC modulation [1], which belongs to nonlinear methods of consolidation, is applied to solve a similar task. However, AltBOC modulation is developed provided that clock frequencies of the modulating sequences of the condensed signals and the central frequencies of their ranges are a multiple of the frequency of 1.023 MHz. In case of GLONASS signals, this condition it is not satisfied and leads to the fact that the clock frequency of the nonlinear consolidation device (NCD) within these methods has to be unacceptably high. For example, if in the range of L1 code GLONASS signals (the central frequency of the spectrum is 1600.995 MHz) and GLONASS frequency signals at a frequency with the number $k = 6$ are condensed, i.e., at the frequency (1600.995 + 4.38) MHz, then in case of application of AltBOC –type modulation, the clock frequency of NCD will be equal 41820.24 MHz. This value is equal to a least common multiple of the following frequencies (in megahertz): 1.023; 2.046; 10.23; 0.511; 5.11; 4.38×4.

In [2] and [3] it is shown that in the mathematical model of a compound AltBOC signal, a method of linear summation of components (condensed signals) with the subsequent restriction of an amplitude is used and that this method is optimum by the minimum criterion of power losses from alignment. In [2] and [3] it is also shown that the simulating sequence of a compound AltBOC signal is formed by calculation of model values of this sequence in discrete moments of time.

In the paper, the algorithm of calculation of model values of GLONASS compound signals, which allows one to simplify technical implementation of the shaper of these signals is offered. This algorithm is applicable for consolidation of two quadrature couples of any signals.

Structure of the multiplexed GLONASS signals

Initially in the GLONASS system, frequency navigation signals were used. Each navigation spacecraft of the GLONASS system has two carrier frequencies, one in the radio-frequency range L1, another is in L2 range. These carrier frequencies are determined by the formulas:

$$f_{k1}=f_{01}+k\cdot\Delta f_1,$$

$$f_{k2}=f_{02}+k\cdot\Delta f_2$$

where k is the number of the carrier frequency that takes the values from -7 to +6;

$f_{01}=1602$ MHz, $\Delta f_1=562.5$ kHz are the parameters for the L1 band;

$f_{02}=1246$ MHz, $\Delta f_2=437.5$ kHz are the parameters for the L2 band.

On each of the carrier frequencies f_{k1} and f_{k2}, the navigation spacecraft radiated two signals of an equal power called by average precision (AP) and high precision (HP). Thus, each navigation spacecraft radiated four navigation signals: L1 AP, L1 HP, L2 AP, and L2 HP. These signals are also known as L1OF, L1SF, L2OF, L2SF, respectively. At first, these signals were multiplexed with a quadrature method in each of the L1 and L2 ranges, and then the received quadrature couples were multiplexed by a diplexer. Range codes for AP and HP signals have clock frequencies of 0.511 and 5.11 MHz, respectively.

In the course of modernization of the GLONASS system, new code navigation signals were introduced into it. Each navigation spacecraft of the GLONASS system were given three carrier frequencies in the L1, L2, L3 radio-frequency ranges:

$$f_{L1}=1565\cdot 1.023=1600.995 \text{ MHz},$$

$$f_{L2}=1220\cdot 1.023=1248.06 \text{ MHz},$$

$$f_{L3}=1175\cdot 1.023=1202.025 \text{ MHz}.$$

On these carrier frequencies, it is planned to radiate L1OC, L1SC, L2OCp, L2 KSI, L2SC, and L3OC code signals.

Vector charts of the specified GLONASS navigation signals are given in Fig. 1 (a HP signal lags behind in phase from an AP signal by 90 °). The powers of quadrature couples of signals in the L1 and L2 ranges for GLONASS code signals are twice higher, than for GLONASS frequency signals.

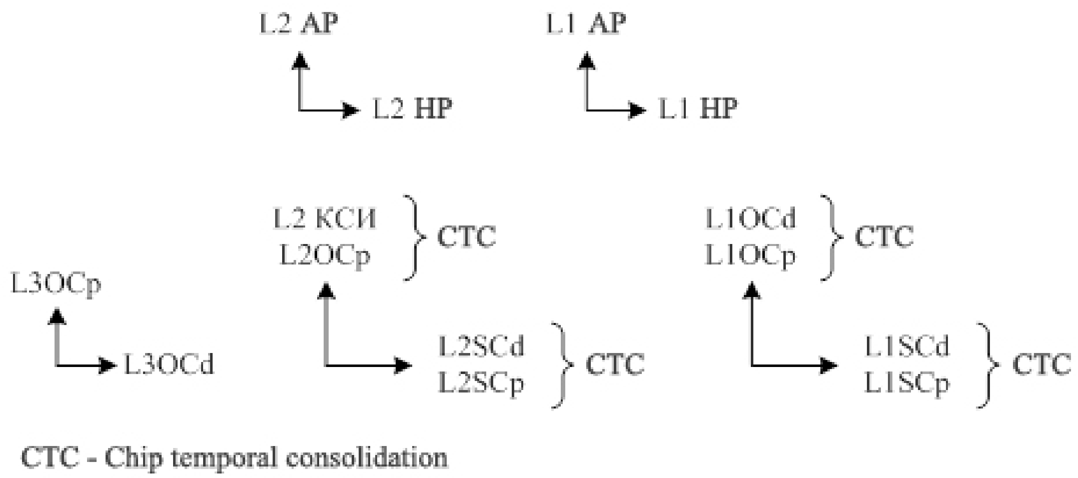

Fig. 1. Vector diagrams of GLONASS navigation signals

The offered scheme of creation of NCD signals of L1 GLONASS

In terms of NCD, L1 and L2 GLONASS signals differ only by carrier frequencies therefore consolidation only in the L1 band will be considered further. As a mathematical model of a compound signal the following complex function is offered:

$$s(t)=\mathrm{sign}[s_{L1SC}(t)+s_{L1OC}(t)+ +s_{HP}(t)+s_{AP}(t)] \cdot \exp(j2\pi f_0 t) \qquad (1)$$

where f_0 is the carrier frequency of a compound signal equal to 1600.995 MHz for simplification of NCD;

sign (z) is the operation of amplitude restriction, equates the module of the complex number z to one unit, and leaves the argument invariable according to the formula $\mathrm{sign}(z) = z/|z| = [\mathrm{Re}(z) + \mathrm{j}\cdot\mathrm{Im}(z)]/\sqrt{\mathrm{Re}(z)^2 + \mathrm{Im}(z)^2}$;

$s_{L1SC}(t)$, $s_{L1OC}(t)$, $s_{HP}(t)$, $s_{AP}(t)$ are the complex signals determined by the formulas:

$$s_{L1SC}(t)=\mathrm{PRS}_{L1SC}(t),$$

$$s_{L1OC}(t)=\mathrm{j}\cdot \mathrm{PRS}_{L1OC}(t),$$

$$s_{HP}(t)=\mathrm{PRS}_{HP}(t)\cdot a\cdot \exp[\mathrm{j}2\pi f_1 t]= =\mathrm{PRS}_{HP}(t)\cdot a\cdot [\cos(2\pi f_1 t)+j\cdot \sin(2\pi f_1 t)],$$

$$s_{AP}(t)=\mathrm{PRS}_{AP}(t)\cdot a\cdot \exp[\mathrm{j}(2\pi f_1 t+\pi/2)]= =\mathrm{PRS}_{AP}(t)\cdot a\cdot [\cos(2\pi f_1 t+\pi/2)+j\cdot \sin(2\pi f_1 t+\pi/2)]= =\mathrm{PRS}_{AP}(t)\cdot a\cdot [-\sin(2\pi f_1 t)+j\cdot \cos(2\pi f_1 t)];$$

$\mathrm{PRS}_{L1SC}(t)$, $\mathrm{PRS}_{L1OC}(t)$, $\mathrm{PRS}_{HP}(t)$, $\mathrm{PRS}_{AP}(t)$ are the modulating sequences of navigation signals L1SC, L1OC, L1 VT, and L1 ST taking the valuesvalues {1; −1};

a is the amplitude coefficient equal to 0.903585 that in the compound signal the power of HP and AP signals was twice less than the power of L1SC and L1OC signals according to the calculation procedure given in the section "Calculation of characteristics of nonlinear consolidation";

$f_1=(1.005+k\cdot 0.5625)$ is the difference (in megahertz) between the carrier frequency of HP and AP signals and the carrier frequency of L1SC and L1OC signals.

The Formula (1) is the foundation of the NCD building. The equalized signal $\mathrm{sign}[s_{L1SC}(t)+s_{L1OC}(t)+s_{HP}(t)+s_{AP}(t)]$ is a signal for modulation. Its real part is fed onto an inphase (I) input of the quadrature modulator, and an imaginary part is fed onto a quadrature (Q) input (in the present article it is accepted that a quadrature component of the carrier advances in phase the inphase component by 90 °). The multiplier $\exp(\mathrm{j}2\pi f_0 t)$ describes transfer of the modulating signal to the carrier frequency f_0.

In the sum signal $[s_{L1SC}(t)+s_{L1OC}(t)+s_{HP}(t)+s_{AP}(t)]$,one can it is possible to allocate the real $x(t)$ and the imaginary $y(t)$ part:

$$x(t)=\mathrm{PRS}_{L1SC}(t)+\mathrm{PRS}_{HP}(t)\cdot a\cdot \cos(2\pi f_1 t) - -\mathrm{PRS}_{AP}(t)\cdot a\cdot \sin(2\pi f_1 t),$$

$$y(t)=\mathrm{PRS}_{L1OC}(t)+\mathrm{PRS}_{HP}(t)\cdot a\cdot \sin(2\pi f_1 t) - -\mathrm{PRS}_{AP}(t)\cdot a\cdot \cos(2\pi f_1 t). \qquad (2)$$

Hence, we receive the formula defining input signals of the quadrature modulator:

$$I(t) = x(t)/\sqrt{x^2(t)+y^2(t)},$$

$$Q(t) = y(t)/\sqrt{x^2(t)+y^2(t)}. \qquad (3)$$

The compound signal created on the formulas (1)–(3) has power losses of 17.17% according to the calculation procedure which will be given later.

The $I(t)$ and $Q(t)$ signals are calculated using the functions sin, cos, $f(x,y)=1/\left|\sqrt{x^2+y^2}\right|$. These three functions in the real wave shaper can be realized only in the tabular way. To ease NCD, it is offered instead of employing the tables for the above-stated functions sin, cos and $f(x,y)$, to calculate $I(t)$ and $Q(t)$ directly as a tabular function of phases of components. Further, the basic principles of realization of this tabular function are described.

Let us consider the Formula (1). The constellation (phase chart) of the signal $[s_{L1SC}(t)+s_{L1OC}(t)]$ is made of four phases, evenly distributed on a circle and numbered from 0 to 3 (Fig. 2, *a*). The constellation of the signal $[s_{HP}(t)+s_{AP}(t)]$ are created of an infinite set of phases of this signal by the choice of the final amount of the phase values *n* which are evenly distributed around the circle (Fig. 2, *b*). At the same time it is important that phases with the number 0 in these two constellations differed by *(π/n)rad*. It excludes a possibility of a zero value of the sign (*z*) function in the Formula (1) and also minimizes power losses for the set *n*.

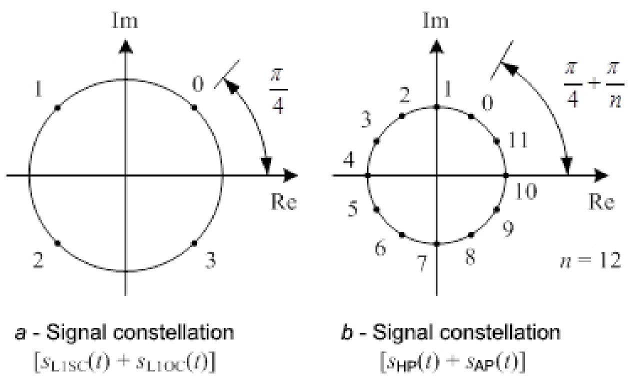

Fig. 2. Phase diagams of GLONASS signals being consolidated

It is obvious that each combination of numbers of phases of two constellations (Fig. 2) can be given the value of signals $I(t)$ and $Q(t)$ as compliance. These values can be calculated and kept in memory in advance. The parameter *n* and also clock frequency NCD f_s and bit depth *C* of the representation of each of the signals $I(t)$ and $Q(t)$ are determined based on the requirements to the precision characteristics if the signals being formed.

Thus, the scheme of NCD creation is offered to be realized in the form of the program which in discrete time points calculates the numbers of phases for two constellations (Fig. 2), and further, depending on these numbers, it takes from the memory the values *I (t)* and *Q(t)*, which move further to the inputs of the quadrature modulator. Below the main ratios based on which it is possible to construct this program are described. The value of the phase in the constellation of the signal $[s_{L1SC}(t)+s_{L1OC}(t)]$ (Fig. 2, a) are calculated by the formula

$$p_1=\pi/4+n_1\cdot\pi/4, \qquad (4)$$

where $n_1=\overline{0,3}$ is the number of the phase, which is determined depending on the values of $PRS_{L1SC}(t)$ and $PRS_{L1OC}(t)$ according to the Table 1.

Table 1. A rule for calculating the phase number n_1 in the constellation $[s_{L1SC}(t)+s_{L1OC}(t)]$

$PRS_{L1SC}(t)$	$PRS_{L1OC}(t)$	n_1	p_1, *rad*
1	1	0	π/4
-1	1	1	3π/4
-1	-1	2	-3π/4
1	-1	3	-π/4

The phase value in the constellation of the signal $[s_{HP}(t)+s_{AP}(t)]$ (Fig. 2, *b*) is calculated by the formula

$$p_2=\pi/4+\pi/n+n_2\cdot 2\pi/n \qquad (5)$$

where $n_2=\overline{0,n-1}$ is the phase number determined by the formula n_2=modn[phase2num$(p)+n_0\cdot n/4$];

p is the phase (in cycles) of the complex harmonica $\exp(j2\pi f_1 t)$

phase2num(*p*) is the operation операция, which carries out the choice of one of the numbers of the phases given in Fig. 2, the one that the value of the phase corresponding to it differed from *p* by minimum;

$n_1=\overline{0,3}$ is determined depended on the values of значений $PRS_{HP}(t)$ and $PRS_{AP}(t)$ в according to the Table 2;

$$\mathrm{modn}(x)=\begin{cases} x,\ 0\le x\le n-1,\\ x-n,\ x\ge n,\\ x+n,\ x<0.\end{cases}$$

Table 2. A rule for calculating n_0

$PRS_{HP}(t)$	$PRS_{AP}(t)$	n_0
1	1	0
-1	1	1
-1	-1	2
1	-1	3

The calculation of p is realized recursively by the formula

$p = \mathrm{mod1}(p+\Delta p)$

where $\Delta p=f_1/f_s$ is the increment p per one step of NCD;

$$\mathrm{mod1}(x)=\begin{cases} x,\ 0 \le x < 1, \\ x-1,\ x \ge 1, \\ x+1,\ x < 0. \end{cases}$$

Using the formulae (4) and (5), for each pair of the numbers n_1 and n_2, it is possible to calculate the values $I(t)$ and $Q(t)$ write them down into the files. However, if n is a multiple of four thus, using reduction formulae from trigonometry, one can store data only for n_1=0. If the values $I(t)$ and $Q(t)$ are written for n_1=0 in to the one-dimensional files A and B indexed from 0 to (n-1), these files can be employed to obtain the values $I(t)$ and $Q(t)$ for all n_1 and n_2 c using the following algorithm.

A case n_1=0, then

$I(t)=A(n_2),\ Q(t)=B(n_2)$.

A case n_1=1, then

$I(t)=-B(\mathrm{modn}(n_2-n/4)$,

$Q(t)=A(\mathrm{modn}(n_2-n/4)$.

A case n_1=2, then

$I(t)=-A(\mathrm{modn}(n_2-2 \cdot n/4)$,

$Q(t)=-B(\mathrm{modn}(n_2-2 \cdot n/4)$.

A case n_1=3, then

$I(t)=B(\mathrm{modn}(n_2-3 \cdot n/4)$,

$Q(t)=-A(\mathrm{modn}(n_2-3 \cdot n/4)$.

It is obvious that in the given algorithm the index of the element of the files A and B for each of the stated four cases can be calculated by the formula

$index=\mathrm{modn}(n_2-n_1 \cdot m)$

where $m=n/4$.

The scheme for NCD building given in Fig. 3, where the parameters f_s=102.3 MHz and $n=2^{12}$=4096 were given as an example, corresponds to the stated mathematical ratios.

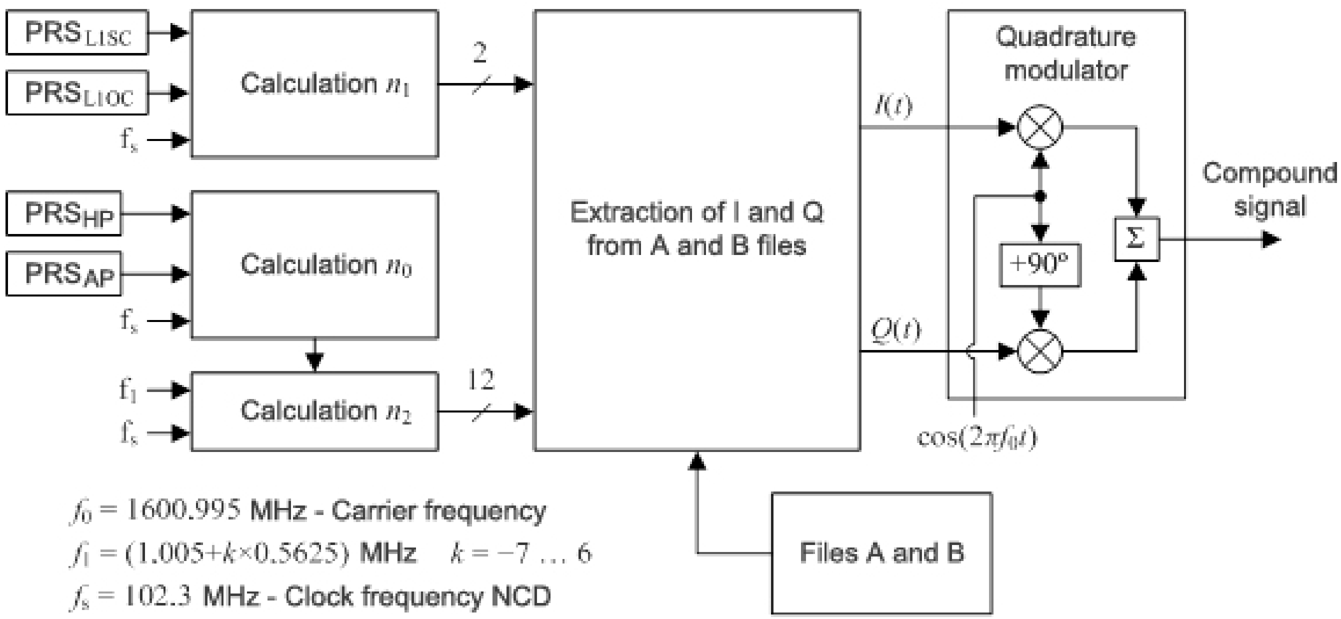

Fig. 3. The offered scheme for NCD building of L1 GLONASS signals

Calculation of nonlinear consolidation characteristics

The main characteristics of nonlinear consolidation are energy losses and distribution of the power of the components. There are no analytical expressions to calculate these characteristics in general case; hence, it is necessary to use numerical methods. One should calculate a spectral density of power flow (SDPF) in the radioastronomical range (RAR) (1610.6–1613.8) MHz for a compound GLONASS signal in the L1 range.

The present article calls energy losses as a share of power of a compound signal, which cannot be used in user navigation equipment (UNE). The most simple and vivid but not always precise accurate way to calculate energy losses is the following: a sum signal is formed (a linear sum of components) as well as compound (the same linear sum of components, but with the following amplitude limitation) in the complex form. These signals are being normed, thus their energies are equal. Later, two scalar products are calculated:

- a_{sign} is the scalar product of the reference signal of the reference and compound signals;
- a_Σ is the scalar product of the reference and compound signals.

These scalar products modulate the response of the correlator, respectively, onto the compound signal and sum signal. The squared ratio of these scalar products equals the ratio of signal powers when there is an amplitude limitation and the absence of such (squaring is needed because the response of the correlator is proportional to the amplitude but not to the power of the received signal). Energy losses are calculated by the formula

$$L = \overline{1-(a_{\text{sign}}/a_\Sigma)^2} \quad (6)$$

where the horizontal line is a statistical averaging.

A separate component and sum of several or all components can be chosen as a reference signal, i.e., energy losses can be calculated for both separate components and sum of components. The simulation has shown that in case when the amplitudes of the signals $s_{\text{L1SC}}(t)$, $s_{\text{L1OC}}(t)$, $s_{\text{HP}}(t)$, $s_{\text{AP}}(t)$ differ in the Formula (1), thus losses for separate components calculated by the formula (6) turn out to be different. That means that at the amplitude limitation, redistribution of the power of components takes place. Under such conditions, the components with a bigger amplitude strengthen and the components with a less amplitude weaken.

If the amplitudes of the signals $s_{\text{L1SC}}(t)$, $s_{\text{L1OC}}(t)$, $s_{\text{HP}}(t)$, $s_{\text{AP}}(t)$ are designated as a_1, a_2, a_3, a_4, and the corresponding losses calculated by the Formula (6) are designated as L_1, L_2, L_3, L_4, so the power of separate components of a compound signal are determined by the formulae:

$$P_1 = a_1^2 \cdot (1-L_1),\; P_2 = a_2^2 \cdot (1-L_2),$$

$$P_3 = a_3^2 \cdot (1-L_3),\; P_4 = a_4^2 \cdot (1-L_4) \quad (7)$$

And the power of a compound signal (the one based on the stipulation above equals to the power of a sum signal) is determined by the formula

$$P_\Sigma = a_1^2 + a_2^2 + a_3^2 + a_4^2. \quad (8)$$

Based on the formulae (7) and (8), it is possible to determine the shares of the power of the components in the compound signal (they are equal to P_1/P_Σ, P_2/P_Σ, and so on) and the ratio of the power of the components (P_1/P_2, P_1/P_3 and so on).

Since energy losses can be determined as a share of the power of a compound signal, which does not account for useful components, we receive one more formula to determine energy losses:

$$L_\Sigma = 1-(P_1+P_2+P_3+P_4)/P_\Sigma. \quad (9)$$

The difference between the formulae (6) and (9) is the following: the Formula (9) defines losses when all components are taken independently, i.e., for reception of each component one of the reference signals $s_{\text{L1SC}}(t)$, $s_{\text{L1OC}}(t)$, $s_{\text{HP}}(t)$, $s_{\text{AP}}(t)$ is used. The Formula (6) defines losses when a reference signal is equal to the linear sum of two or more components.

The simulation has shown that in general case the formulae (6) and (9) give a different result. For example, if GLONASS signals are consolidated by the formula (1), thus L=0.1835 and L_Σ=0.1717. Hence, when receiving the components separately, the sum accumulated energy is bigger than when joint reception of the components. It can be concluded that a sum signal is not considered to be an optimum reference signal, and the formula (6) gives an overestimated value of energy losses. Thus, the present paper determines energy losses by the formula (9).

Table 3 gives the findings of the calculation of energy L_Σ and amplitude coefficient a for different values of the P_3/P_1 ratio of the output power of one quadrature pair of equal power signals to another one. The calculation if carried out for the case of using the n = 4096 parameter.

Table 3. The calculation of nonlinear consolidation of two quadrature signal pairs

P_3/P_1	L_Σ, %	a	P_3/P_1	L_Σ, %	a	P_3/P_1	L_Σ, %	a	P_3/P_1	L_Σ, %	a
0.01	0.97	0.197073	0.26	13.36	0.769662	0.51	17.26	0.907173	0.76	18.64	0.970622
0.02	1.87	0.274757	0.27	13.61	0.777985	0.52	17.35	0.910657	0.77	18.66	0.972364
0.03	2.71	0.331894	0.28	13.84	0.785960	0.53	17.44	0.914040	0.78	18.69	0.974058
0.04	3.51	0.378142	0.29	14.07	0.793608	0.54	17.52	0.917326	0.79	18.71	0.975705
0.05	4.25	0.417317	0.30	14.28	0.800949	0.55	17.60	0.920518	0.80	18.74	0.977306
0.06	4.95	0.451412	0.31	14.49	0.808002	0.56	17.67	0.923621	0.81	18.76	0.978862
0.07	5.61	0.481629	0.32	14.69	0.814785	0.57	17.74	0.926636	0.82	18.78	0.980373
0.08	6.24	0.508763	0.33	14.88	0.821311	0.58	17.81	0.929568	0.83	18.80	0.981841
0.09	6.83	0.533374	0.34	15.06	0.827596	0.59	17.88	0.932419	0.84	18.82	0.983265
0.10	7.39	0.555873	0.35	15.24	0.833652	0.60	17.94	0.935191	0.85	18.83	0.984647
0.11	7.91	0.576574	0.36	15.41	0.839492	0.61	18.00	0.937887	0.86	18.85	0.985986
0.12	8.41	0.595724	0.37	15.57	0.845127	0.62	18.06	0.940510	0.87	18.86	0.987283
0.13	8.89	0.613519	0.38	15.73	0.850567	0.63	18.11	0.943062	0.88	18.87	0.988539
0.14	9.34	0.630121	0.39	15.87	0.855822	0.64	18.16	0.945545	0.89	18.89	0.989753
0.15	9.77	0.645662	0.40	16.02	0.860900	0.65	18.22	0.947961	0.90	18.90	0.990925
0.16	10.18	0.660254	0.41	16.16	0.865811	0.66	18.26	0.950312	0.91	18.90	0.992056
0.17	10.57	0.673992	0.42	16.29	0.870561	0.67	18.31	0.952600	0.92	18.91	0.993144
0.18	10.94	0.686957	0.43	16.41	0.875159	0.68	18.35	0.954827	0.93	18.92	0.994188
0.19	11.29	0.699218	0.44	16.54	0.879611	0.69	18.40	0.956994	0.94	18.93	0.995188
0.20	11.63	0.710837	0.45	16.65	0.883923	0.70	18.44	0.959104	0.95	18.93	0.996143
0.21	11.95	0.721868	0.46	16.77	0.888101	0.71	18.47	0.961156	0.96	18.94	0.997048
0.22	12.26	0.732356	0.47	16.87	0.892151	0.72	18.51	0.963154	0.97	18.94	0.997900
0.23	12.55	0.742345	0.48	16.98	0.896079	0.73	18.54	0.965099	0.98	18.94	0.998693
0.24	12.83	0.751870	0.49	17.08	0.899889	0.74	18.58	0.966990	0.99	18.94	0.999422
0.25	13.10	0.760966	0.50	17.17	0,903585	0.75	18.61	0.968831	1.00	18.94	1.000000

As for power spectrum of the composed signal, its form is strongly depended on the number of the k frequency. Fig. 4 depicts the case $k = 6$, for which the excess of the admitted radiation level in rad. is maximum and equals 26 dB (this is about by 3 dB more than for the case of linear summation of signals). However, for the other k the situation is different. For instance, for $k = -3$ and $k = 0$, an admitted radiation level in rad. is exceeded insignificantly, and for $k = -1$ and $k = -2$ is not exceeded.

Conclusion

The present article based on the example of frequency and code GLONASS navigation signals, the calculation algorithm of model values of the compound signal formed by nonlinear consolidation of two quadrature pairs of signals having any central frequencies of ranges and any clock frequencies of the modulating sequences is offered. This algorithm allows one to significantly simplify technical implementation of NCD.

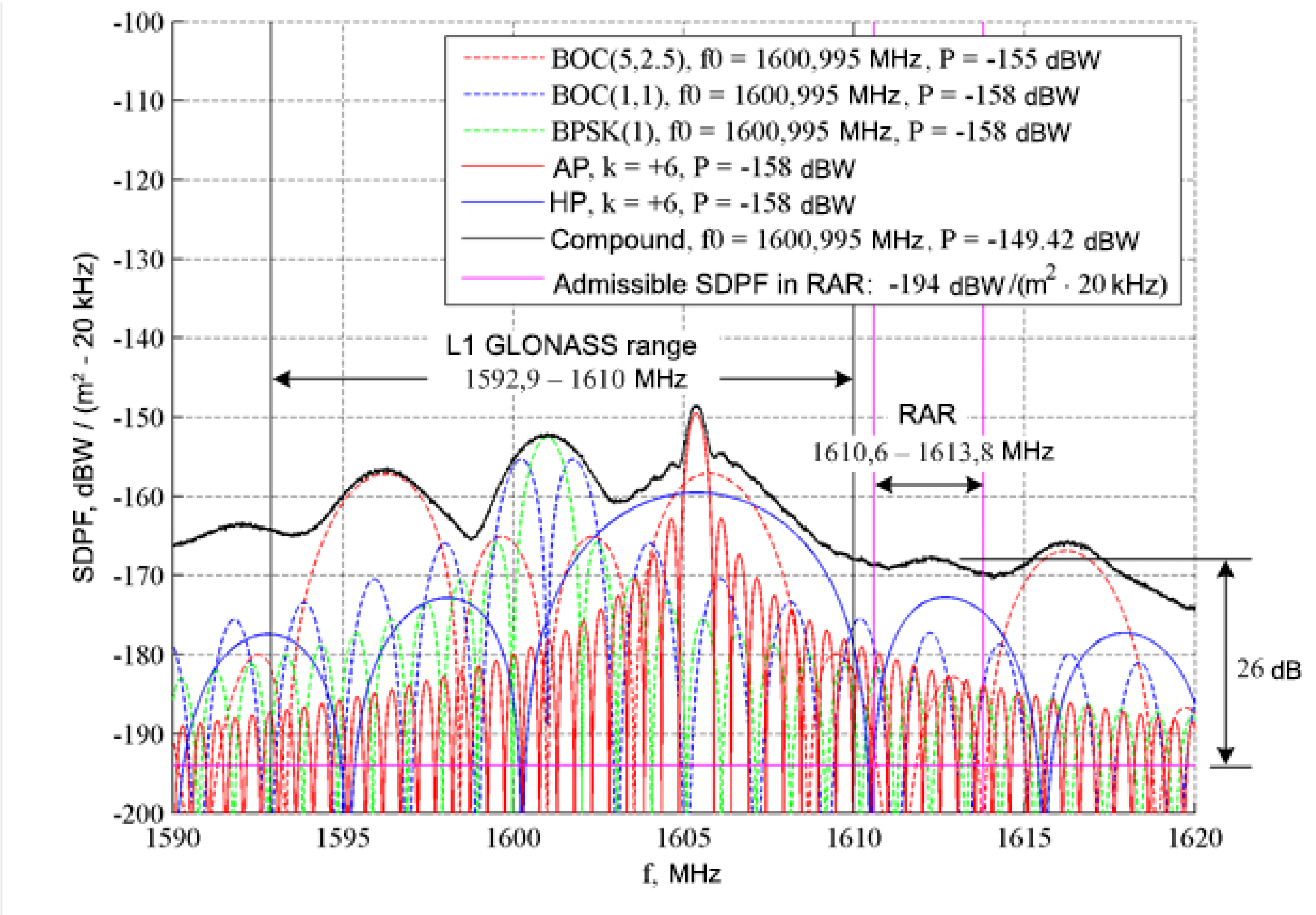

Fig. 4. SDPF of the compound L1 GLONASS signal for the number of the frequency of the AP and HP signals $k = 6$

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