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ANALYSIS EFFICIENCY OF PROCESSING COMPOUND MULTIPHASE AND LFM SIGNALS

АНАЛИЗ ЭФФЕКТИВНОСТИ ОБРАБОТКИ СОСТАВНЫХ МНОГОФАЗНЫХ И ЛЧМ СИГНАЛОВ

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ABSTRACT

Frequency Modulated Continuous Wave (FMCW) or broadband radars currently realized implementation on small unconventional vessels and at costal radar stations due to their power economy and high detection capabilities in the near-by environment. Optimization of sweep signal and correlation filter is carried out by means of applying windowing function. Compound linear frequency modulated (LFM) signals are suggested, which beingderived from compound multiphase signals, have proper ambiguity and cross-ambiguity functions.

Keywords: ambiguity function, cross-ambiguity function, linear frequency modulated, compound signal

Problem setting in general and its connection with important scientific and practical tasks

Most of the modern marine radars use pulsed mode of operation. However, this mode has significant drawback. In the pulsed radars resolution is limited by pulse width, and the peak power is reduced while maintaining resolution in the continuous radar. Since the continuous radars work with compound multiphase and LFM signals, all of this is the basis for further research of methods of thesynthesis of LFM and phase-coded signals, andthe studying of the effectiveness of their correlation properties.

Analysis of recent achievements and publications, in which a solution of the problem and the selection of the unsolved aspects of the problem are being under studying

In [1] and [2] a task to choose the optimal biphasic signal by using a matched and mismatched processing was set. We illustrate the research of the spectral properties of such signals in a periodic mode. There were good correlation properties of the signal obtained. However, these articles do not solve the problem of increasing the side lobe level by Doppler shift, and it is considered to be a drawback.As a resultthestudyingof the multi-phase signals is interesting for analysis. Such signals allowto obtain not only good correlation properties, but at the same time lowsidelobe level is in the plane of uncertainty. According towork [3] a class of signals has beenproposed and its good correlation properties have been confirmed on the plane. For the modern marine radars, discussed above, it is interesting and important to use LFM and phase-coded compound signals in both aperiodic and periodic mode, so we choose this subject of this article.

Purposes of the article (problem setting)

The aim of this work is the studying of the effectiveness of using LFM and multiphase compound signals in theperiodic mode. We have obtainedthe formula for the ambiguity function (AF) and the cross-ambiguity function (CAF) for such signals. Analysis of the effectiveness of reducing the side-lobe level of the CAF under the weighting processing has been taken.

Main material research description with detailed analysis of the scientific results obtained

LFM waveform is one of the well-known and most useful radar pulse compression waveforms due to its high range resolution (depended of the waveform bandwidth) and its tolerance to Doppler shift and easy for the receiver processing.

The LFM signal with unit energy is defined as

$$x(t)=\frac{1}{\sqrt{T}}e^{i\left(2\pi f_0 t+\frac{v_0}{2}t^2\right)}\;,\; -\frac{T}{2}\le \mathrm{t}\le\frac{T}{2}, \quad (1)$$

where f_0 – carrier frequency and sweep $v_0 = {2\pi\Delta F}/{T}$.

Pulse compression is performed by convolving the received signal with a filter matched to the transmitted LFM. Compressed pulse yields the length and it is $1/\Delta F$.

Compression ratio, defined as the ratio of the transmitted time length to the compressed pulse length, is ΔFT .

Since the AF of a the LFM

$$\chi(\tau,f)=\int_{-\infty}^{\infty}x^*(t)x(t-\tau)e^{i2\pi ft}dt \quad (2)$$

has its energy, it is concentrated along a ridge that passes through the origin of the delay – Doppler plane with slope $v_0 = {2\pi\Delta F}/{T}$.

According to this kind of the AF, uncertainty is appeared in range and velocity determination. For marine radars the compression ratios, for example, must be over 10^5, if we want to neglect this kind of uncertainty (with consideration of the maximum speeds of vessels). But such value of compression ratio is rather a difficult task for practical implementation in X-band radar (main band for marine radars). The necessity of using such big compression ratio can be avoided by means of compound LFM signals, which have the shape of an AF different from the AF of single LFM pulse, without uncertainty in range and velocity determination. The modulation waveform of these signals may be obtained on the basis of compound multiphase signals [1]. Compound multiphase signals in its turn are constructed on the base of multiphase signals, which are derived from LFM signals [5, 4].

Compound signals in [3] are constructed on the base of producing two sequences

$$u_n^B = \exp\left\{ i\frac{\pi}{4}\alpha'[2\left(n - N_B E\left[\frac{n}{N_B}\right] + 1\right) - (N_B + \mu_0)]^2 \right\} \quad (3)$$

$$u_n^V = \exp\left\{ i\frac{\pi}{4}\beta' \left[2\left(E\left[\frac{n}{N_{B_1}}\right] - N_V E\left[\frac{E\left[\frac{n}{N_{B_1}}\right]}{N_V}\right] + 1 \right) - (N_V + 1) \right]^2 \right\}, \quad (4)$$

where $n = 0 \div N-1$; $N = N_B \cdot N_V$; N_B – period of sequence u_n^B; N_V – period of sequence u_n^V; $E[x]$ – integer part x; $\alpha', \beta', \mu_0, N_{B_1}$ – parameters of phase modulation (μ_0=[0;1]).

The AF of a compound signal is the product of the AF of each of these signals [3]. Signals (3) and (4)have AF comb-shaped structure [4].When they are multiplied, the AF of a multiphase compound signal has the multi-peak structure. Expression for the calculation of a discrete periodic CAF has the form

$$\chi_{SW}(k,l) = \sum_{n=0}^{N-1} w_n^* s_{(n+k)} e^{i\frac{2\pi l n}{4N}}, \quad (5)$$

Where k is the discrete values of delay and l is discrete values of frequency with the steps correspondingly T_0 and $\Delta f = 1/4NT_0$; T_0 is elementary pulse duration; w_n is the filter coefficients for the compound signal; $s_n = u_n^B u_n^V$ code sequence of the compound signal (according to (3) and (4)).

The resulting AF is divided into three regions formed by multiplying:

1 The chest to the chest, i.e. the area of the central peak (CP).
2 The chest to the absence of the chest.
3 The absence to the absence of the chest.

Consider two types of multiphase compound signals each of which has:

1 N=342 (N_B=18, N_V=19) with the values of the coefficients $\alpha'=1/N_B$, $\beta'=2/N_B$, $\mu_0=0$, $N_{B1}=1$.

2 N=324 (N_B=18, N_V=18) with the values of the coefficients $\alpha'= -1/N_B$, $\beta'=1/N_B^2$, $\mu_0=0$, $N_{B1}= N_B$.

In Figure 1 the results of calculation of the body of the AF for: a) aperiodic signal and b) periodic signal, under a matched filter case are represented. The AF is considered in discrete time k and discrete frequency l. The upper part of the figure shows the 3D image of the AF. The area around the CP is also considered. Below on the right the sections along the time axis of the AF are shown. The left part shows the section along the frequency axis of the AF. Section l=0 shows the correlational function of the signal.

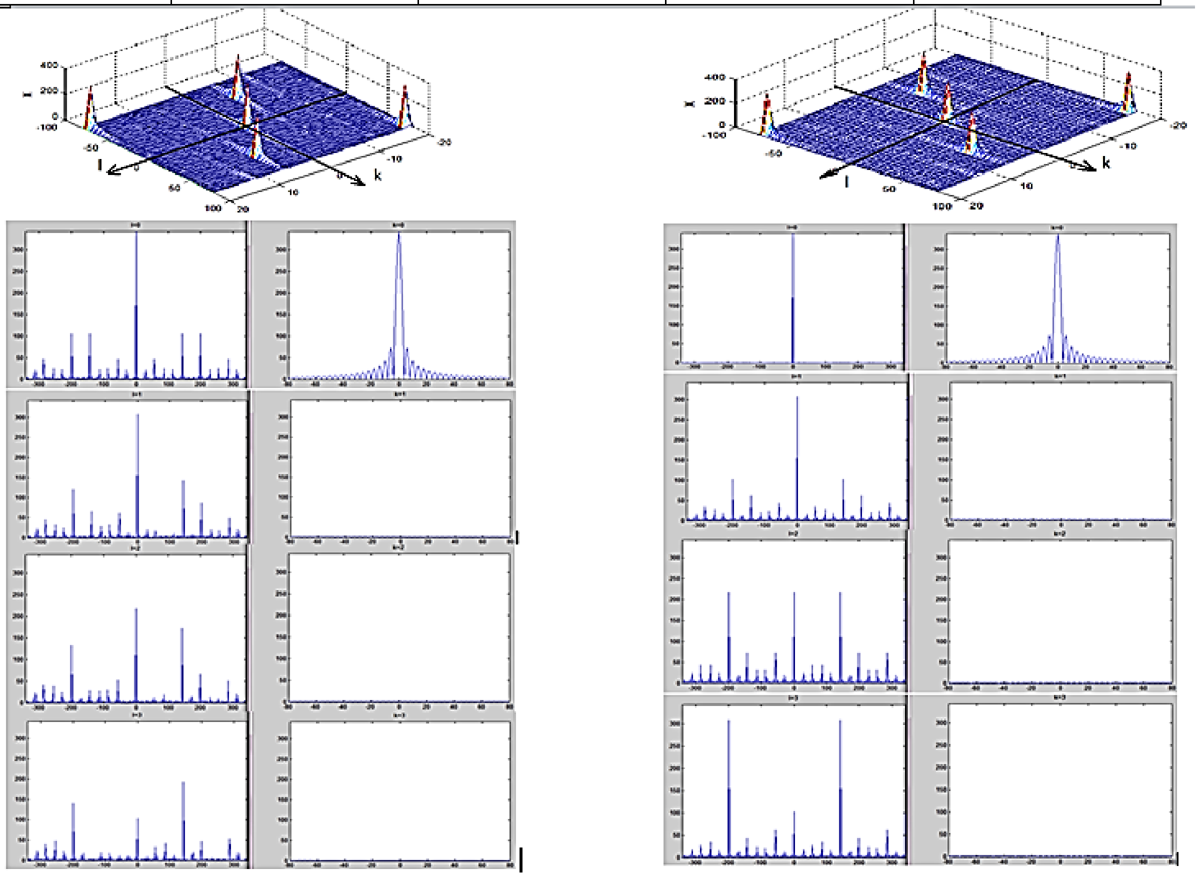
The first case is the signal with N=342 (N_B=18, N_V=19) and the values of the coefficients α'=1/N_B, β'=2/N_B, $\mu_0=0$, $N_{B1}=1$ in the periodic and aperiodic modes. The results are summarized in Tables 1 & 2.

Table 1. The ratio of the CP to the maximum level of side lobes for multiphase compound signal with parameters N=342 (N_B=18, N_V=19), $\alpha'=1/N_B$, $\beta'=2/N_B$, $\mu_0=0$, $N_{B1}=1$ (the second region)

Type processing	*l*=0	*l*=1	*l*=2	*l*=3
Aperiodic mode	61,29	37,21	44,76	40,10
Periodic mode	perfect	54,31	39,18	56,52

Table 2. The ratio of the CP to the level of the side lobes in the cross sections k = 2,3 in points l = -40 and l = +40 for a multiphase compound signal with parameters N=342 (N_B=18, N_V=19), $\alpha'=1/N_B$, $\beta'=2/N_B$, $\mu_0=0$, $N_{B1}=1$ (the third region)

Type processing	*k*=2		*k*=3	
	l=-40	*l*=+40	*l*=-40	*l*=+40
Aperiodic mode	282,64	380,00	374,18	345,45
Periodic mode	≥ 10 ^ 5	≥ 10 ^ 5	≥ 10 ^ 5	≥ 10 ^ 5



a) b)

Figure 1. The body of the AF multiphase compound signal N=342 (N_B=18, N_V=19) for aperiodic (a) and periodic (b) modes of operation with coefficients $\alpha'=1/N_B$, $\beta'=2/N_B$, $\mu_0=0$, $N_{B1}=1$,(the area around the CP)

Also the signals are examined with another set of pulses: N_B=14, N_V=23 and N_B=34, N_V=43,but with the same parameters α'=1/N_B, β'=2/N_B, $\mu_0=0$, $N_{B1}=1$. The AF has multi-peak character. Free zone is formed around the CP. In all cases with increasing number of pulses in the signal, the area of the free zone around the CP of the AF body is grown. It must be noted, that for all the cases, considered above, the perfectness of periodic correlation functions has been reserved. So we obtained the signals, which do not only have proper behavior of the AF on the range-Doppler plane, but the perfect periodic correlation function as well.

Let us consider the next type of a signal with parameters N=324 (N_B=18, N_V=18) and the values of the coefficients α'= -1/N_B, β'=1/N_B^2, $\mu_0=0$, N_{B1}= N_B. After calculation of the AF body for aperiodic signal and periodic signal under matched filter we don't have low enough side-lobe level. We may reduce it in free zone by using weighting sequence obtained from the formula (3) and formula (4). The weighting function of the processing of the entire signal can be written as:

$$\begin{aligned} w_n &= s_n \cdot v_n \\ v_n &= v^B_{n-E[n/N_B]N_B} v^V_{E\left[\frac{n}{N_V}\right]+1}, \ n = \overline{0 \div N-1}, \end{aligned} \tag{6}$$

where $v^B_{n-E[n/N_B]N_B}$ – weighting coefficients for the sequence obtained by the formula (3); $v^V_{E\left[\frac{n}{N_V}\right]+1}$ - weighting coefficients for the sequence obtained by the formula (4). The formula (7) describes one of the possible weighting functions for the signals (3) and (4):

$$\begin{aligned} v_n^B &= sin\left[\frac{\pi(n+1)}{N_B+1}\right], n = 0 \div N_B - 1 \\ v_n^V &= sin\left[\frac{\pi(n+1)}{N_V+1}\right], n = 0 \div N_v - 1 \end{aligned} \tag{7}$$

We analyze the behavior of the AF of the aperiodic compound multiphase signal N=324 (N_B=18, N_V=18). The results are summarized in Figure 2 and Tables 3-5. On the right side of the figure the law of changing of the phases of the compound signal is shown.

Table 3. The height of the CP for aperiodic multiphase signal with parameters α'=-1/N_B, β'=1/N_B^2, μ_0=0, N_{B1}=N_B and N=324 (N_B=18, N_V=18) (the first region)

Type processing	l=0
Matched processing	324
Weighting processing	145,64

Table 4. The ratio of the CP to the maximum level of side lobes for aperiodic multiphase signal with parameters α'=-1/N_B, β'=1/N_B^2, μ_0=0, N_{B1}=N_B and N=324 (N_B=18, N_V=18) (the second region)

Type processing	l= 0	l= 1	l= 2	l= 3
Matched processing	297,52	223,45	314,56	120,90
Weighting processing	1213,67	1693,49	291,28	280,08

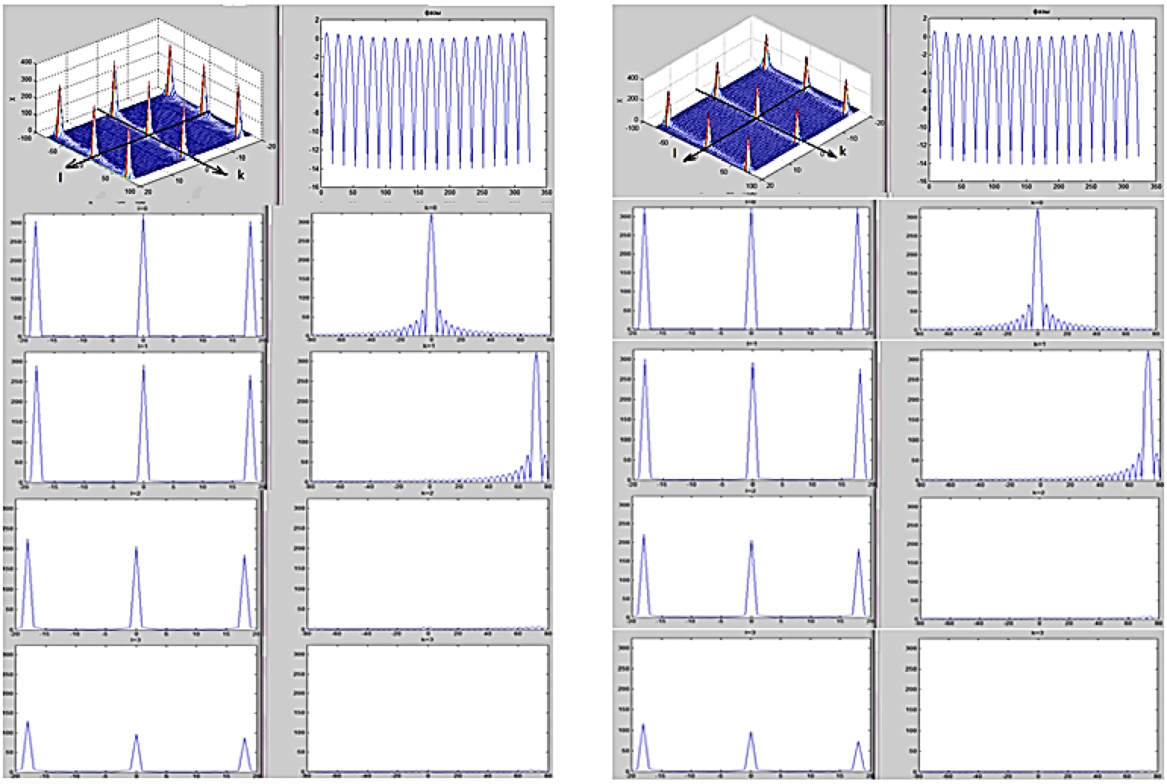


Figure 2. The body of the AF of the multiphase compound signal $N=324$ ($N_B=18$, $N_V=18$) for aperiodic (a) and periodic (b) modes of operation with coefficients $\alpha'= -1/N_B$, $\beta'=1/N_B^2$ $\mu_0=0$, $N_{B1}= N_B$ (the area around the CP)

Table 5. The ratio of the CP to the level of the side lobes in the cross sections $k=2,3$ in points $l=-40$ and $l=+40$ for a multiphase aperiodic signal with parameters $\alpha'=-1/N_B$, $\beta'=1/N_B^2$, $\mu_0=0$, $N_{B1}=N_B$ and $N=324$ ($N_B=18$, $N_V=18$) (the third region)

Type processing	k=2		k=3	
	l=-40	l=+40	l=-40	l=+40
Matched processing	188,37	164,47	206,37	137,87
Weighting processing	2086,53	1820,50	1471,11	1125,50

Based on these results we can see that the weighting function, which is described by (7), provides a side-lobe suppression around the CP. Under weighting the multi-peaks structure of the CAF signal has not changed.

Let us consider the behavior of the CAF of the multiphase periodic signal with the following parameters: $\alpha'=-1/N_B$, $\beta'=1/N_B^2$and $N_B=18$, $N_V=18$. Figure 3 shows the structure of the CAF of such signal under the weighting processing by a function *sin* (7).

From Figure 3 one can see that the CAF of the multiphase signal retains the multi-peak structure under the weighting processing (7). The side-lobe level is reduced. The results of research are summarized in Table 6 & 7.

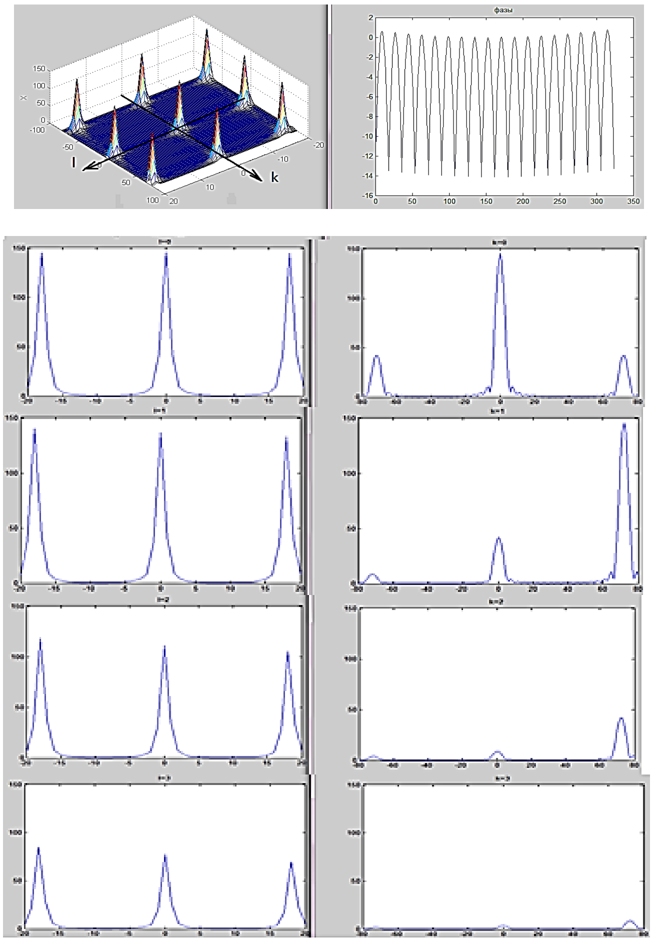


Figure 3. The body of the CAF multiphase compound signal for periodic mode with coefficients $\alpha'=-1/N_B$, $\beta'=1/N_B^2$, $\mu_0=0$, $N_{B1}=N_B$ and $N=324$ ($N_B=18$, $N_V=18$) after weighting, described by a function sin (7) (the area around the CP)

Table 6. The ratio of the CP to the maximum level of side lobes for periodic multiphase signal $\alpha'=-1/N_B$, $\beta'=1/^{NB2}$, $\mu_0=0$, $N_{B1}=N_B$ and $N=324$ ($N_B=18$, $N_V=18$) (the second region)

Type processing	*l*=0	*l*=1	*l*=2	*l*=3
Matched processing	2945,45	272,27	265,57	183,05
Weighting processing	7282,00	416,11	364,10	309,87

Table 7. The ratio of the CP to the level of the side lobes in the cross sections k=2,3 in points l=-40 and l=+40 for a periodic signal in a multiphase parameters $\alpha'=-1/N_B$, $\beta'=1/N_B^2$, $\mu_0=0$, $N_{B1}=N_B$ and $N=324$ ($N_B=18$, $N_V=18$) (the third region)

Type processing	*k*=2		*k*=3	
	l=-40	*l*=+40	*l*=-40	*l*=+40
Matched processing	1022,08	952,94	1080,00	790,24
Weighting processing	7282,00	7282,00	5394,07	4854,67

Coming from these results we may conclude, that by means of using the weighting function (7), the side-lobes are reduced. The multi-peak structure of the CAF has not changed under weighting.

The signal-to-noise ratio losses are determined by next

$$\rho = \frac{\left|\chi_{sw}(0,0)\right|^2}{\sum_{n=0}^{N-1}\left|s_n\right|^2 \sum_{n=0}^{N-1}\left|w_n\right|^2}, \quad (8)$$

where s_n - the complex envelopes of the signal; w_n - the complex envelopes of the filter; *s/n* - the ratio of signal power to noise power; $\chi_{sw}(0,0)$ - CAF value with the absence of frequency and time shift (l=0, k=0). The results of studies for periodic and aperiodic compound multiphase signal with parameters α'=-1/N_B, β'=1/N_B^2, $\mu_0=0$, $N_{B1}=N_B$ and N=324 (N_B=18, N_V=18) are presented in the Table 8:

Table 8. The signal-to-noise ratio losses for the signal with the phase modulation parameters $\alpha'=-1/N_B$, $\beta'=1/N_B^2$, $\mu_0=0$, $N_{B1}=N_B$ and $N=324$ ($N_B=18$, $N_V=18$)

Type processing	ρ
Matched processing	1
Weighting processing	0,725

It should be noted that we observe similar changes in the structure of the compound multiphase signal with parameters α'=-1/N_B, β'=1/N_B^2, $\mu_0=0$, $N_{B1}=N_B$ and N=324 (N_B=18, N_V=18) for aperiodic and periodic modes. Under weighting the side lobe level is decreased. The multi-peak structure of the CAF under weighting is not changed. The signal-to-noise ratio loss is equal $\rho =$ 0.725.

So, using the weighing processing we get the possibility for significant suppressing the side-lobe level in the area around the CP of the CAF.

We can use not only compound multiphase signals, but also equivalent compound LFM signals. As example in Figure 4 shows the signal with saw-tooth modulation [6], which is equivalent to the compound multiphase signal from Figure 3 (derivative of the law of phase modulation) gives us the law of frequency modulation. In Figure 5 functional diagram of transceiver and processing unit for this kind of signal is shown [7].

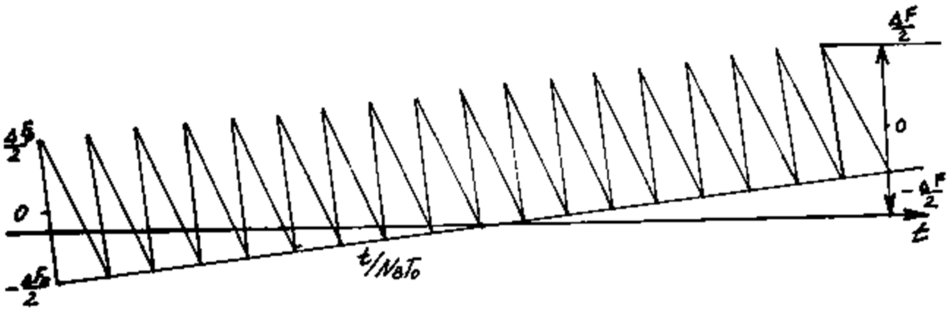


Figure 4.The signal with saw-tooth modulation

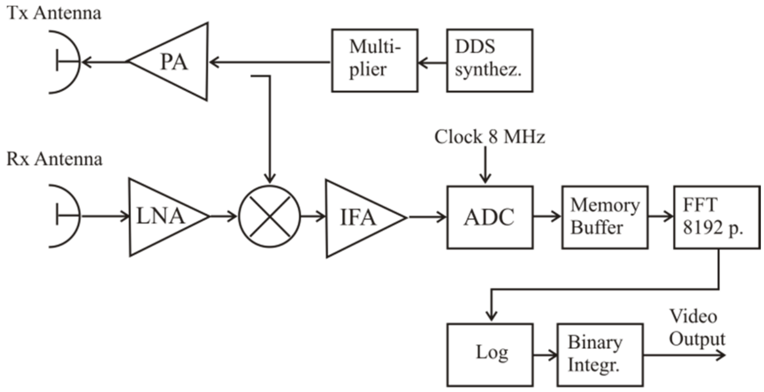


Figure 5. The functional diagram of transceiver and processing unit for LFM and phase-coded compound signals

DDS – Direct Digital Synthesizer produces a synthesized “chirp”(compound frequency modulated) signal;

Multiplier – up-converted of modulated signal;

PA – power amplifier, which feeds X-band Compound FMCW signal to antenna;

LNA – low noise amplifier;

IFA – intermediate frequency amplifier;

ADC – analog-digital convertor;

FFT – spectrum analyzer that perform Fast Fourier Transform.

Conclusions and prospect for further work in this area

Demands to the value of compression ratio of the LFM signals for Marine radar were analyzed. The way of decreasing demand to the value of compression ratio was suggested by means of using the compound LFM signals, which were derived from compound multiphase signals. The analysis of the AF and the CAF of compound multiphase signals and filters were provided. It was shown that the extent of zone with low level of side-lobes around the CP of the AF and the CAF increases with increasing number of pulses in the signal. It was also shown that by means of the proper choice of the parameters of the phase modulation in compound multiphase signals we may obtain not only good property for clutter rejection, but also perfect property of the periodic correlation function. The example of transformation of the modulation of the multiphase compound signal to modulation of corresponding compound LFM signal was represented. The received signals allow to obtain not only a low peak power butthe good range resolution and the range rate resolution of radar as well.

REFERENCES

1. Кошевий В. М. Оптимізація фільтрів придушення бічних пелюстків взаємної функції невизначеності періодичних сигналів при додаткових обмеженнях/ В.М. Кошевий, А.О. Шаповалова. Судоводіння: Зб. Наук. Праць / ОНМА.– Вип. 20. – Одеса: «ВидавІнформ», 2011. – с.264

2. Кошевой В.М. Методы синтеза дискретно-кодированных сигналов на основе использования их спектральных свойств / В.М. Кошевой, Д.О.

Долженко. Судоводіння: Зб. Наук. Праць / ОНМА. – Вип. 20. – Одеса: «ВидавІнформ», 2011. – с.264

3. Кошевой В.М. Синтез составных многофазных сигналов / В.М. Кошевой // Радиоэлектроника.-1988.-№ 8.- с.56-58.
4. Кошевой В.М. Синтез оптимальных одноканальных дискретных сигналов и фильтров / В.М. Кошевой, А. А. Кононов // Радиоэлектроника.-1984.-№ 8.- с.62-65.
5. B.L. Lewis, F.F. Kretschmer. Linear frequency modulation derived polyphase pulse compression codes, IEEE Trans. on Aerospace and Electronic Systems Vol. AES-18, N5, Sept. 1982, pp. 637-641.
6. N. Levanon, E. Mozeson. Radar signals. J. Wiley, NJ, 2004.
7. S. Plata, R. Wawruch, CRM-203 Type Frequency Modulated Continuous Wave (FM CW) Radar, TransNav, the International Journal of Marine Navigation and Safety of Sea Transportation, Vol. 3, N3, Sept. 2009, pp. 311-314.