Target detection modeling against the clutter background of the radar with quasi-continuous mode of transmission and reception of signals with pseudorandom law of amplitude-phase shift keying

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Abstract. This paper presents the mathematical model of moving target detection against the clutter background of the radar with quasi-continuous mode of transmission and reception of signals with pseudorandom law of amplitude-phase shift keying (APSK). The modeling results of the optimal pair of “signal - processing method” research, which provides the maximum range of target detection under noise conditions, are presented.

1. Introduction
Synthesis and processing modeling of an additive mixture of a useful signal, passive interference and noise makes it possible to estimate target detection probability for a given set of parameters of a radar station (radar) in a complex interference environment. The simulation at the design stage of a radar with a quasi-continuous mode of transmission and reception of signals with a pseudo-random amplitude-phase shift keying (APSK) signal on common aerial is especially important.

The emitted pulses of a probing APSK signal differ from each other in duration and a law of phase shift keying. The intervals between the transmission of pulses are not consistent with the radar range, nor with the analyzed range of Doppler frequencies. Reception of return signals is performed during transmission pauses.

Due to the absence of periodicity, APSK signals have a thumbtack shape of the ambiguity function (AF) [1]. This allows us to detect the target and unambiguously measure its range and speed. In addition, when detected, there are no “blind” range and velocity areas.

Reflections from the underlying surface and high-power reflectors overlap in time and amplitude spectrum with a useful APSK signal and create an additional noise level at the output of a multichannel processing device.

These high-power returns are delayed and have Doppler frequency shift, and their additional noise level prevents the detection of weak signals. The level of this background is determined almost uniformly in the “delay-frequency” plane by the level of side lobes of the AF APSK signal.

The level of side lobes in the AF sections and the noise immunity of the radar are determined by the time-bandwidth product of the APSK signal [2].

However, the APSK signal time-bandwidth product, even a few hundred thousand, does not provide the required noise immunity when the range of power variation of the reflected signals in the radar range reaches 100 dB or more. Efficient signal processing techniques are required. The synthesis and processing of APSK signals simulation can help to choose the optimal pair of “signal - processing method”.

This article summarizes theoretical information on synthesis and processing of APSK signals simulation in the quasi-continuous mode of their transmission and reception. It presents synthesis and processing of APSK signals simulation results when searching for the optimal “signal-processing method” pair while solving problems of detecting a low-flying target against reflections from a disturbed sea surface.
2. Synthesis and signals processing mathematical model

A generalized functional diagram of signal synthesis and coherent processing model on the time interval $T$ of the additive mixture of the useful signal, passive interference and noise is presented in figure 1.

**Figure 1.** A generalized functional diagram of formation and coherent signals processing model.

The initial data of the model are:

1) parameters of the radar carrier: height $h$, speed $V$;
2) parameters of the transmit-receive path and antenna pattern (antenna directivity diagram ADD): carrier wave length $\lambda$, peak power $P_t$, antenna gain $G$, ADD width in azimuth section $\theta_{ADD}$ and elevation section $\theta_{\varepsilon}$, the main beam ADD direction in azimuth $\alpha_{ADD}$ and the elevation $\varepsilon_{ADD}$;
3) parameters of the APSK signal: duration $T$, signal spectrum width $\Delta F$, coefficient of multiplicity of discrete amplitude durations and phase shift keying $k_x$, average duty cycle $C$.
4) Range resolution $d$.
5) Characteristics of the underlying surface: land, forest, sea, urban area
6) Detected target parameters: (radar cross section) RCS $\sigma_0$, range $D_s$, radial velocity $V_s$

All computational operations during simulation are performed on the samples of the complex envelope with a sampling interval of $t_b = 2d/c$, $c$ is the speed of light.

The probing APSK signal of duration $T = N t_b = N x k_x t_b$ consists of $N$ elementary pulses of duration $t_b$ or $N_x$ phase of manipulated pulses of duration $k_x t_b$. Its complex envelope is given by the discrete sequence $w_n = x_i \exp[j \varphi_n]$, $n=0..N-1$, where $x_i \in \{1,0\}$, $i=0..N_x-1$, - amplitude code; $\varphi_n$ - phase code; $\lfloor \cdot \rfloor$ is the operator of integer division, $\varphi_n \in [0, \pi]$ when phase-shift keying has two levels and $\varphi_n \in [-\pi, \pi]$ when probing signal phase has multilevel value. The probability of transmission of phase-shifted pulses is defined as

$$C = \frac{1}{N_x} \sum_{i=0}^{N_x-1} x_i .$$

A fragment of the modulating sequence $w_n$ of the probing APSK signal with $C = 1/5$ and $k_x = 16$ is shown in figure 2.
The synthesis of an APSK signal is possible using other sequences, such as pseudo-random sequences [3], Gold sequences [4], GMW sequences [5]. To reduce the effect of interference in the detection of weak signals, it is possible to use signals with a low level of side lobes of the AF in the time-frequency region of interest. The algorithm of the synthesis of signals with similar properties is described in [6].

When simulating the detection of a moving target against the clutter background from the underlying surface, the return signal with the complex envelope samples \( \xi_n, n=0..N-1 \), is the sum of the useful signal sample \( s_n \), passive interference \( \xi_r \), and the receiver’s own noise \( \eta_n \) in the signal frequency band: \( \xi_n=s_n+\xi_r+\eta_n, \)

Signals are processed by multichannel by delay \( m \) and Doppler frequency shift \( v \) correlation receiver in the range \( m=m_{\min..m_{\max}}, v=v_{\min..v_{\max}} \). The response at the output of each \((m,v)\) processing channel is described, [2], by a module of the function

\[
R_{m,v} = \sum_{n=0}^{N-1} z_{n,m}w_{n,m}^* \exp\left(\frac{j2\pi vn}{N}\right)
\]

where \( z_{n,m} \) are samples of the signal processed in the \( m \)-th range channel after preprocessing of samples \( \xi_n \) according to one of the following algorithms:

1) \( z_{n,m} = b_n \), where \( b_n = \xi_n^* \left(1 - x_{n/k_s} \right) \) is the blanking signal of the reception path of the radar station for the duration of the next phase shift keyed pulse;

2) \( z_{n,m} = \begin{cases} b_n, & |b_n| \leq U_O \\ U_O \cdot \exp\left(j \cdot \xi_n \right), & |b_n| > U_O \end{cases} \), blanking signal of the reception path of the radar for the time of transmission of the next phase-shift keyed pulse and amplitude clipping of powerful reflections at the \( U_O \) level;

3) \( z_{n,m} = b_n \prod_{i=1}^{r_m} \left(1 - x_{n/k_s} \right) \) refers to the time rejection of signals after blanking in the receiving path in the range of delays \([1; r_m]\);

* - complex conjugation operator.

Note that in the first two cases the same signal is received in all range processing channels. When performing a time rejection, it is not the receiver input that is blanked, but only the inputs of the individual correlation processing channels. Blanking of the input of the distance channel is carried out at the time of arrival of the pulses from a predetermined range of distances from 0 to \( d r_m \), and \( r_m < (m-k_s) \). In this case, each range channel can have its own range of rejected distances, which makes a difference in the input signals \( z_{n,m} \) of different range channels. As the processing range increases, the size of the time rejection zone increases. As a result, the interference power remaining after time rejection decreases when moving from the near to more distant group. The reliability of target detection increases.

The combination of clipping and time rejection is possible.

As a criterion function determining the efficiency of the processing method, it is advisable to use the signal-to-clutter-plus-noise ratio at the output of the processing channel, the number \((m,v)\) of which coincides with the parameters of the \( m \) delay and the Doppler frequency shift \( v \) of the detected target. The noise level will be determined by the root-mean-square value of the responses in the channels adjacent to the \((m,v)\)-th channel, described as

\[
R_{\text{RMS}} = \left[ \frac{1}{(m_{\max}-m_{\min})(v_{\max}-v_{\min})} \sum_{m=m_{\min}}^{m_{\max}} \sum_{v=v_{\min}}^{v_{\max}} |R_{m,v}|^2 \right]^{1/2}
\]
The signal-to-clutter-plus-noise ratio in the \((m_{v}, n_{v})\)-th processing channel can be estimated as \(g(m_{v}, n_{v})=\|R(m_{v}, n_{v})\|/\|R\|_{\text{RMS}}\). According to the Neumann-Pearson criterion for detection with a probability of 0.9 and the false alarm probability of \(10^{-4}\) useful signal with a random initial phase and amplitude, \(g(m_{v}, n_{v})\geq24.1\text{ dB} is necessary.

### 3. Model of useful signal formation

When searching for the optimal “signal - processing method” pair in a given interference background, it can be assumed that coherent processing interval the target remains within the bounds of the range and speed resolution element. In this case, the parameters of the useful signal, such as amplitude, delay and Doppler frequency shift, remain constant. When modeling the delay and Doppler shift of the signal frequency, target values are assumed as discrete values.

For the given point target parameters \(\sigma_{n}, D_{n}, V_{n}\) and the parameters of the radar receiving and transmitting path, \(\lambda, P_{n}, G_{s}\), the parameters of the useful signal are defined by the formulas:

\[
A_{s}=[\alpha_{s}G_{s}^{2}\cos((4\pi/\lambda)D_{n})]^{1/2} - \text{amplitude, } m_{s}=[D_{s}/d] - \text{time shift, } \nu_{s}=2V_{n}/\lambda - \text{Doppler shift.}
\]

The samples values of the complex envelope of the useful signal according to the formula

\[
s_{s}=A_{s}w_{s-n}\exp[-j\left(2\pi v_{s}n/N + \phi_{s}\right)] , n=0..N-1
\]

where \(\phi_{s}\) is a random initial phase with a uniform distribution law.

Target maneuvering leads to a change in its speed and range from the radar. If necessary, these changes should be taken into account when calculating the parameters \(A_{s}, m_{s}\) and \(\nu_{s}\).

In general, the model of the useful signal synthesis must take into account the propagation medium for electromagnetic waves.

When modeling the propagation of a target signal near the section of air-to-surface, it is necessary to calculate the amplitude of the reflected signal taking into account the effect of multipath propagation of electromagnetic waves. The electromagnetic wave reflected from the target is represented by the sum of the coherent and incoherent components [7]. In the model, the multipath effect can be taken into account if the RCS \(\sigma_{n}\) of the target is represented by the sum of the coherent \(\sigma_{\text{coh}}\) and the averaged incoherent \(\sigma_{\text{incoh}}\) components: \(\sigma_{n}=\sigma_{\text{coh}}+\sigma_{\text{incoh}}\). For the sea surface, the coherent component of the RCS does not contain random variables and is determined by the formula

\[
\sigma_{\text{coh}}=\sigma_{n}\cos(\Psi)/\left[1+\Gamma_{\text{coh}}^{2}+2\Gamma_{\text{coh}}\cos(\Psi)\right]^{2}
\]

where \(\sigma_{n}\) is the RCS of the target during the propagation of a signal in free space; \(\Psi=4\pi h_{s}\sin(\alpha)/\lambda, h_{s}\) is the height of the target above the surface, \(\alpha=\arctan(h/[D_{s}^{2}-(h-h_{s})^{2}]^{1/2})\) is the minimum glide angle of reflections from the surface; \(\Psi\) is the argument of the complex Fresnel reflection coefficient; \(\Gamma_{\text{coh}}=\Gamma_{\text{coh}}\exp(-8\pi^{2}\alpha_{h})\) is the coherent complex reflection coefficient, \(\alpha_{h}=h_{w}\sin(\alpha)/\lambda\) is the generalized Rayleigh parameter, \(h_{w}\) is the height of the sea wave; \(\Gamma_{\text{coh}}=\Gamma_{\text{coh}}\left(sin(\alpha)(1+\cos^{2}(\alpha))^{1/2}/[\sin(\alpha)+\cos^{2}(\alpha)]^{1/2}\right)\) is the complex Fresnel reflection coefficient for sea-based radars with horizontal polarization of the emitted signal [8], \(\varepsilon=80-j60\alpha_{w}\) is the complex relative dielectric constant of water, \(\alpha_{w}=1+6\text{ cm/m is the conductivity of seawater}\ [9].

The non-coherent RCS component determines the statistical characteristics of reflections from the target near the section of two media and contains all the fluctuation terms of the complex reflection coefficient. For the system “reflector + interface” its average value is described by the formula

\[
\sigma_{\text{incoh}}=8\mu_{2}\sigma_{n}(\mu^{2}+2\Gamma^{2})^{1/2},
\]

where \(\mu=0.283[1-\exp(-276\alpha_{h}^{2})], 0<\alpha_{h}<<0.2\) characterizes the standard deviation of two independent Gaussian random processes determining the incoherent component of the complex reflection coefficient.

### 4. Model of reflections formation from the underlying surface

The signal reflected from the underlying surface is determined by a linear combination of components reflected from infinitely small surface areas and characterized by a delay, Doppler frequency shift, amplitude, and initial phase. For an approximate estimate of the probability of detecting a target against the background of reflections from the underlying surface, it is permissible to consider the surface as uniform. Then, from the limiting central theorem, it is permissible to consider not an infinitely large number of infinitely small reflectors, but a finite number of surface regions that can be resolved by delay and Doppler shift.

The model of the additive mixture of reflections from the underlying surface is described, [10], by the formula
\[ \xi_n = g \sum_{m= -m_{\text{max}}}^{m_{\text{max}}} \sum_{n= -n_{\text{max}}}^{n_{\text{max}}} \sqrt{\rho_{m,n}} \exp \left[ -j \left( 2\pi (n-m) \nu / N + \phi_{m,n} \right) \right], \]  

(7)

where \( g \) are the fluctuations of the amplitude of reflections, calculated on the basis of the energy spectrum interference \( G_s(F_i) \) with the effective step width \( \Delta F_s \), \( K \) is the discrete phase spectrum of passive interference (in the simulation, you can set a random function with a uniform distribution law in the range \([0.2 \pi] ; \sigma_m settlements \) GAPS \( \rho_{m,n} \) is a random variable with a uniform distribution law in the range \([0.2 \pi] ; m_{h} and m_{rh} are the time shifts corresponding to the height of the carrier and the range to radio horizon. The maximum number \( \nu_{\text{max}} \) of frequency-resolved surface areas located at the same distance depends on the carrier speed for a given coherent accumulation time. The model of the energy spectrum of interference is defined in \([11]\).
Figure 4. The real part of the complex signal envelope: 1 − ωn; 2 − bni; 3 − 10 sn.

If no interference is suppressed, then for a given width (1/b) of the spectrum of the APSK signal, its duration T is insufficient for detecting the useful signal, figure 5, a. After time rejection (figure 5, b) or amplitude clipping (figure 5, c), the useful signal is detected. The signal-to-clutter-plus-noise ratio \( q(m, \nu_v) \) is 15.4 dB and 19.4 dB, respectively. Increasing \( k_x \) to 64 increases \( q(m, \nu_v) \) to 31.7 dB with time rejection from \( r_m = 64d \) and up to 25±28 dB at different levels of amplitude limiting. Combining the use of time rejection and amplitude clipping does not increase \( q(m, \nu_v) \) for data simulation parameters.

Figure 5. The results of the correlation processing.

a) without interference suppression;

b) with time rejection of interference \( r_m = 16d \);

c) with amplitude clipping.

This example demonstrates the feasibility of modeling when searching for the parameters of the APSK signal and its processing method, which ensure the detection of a moving target on a passive interference fan.

6. Conclusion

The considered model reproduces the specifics of radar with quasi-continuous transmission and reception of APSK signals on common aerial. In particular, the reception of return signals in the intervals between the transmissions of the phase-shift keyed pulses, the duration and interval of which are determined by the pseudo-random law of amplitude manipulation of the probing signal. The model of the formation of an additive mixture of reflections and noise takes into account the reflective properties of the surface, as well as the parameters of the radar carrier: its location in space, the parameters of the antenna pattern, the parameters of the transmitting and receiving path. As a result, it is possible to determine the degree of overlap in time and frequency of the useful signal and clutter.

The signal processing model implements methods that reduce the influence of interference created by reflections from the underlying surface when solving the problem of detecting a weak useful signal. The calculation of the signal level at the output of the multi-channel processing device allows you to determine the signal-to-clutter-plus-noise ratio and compare its values for different signal parameters and methods for
suppressing noise. As a result, modeling helps to find the optimal “signal-processing method” pair for given radar operating conditions.

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