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Synthesis of Wideband Signals with Irregular Bi-level Structure of Power Spectrum

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ABSTRACT

Radar sensors are wide spread as ranging and navigation systems, especially in ATC and prevention of wings' collisions. Traffic handing on routes and commuter areas is held with their use. Therefore, improving the noise immunity of radar sensors remains as priority, especially in aviation sector. In this connection, we consider a synthesis method of complex signals with irregular bi-level structure envelope of power spectrum. We conducted analysis of synthetic signal's spectral characteristics. We described the possibility of the use of such signals for frequency clutter rejection localized in a relatively small range of Doppler frequency shifts. The frequency rejection of ground reflection is proposed to improve the noise immunity of radar sensors.

KEYWORDS
Radar sensors, wideband signals, bi-level irregular structure, power spectrum, noise immunity improvement.

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Introduction

Improving noise immunity of radar sensors with high-output ground reflection at hand requires probing signals providing minimization of valid and interfering signals' power spectrum overlap (Liu et all., 2015; Sheen, 2015; Pralon, Pompeo & Fortes, 2015). Targeting problems widely use probing signals in the form of coherent radio pulse clusters with a high repetition rate (Chen et all., 2012; Yao, Lorenzelli & Chen, 2013). Such signals are characterized by line structure, wide and "pure" frequency domain of ambiguity function. These properties provide an effective frequency selection of high-speed targets against ground reflection. The most significant drawback of this type of signals is high range ambiguity ambiguity (Levanon & Mozeson, 2004; Skolnik, 2008; Nathanson, 1969).

On the other hand, the wideband signals of long duration eliminate range ambiguity. At the same time, the detection of weak signals is possible only by the frequency rejection of high-output passive clutters with a Doppler frequency shift

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(Richards, 2005; Schleher, 1991; Skolnik, 2001). In the case of wideband signals with a large time-frequency product, the use of frequency rejection is problematic due to the almost complete valid and interfering signals' power spectrum overlap.

As an alternative, the authors of this article provide the use of a special type of wideband signals with a multilevel phase-shift-keying having a bi-level irregular structure envelope of power spectrum. Such spectrum allows conducting the frequency rejection of ground reflections distributed by means of delay and localized by means of frequency (Levanon & Mozeson, 2004; Bystrov, 2005; Kutuzov, 1996). As a result, the processed signal reveals a significant part of interfering signals' energy promoting valid signals detection.

The objectives of this article are to describe the method of synthesis of multiphase signals with the bi-level power spectrum and to evaluate the effectiveness of frequency rejection of point radar clutter.

Method

The theoretical and methodological basis of the study is a set of methods relevant to desired goal: induction and deduction, abstraction and generalization, analysis and synthesis, analogy, as well as modeling. The paper describes the experience of leading domestic and foreign researchers, who studied the issues.

The basis of the study is the analysis method; functions of considered objects were comprehensively studied under this method. We also used mathematical modeling method, which has allowed considering the main characteristics of the research subject.

Data, Analysis, and Results

Synthesis of multiphase signals with bi-level irregular structure of power spectrum

Let us consider the method of synthesis of signals with bi-level irregular structure of power spectrum. It uses the features of ternary sequence (TS) $b_n \in \{0, \pm 1\}$, $n = 0 \ldots N-1$, with certain side-lobe relief of autocorrelation function (ACF). After completing the discrete Fourier transform of the original TS we obtain its spectrum:

$$B_k = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} b_n \exp\left(-j\frac{2\pi ki}{N}\right), k = 0 \ldots N-1 \tag{1}$$

If TS has an ACF with zero sidelobe level, the spectral module of such sequences is uniform. In the case TS has an ACF with non-zero sidelobe level, the amplitude fluctuation of module's spectral components appears in spectrum module.

Using time-frequency transformation duality, a multi-phase modulating sequence $y_n = B_n$, $n = 0 \ldots N-1$ might be constructed. In terms of mentioned properties of duality, the sequence y will have the envelope of spectrum module of a type

$$|Y_k| = \left| \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} y_n \exp\left(-j\frac{2\pi}{N} nk\right) \right|, \quad k = 0 \ldots N-1 \tag{2}$$

identical in form to the module of initial ternary sequence $|Y_k| \approx |b_k| \in \{0, 1\}$.

In general, the envelope of multiphase signal will not be constant in time. This is highly undesirable. Therefore, constructing multiphase signals with a constant envelope is produced with the use of complex value y_n:

$$w_n = exp[j \times \varphi_n], \varphi_n = arg(y_n), n = 0..N-1 \quad (3)$$

Phase value of such signal is a continuous value, but the discrete phase values with $\Delta\varphi=2\pi/K_\varphi$ step, where K_φ – the number of level phase, is more interesting from a practical point of view.

The envelope of synthesized multiphase sequence $\{w_n\}$ power spectrum will be closer in form to the envelope of initial ternary sequence module. The envelope of synthesized signals' power spectrum will contain spectral components concentrated near two certain levels: high and low – that differ in value. The spectrum becomes a comb shape. The number of high-level spectral components constituting the "comb" tooth, as well as their repetition interval differ and have a pseudo-random nature in terms of pseudorandom TS module law.

As an example, Figure 1 shows a multiphase signal of length N=63 synthesized from TS (Ipatov, 1979, 1992) $\{b_k\}$ = {0 0 0 -1 0 0 0 1 0 1 0 0 1 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 1 -1 -1 0 -1 0 0 0 -1 1 0 0 0 1 0 0 -1 0 1 1 0 0 0 0 0 0 1 0 0}, as well as its power spectrum. The number of phase gradations is equal to K_φ =64.

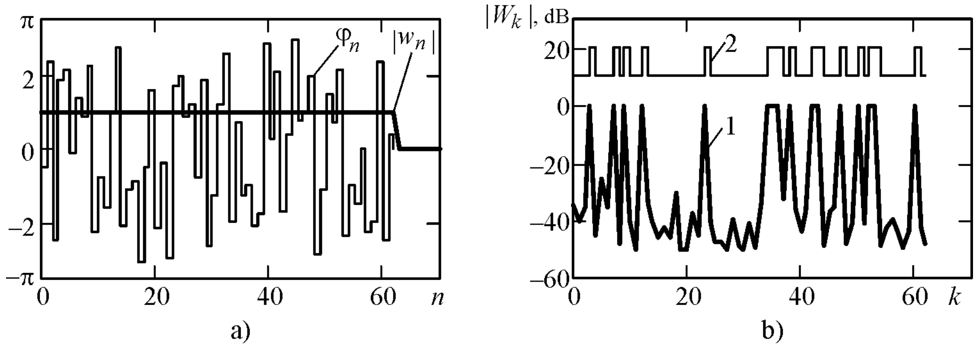

Figure 1. Multiphase signal of length N=63

The power spectrum of synthesized signal (Figure1b, Diagram 1) has a bi-level structure of the envelope, changes of which align with the law of sequence changing $|b_k|$, represented in Diagram 2.

Indicators of synthesized signals' quality

We characterize the quality of synthesized signals by means of QM ratio of high- and low-level spectral components of amplitude spectrum $|W_k|$. We work in an expression reflecting the dynamic range of spectral components:

$$\eta = \sqrt{\frac{\sum_{k=0}^{N-1}(1-|b_k|)\sum_{k=0}^{N-1}\left(|b_k||W_k|^2\right)}{\sum_{k=0}^{N-1}|b_k|\sum_{k=0}^{N-1}\left((1-|b_k|)|W_k|^2\right)}} = \sqrt{\left(\frac{1}{Q_b}-1\right)\frac{\sum_{k=0}^{N-1}\left(|b_k||W_k|^2\right)}{\sum_{k=0}^{N-1}\left((1-|b_k|)|W_k|^2\right)}}, \quad (4)$$

where $Q_b \approx \frac{\sum_{k=0}^{N-1} |b_k|}{N}$ - TS is the duty cycle $\{b_n\}$.

In the example given above, the TS $\{b_n\}$ has Q_b=25%. The dynamic range of signal spectrum levels synthesized on its basis was 37.1 dB with the phase gradation of 64 levels.

There is an obvious η dependence on TS $\{b_n\}$ duty cycle Q_b, as well as on the number of phase gradations K_φ of multiphase signal $\{w_n\}$.

Increasing the number of phase levels, the dynamic range of synthesized signal's spectrum levels increases as well. This follows from dependency graph represented in Figure 2 for the signal of length N=1023. However, it is not possible to increase the number of phase gradations in real conditions due to the influence of transmit-receive chain phase errors. Thus, the number of phase gradations is necessary to be chosen maximum, but not inconsistent with the parameters of the real system.

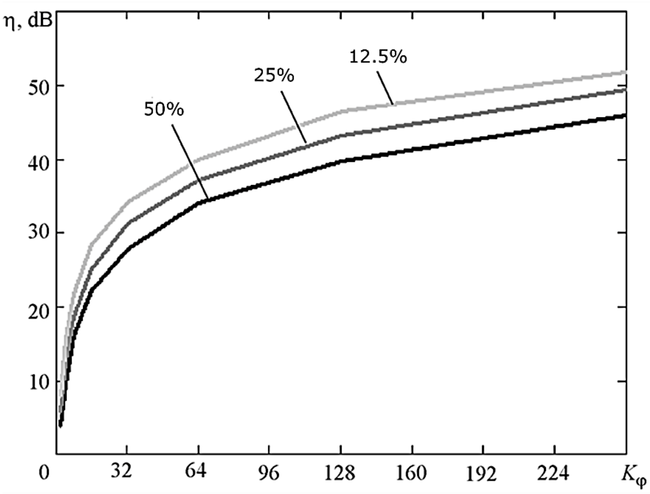

Figure 2. Signal of length N=1023

Decreasing duty cycle Q_b of the ternary sequence $\{b_n\}$, the dynamic range of synthesized signal spectrum levels increases. It can be clearly seen from the comparison data (Table 1) for various lengths of synthesized signal under phase gradation at K_φ=32 levels. Changing Q_b from 50% to 12.5%, η value increased by 6 dB in average. Upon that, η parameter for defined TS duty cycle values $\{b_n\}$ practically does not depend on the length of synthesized signal.

Table 1. Dynamic range of synthesized signal spectrum levels

Q_b	N	η, dB
50%	511	27,41
	2047	27,83
	8191	27,89
	32767	27,79
25%	1023	31,26
	16383	31,23
12.5%	511	34,13

Ambiguity function of synthesized signals

An important characteristic of synthesized signal is the ambiguity function (AF). As an example, Figure 3 shows the AF relief of synthesized signal with length N=511. It can be seen that AF has a pronounced narrow peak. This indicates the signals' high resolution in terms of delay and Doppler frequency, as well as indicates an unambiguous measurement of these parameters over a wide range. AF feature of these signals is the "ridge" along the delay axis at zero Doppler frequency shift. The size of the ridge exceeds the background of AF lift and depends on the spectrum's average duty cycle. The mean square of ridge side lobes for synthesized signal of length N = 511 is equal to 18.64 dB; the lift level of 27.12 dB corresponds to the traditional value $R_{RMS} = 1/\sqrt{N}$ of RMS of AF side lobes of complex digital signals (Bystrov, 2005; Chebotarev, 2007; Kutuzov, 1996).

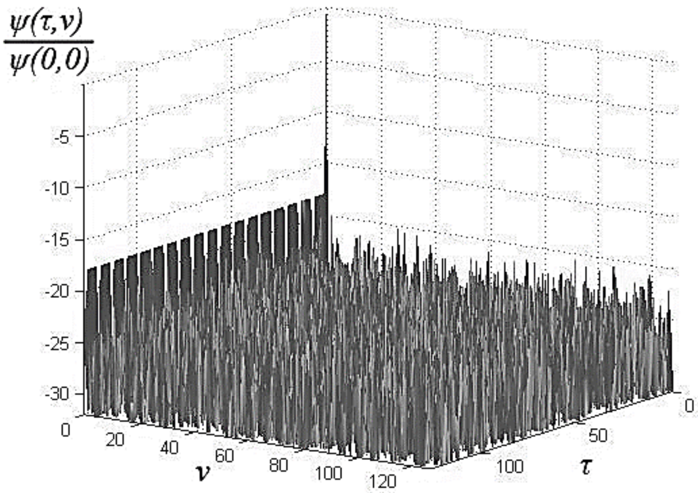

Figure 3. AF of synthesized sequence with length N=511

The level of AF lift side lobes establishes a potential limit of weak signals detection under the influence of high-energy clutter. As it was previously mentioned, the irregular bi-level structure of power spectrum allows conducting frequency rejection of interfering signals to recover weaker signals.

Discussion

The Doppler frequency shift causes a shift of signal spectrum along the frequency axis. As a result, only a part of high-level components of initial spectrum will interfere with the high-level components of the spectrum shifted spectrum. After high-level components frequency rejection, the interference level minimization will be achieved, and this level is determined by the average duty cycle of power spectrum and depth of the low-level components in the synthesized signal spectrum.

Efficiency of frequency clutter rejection can be estimated by the decrease of interference level at the output of the processing unit. The second factor of frequency rejection efficiency is the valid signal energy loss.

Let us consider a matched signal processing in the frequency domain based on the calculation of spectrum of the sum of returns and reference signals with the following calculation of inverse DFT (Skolnik, 2005):

$$\psi_{\tau,\nu} = \sum_{k=0}^{N-1} S_k W_{k-\nu}^{*} \exp\left(j\, 2\pi k\tau/N \right), \tag{5}$$

Where: $\tau = \tau_{\min} \dots \tau_{\max}$ и $\nu = \nu_{\min} \dots \nu_{\max}$ – numbers of range and frequency channels.

We will show the efficiency of frequency rejection on the example of synthesized signal of length $N = 511$ with spectrum average duty cycle $Q_b = 12.5\%$. Let us consider the processing results of additive sum of three signals $s(t) = s_1(t,\, a_1,\, \tau_1,\, \nu_1) + s_2(t,\, a_2, \tau_2,\, \nu_2) + s_3(t,\, a_3,\, \tau_3,\, \nu_3)$ with the following parameters:

– amplitude $a_1 = 1,\;\; a_2 = 0.5\;(-6\text{ dB}),\;\; a_3 = 0.1\;(-20\text{ dB})$;

– discrete delays determined by the number of signal time samples $\tau_1 = \tau_2 = \tau_3 = 100$;

– normalized Doppler frequency shifts determined by the number of spectrum samples $\nu_1 = 40,\; \nu_2 = 20,\; \nu_3 = 60$.

Signals $s_1 - s_3$ differ in terms of intensity and Doppler frequency shifts, but they have the same delay. After coherent processing, s_1 and s_2 signals' responses are observed at levels 0 and – 6 dB, respectively (Figure 4.). QM noise level in other channels of processing is 25.86 dB, so the signal s_3 is masked by noises caused by AF side lobes of stronger signals.

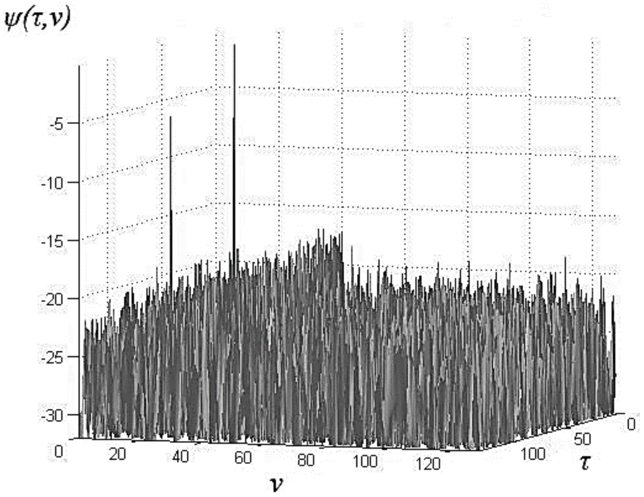

Figure 4. Results of quasi-matched processing of additive sum of signals s_1 and s_2 at levels 0 and – 6 dB.

Let us consider the quasi-matched processing with the use of frequency rejection. It sets to zero high-level spectral components of reference spectrum $W_{k-\nu}$, which has same frequency shift as the high-level clutter components.

After completing the inverse DFT of spectral input and reference signal response, we obtain the response function of quasi-matched signal processing:

$$\psi r_{\tau,\nu} = \sum_{k=0}^{N-1} S_k \left(W_{k-\nu}^{*} br_k \right) \exp\left(j\, 2\pi k\tau / N \right), \;\; \nu \neq \omega_n, \tag{6}$$

Where: $br_k = 1 - |b_{k-\nu}| \in \{1,\ 0\}$ – the sequence of frequency samples, describing the ideal signal's power spectrum;

ω_n – normalized Doppler frequency shifts of valid signals.

Figure 5 shows the results of quasi-matched processing of additive sum of signals after the frequency rejection of only the most intense signal.

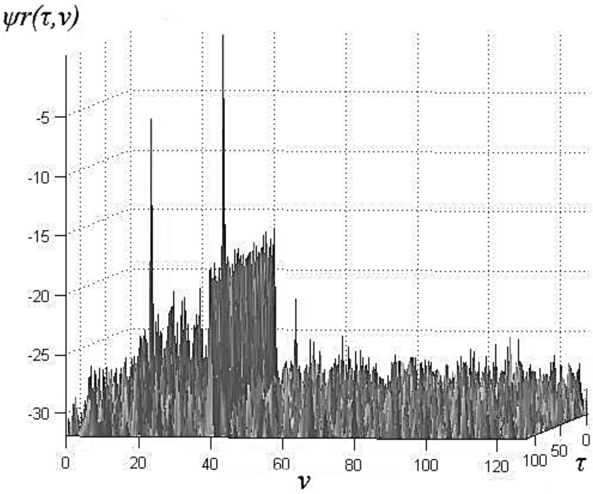

Figure 5. Results of quasi-matched processing of additive sum of signals after frequency rejection of s_1 clutter

Signal response s_1 is not changed due to the fact that rejection was not conducted in this frequency channel. Magnitude of the signal response was -7.15 dB. Therefore, the energy loss after frequency signal rejection is -1.15 dB. The level of interference in other channels fell to -31.9 dB. This allowed identifying the weakest signal s_3. Its level amounted to -21.14 dB, taking into account energy losses.

The residual level of interference caused by the overlap of reference signal's spectrum with low-level components of signal spectrum s_1 and AF side lobes of the s_2 signal. Frequency rejection of s_2 signal should be performed in a similar method to reduce noise level (Figure 6).

Noise level has decreased to -44.3 dB, all three signal responses are observed at levels -1.14, -7.16 and -22.3 dB. Energy losses in the processing of the most intense signal s_1 were -1.14 dB, for the least intense signal they are -2.3 dB.

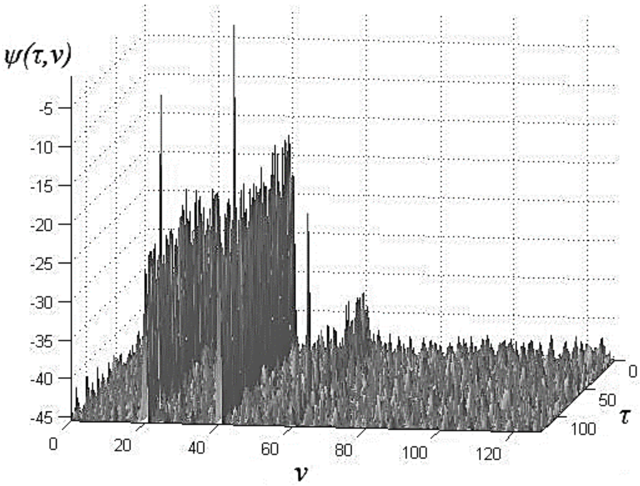

Figure 6. Results of quasi-matched processing of additive sum of signals after frequency rejection of s_1 and s_1 and s_a clutter

Conclusion

One of the ways to improve the noise immunity of radar sensors is the frequency rejection of ground reflection. This way is possible in the presence of probing signals providing minimization of valid and interfering signals' power spectrum overlap.

This article presented wideband signals with irregular bi-level structure of power spectrum, considered their synthesis, the basic parameters and characteristics, presented the ambiguity function. Signals with such power spectrum structure allow using the clutter frequency rejection distributed in terms of delay, but localized at a relatively small range of Doppler frequency shifts.

Disclosure statement

No potential conflict of interest was reported by the authors.

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