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DETECTION OF ULTRAWIDEBAND RADAR SIGNALS SCATTERED FROM COMPLEX TARGETS

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The questions of detection of radar-tracking signals are discussed, which parameters are unknown. The method for detection of radar signals which parameters are unknown is considered. The method is based on correlation processing of signals received in the adjacent periods of sounding – the interleaved periodic correlation processing (IPCP).

1. Introduction

Signals radiated by narrow band radar (the instantaneous bandwidth $\Delta f \leq 10\ \%$ of the band medium frequency) are harmonic or quasi-harmonic oscillations. This makes an opportunity to perform filter and correlation signal processing.

The signal shape differs from harmonic oscillation more and more as the signal spectrum is extended. In ultra wide band (UWB) radar (the instantaneous bandwidth $\Delta f \approx 100\ \%$ of the band medium frequency, radiated pulse width is about 1 ns) space signal duration is significantly less than antenna size and target length. During the process of target location a signal changes its shape many times including the cases of signal scattering from target bright points. As a result a returned signal is transformed into the sequence of pulses with random parameters. Target configuration and aspect angle determine pulses arrangement. Pulses amplitude depends on RCS of corresponding target bright point. Pulses polarity depends on magnetic permeability of the target material that scatters the signal. The initial shape of the returned pulses is influenced by resonance characteristics of target bright points.

So a narrow band signal changes its parameters but holds its shape during the location process, whereas a UWB signal changes its parameters and initial shape as well. Such signal is often named as "target image" because it carries knowledge of not only target presence and target coordinates but also target structure. Proper image processing makes possible to recognize a target and to form radioimage of target. At initial stage of location before target recognition it is necessary to detect a target. It is not advisable to use for UWB signal detection the traditional methods such as optimum signal processing by matched filtering or correlation with the reference signal as the structure of UWB returned signal is fully unknown.

2. Interleaved Periodic Correlation Processing

Methods for quasi-optimum processing of fully unknown signals are well known. Some such detectors are described in [1,2 and other]. But all these detectors suffer from significant losses compared to optimum detector.

The repetition period T_r is the only known parameter in our case. This parameter may be used for development of the optimum detector for UWB signals, all other parameters we consider as unknown. It uses as the reference signal a signal received in the adjacent repetition period and delayed at time interval T_r. So the received signal is not compared to the reference signal as in a traditional correlator but to the identical echo signal. So the signal shape becomes the parameter that determines the efficiency of such correlation detector. This signal processing is named as interleaved periodic correlation processing (IPCP). The schematic diagram IPCP is shown in Fig. 1.

At this Figure: U(T) – voltage at correlator output; $u_{echo}(t)$ – echo signal; $u_n(t)$ – noise; U_{thresh} – threshold.

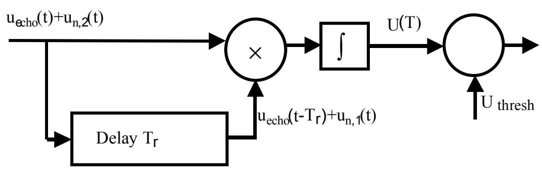

Fig. 1. *Schematic diagram of interleaved periodic correlation processing*

IPCP has three dissimilarities from the conventional correlator. They are as follows:

a. the received signal is compared not with a radiated signal but with a signal scattered by a target;
b. noises are fed to both correlator inputs (these noises are not correlated, as they are received in different repetition periods);
c. integration period T is determined not by the radiated signal duration, but by the observation interval, that is, by the scattered signal duration. If a physical target length is L the integration time is equal to $T = (2L/c) - \tau$, where c is velocity of light and τ is a duration of a radiated signal.

Let us, first, determine the general laws of the IPCP by the example of a signal scattered by a stationary target. In this case the signals at two correlator inputs are noncorrelated noises having the same normal distribution with zero mean values and a variance $\sigma^2 = N_0 \Delta f$, where Δf is UWB signal bandwidth and N_0 is noise spectrum density. The Neumann-Pearson criterion is used to estimate the IPCP method efficiency.

The detection characteristics calculated for the IPCP detector we compare with those for the traditional optimum detector for fully known signal with fixed width received against white noise background [2,3].

For the IPCP method the voltage at correlator output is:

$$U(T) = \frac{2}{N_0}\int_0^T u_{rec}(t)\, u_{rec}(t - T_r)\, dt.$$

If the echo signal is absent, then:

$$U(T) = \frac{2}{N_0}\int_0^T u_n(t)\, u_n(t - T_r)\, dt = \int_0^T u_{n,1}(t)\, u_{n,2}(t)\, dt.$$

Unlike the traditional correlator output the IPCP correlator output is the multiplication of two normally distributed and noncorrelated noises received in two adjacent repetition periods. The distribution function for this voltage W_0 determines the threshold value required for given false alarm rate. In the IPCP correlator the threshold does not depend on the reference signal and has a constant value.

If the echo signal is present in the received signal, then:

$$U(T) = \frac{2}{N_0}\left[\int_0^T u_{echo}(t)\, u_{echo}(t)\, dt + \int_0^T u_{echo}(t)\, u_{n,1}(t)\, dt\right] + \frac{2}{N_0}\left[\int_0^T u_{echo}(t)\, u_{n,2}(t)\, dt + \int_0^T u_{n,1}(t)\, u_{n,2}(t)\, dt\right].$$

As in the previous case the first integral determines nonzero mean value of the distribution function at the correlator output W_1. The second and the third integrals determine this function variance when the echo signal is present. The fourth integral determines the distribution function type.

To calculate the detection characteristics we find distribution functions W_0 and W_1 for the IPCP correlator. For this purpose we consider the transformation of normal noise distribution by the correlator components: a multiplier and an integrator.

The distribution function $W_m(y)$ for the multiplication of two normally distributed random values $y = u_1 u_2$ describes the process at the multiplier output when the echo signal is absent. If u_1 and u_2 are noncorrelated random values and variances $\sigma_1^2 = \sigma_2^2$ the distribution is defined in [4] as:

$$W_m(y) = \frac{1}{\pi\sigma^2} K_0\left(\frac{|y|}{\sigma^2}\right),$$

where $K_0(x)$ is the zero order Bessel's function of the 2nd kind for imaginary argument.

The distribution function $W_m(y)$ is illustrated in Fig. 2. The normal distribution function $W_n(u)$ area normalized with $W_m(y)$ is shown too. The comparison of these two functions indicates that multiplication of two normally distributed noises is less

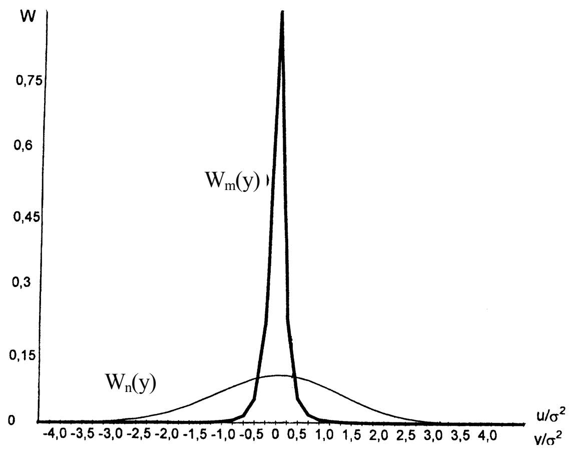

Fig. 2. *Distribution function for the product of two normally distributed random values*

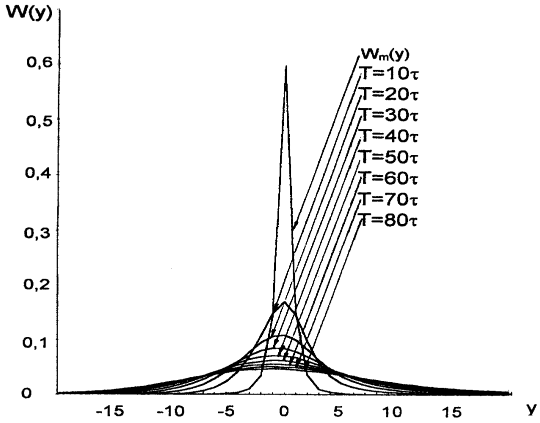

Fig. 3. *Dependence of distribution function Wm(y) on integration period*

dispersed relative to the mean value compared to the initial normally distributed noise at the correlator input. The reason is that bursts of the first noise signal are compensated by the low level of the other noise signal. The coincidence of two burst is of low probability. None the less this event may occur ant it results in more extended "tails" of distribution function $W_m(y)$ than those of distribution function $W_n(u)$. This fact is important for the IPCP correlator as the threshold level determined by the function $W_m(y)$ may be higher than the threshold level determined by the function $W_n(u)$ for the same values of false alarm rate.

The multiplication of noises from the multiplier output is fed to the integrator. The type of distribution function at integrator output depends on the integration interval T. According to the central limit theorem this distribution approach the normal distribution under integration and its variance grows proportionally to the interval T.

If the UWB signal is processes by the IPCP correlator the integration interval is determined not by the duration of a radiated signal as in the traditional narrowband correlator, but by the real target length and equal $T = (2L/c) - \tau$. If UWB signal duration $\tau = 1$ ns the real targets can occupy from 10 to 100 range cells, the integration interval can vary from $10\,\tau$ to $100\,\tau$ correspondingly. This time interval may be too short for full normalization of the noise multiplication distribution function $W_m(y)$. So this function will have an intermediate shape between the noise multiplication distribution and the normal distribution, approaching the normal distribution as the integration interval is increasing. Fig. 3 shows this distribution in relation to the integration interval T. T varies from $10\,\tau$ to $80\,\tau$ in the interval of $10\,\tau$.

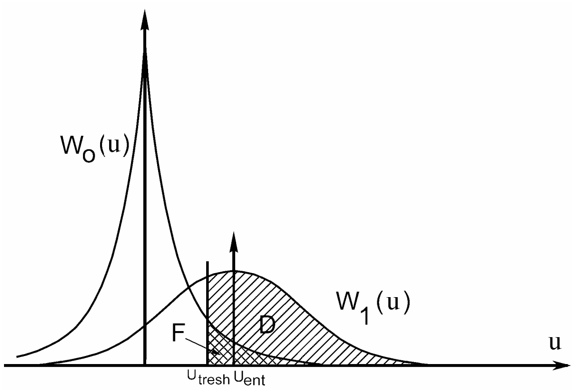

Fig. 4. *Distortion functions $W_0(u)$ and $W(u)$ for IPCP*

The development of analytical expression for distribution function at the integrator output presents a real difficulty if the distribution of input signals differs from the normal distribution. So mathematical simulation was used to calculate and plot the distribution functions W_0 and W_1 at the IPCP correlator output. The approximate view and mutual positions of functions W_1 and W_0 at IPCP are shown in Fig. 4.

As it is rather difficult to have analytical expressions for distribution functions W_1 and W_0 at the IPCP outlet, we use mathematical modeling to plot detection characteristics.

3. Detection Characteristics

Fig. 5(a) and 5(b) show the detection characteristics of IPCP for a signal scattered by a stationary target for two values of false alarm rate 10^{-2} and 10^{-4} (D – probability of detection, q – ratio signal-noise). These Figures also show the detection characteristics of a conventional correlator for fully known signal and detection characteristics of the energy detector for the same false alarm rates. In order to make the comparison valid, the duration of a received signal is

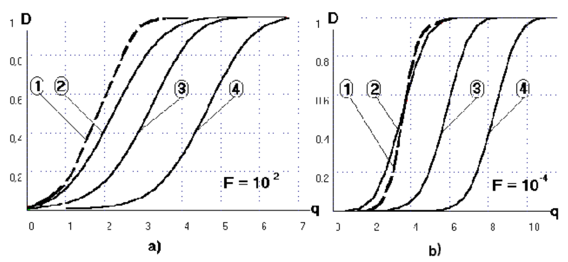

Fig. 5. *Detection curves for a signal scattered by a stationary target at IPCP.*
1 – IPCP for stationary target + Criterion processing;
2 – Traditional correlator for fully known signal;
3 – IPCP for stationary target;
4 – Energy detector

taken equal to the duration a radiated signal (one point target).

The analysis of results shows the following.

The IPCP detection characteristics approach the conventional correlator detection characteristics for high false alarm rates (10^{-2}). The difference between positions of these characteristic increases with reducing the false alarm rates (10^{-4}). This can be explained by the long duration of the "tails" of the distribution function $W_m(y)$. In IPCP the given level of false alarm rate can be maintained by setting the threshold level higher than in the conventional correlator. At the same time the detection characteristics of IPCP are much better, than those of the energy detector.

Fig. 6 shows the dependence of detection characteristics on the integration time T (determined by a target length). The false alarm rate 10^{-4} and the integration time T equal to 2τ, 10τ, and 20τ were taken for modeling. This Figure also shows the detection characteristic for a conventional correlator. It is shown from the picture that with increasing the target length the IPCP detection characteristic for a stationary target approaches more and more the conventional correlator characteristic when it detects the fully known signal. The reason for this is that distribution function $W_m(y)$ approaches the normal distribution, while integrating noise samples.

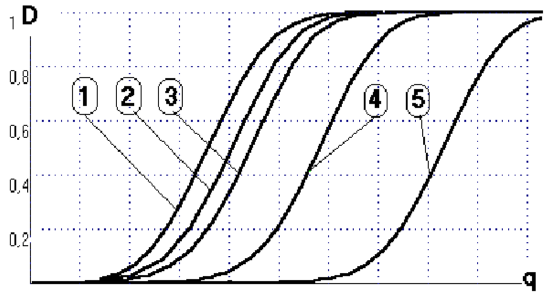

Fig. 6. *Dependence of detection parameters of IPCP on integration period.*

1 – Traditional correlator for fully known signal for $T = 2\tau$;
2 – IPCP for a stationary target for $T = 20\tau$;
3 – IPCP for a stationary target for $T = 10\tau$;
4 – IPCP for a stationary target for $T = 2\tau$;
5 – Energy detector for $T = 2\tau$

4. Criterion Processing of UWB Signals after IPCP

The IPCP detection characteristics can be improved by additional criterion processing. The criterion processing scheme memorizes the resolution cells in which the output signals from the threshold scheme are present. This operation is performed in several pulse repetition periods T_r, after that the cells in which the signals emerge repeatedly are determined. Only the signals from resolution cells which correspond the criterion selected ("two of two", "two of three", "three of four", and etc.) are passed through the scheme. This results in great reduction in false alarms at the processor output. But at the same time the detection probability is also decreasing. It should be mentioned that in practice the detection probability is always higher than the false alarm rate. So the detection probability is decreasing more slowly than the false alarm rate. The criterion processing can be effectively used when the low level of false alarm rate is required (10^{-4} and less).

The schematic diagram of such criterion processing is illustrated in Fig. 7. The signal samples from the same range cells received in two repetition periods are fed to the AND logical scheme. Fig. 5(a) and Fig. 5(b) (dotted line) show the IPCP detection characteristics after the criterion processing "two of two". The characteristics are calculated for the false alarm rate indicated in the Figure.

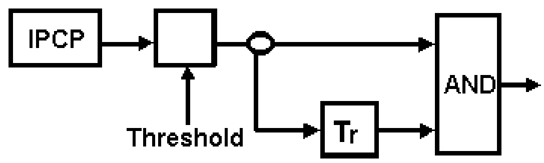

Fig. 7. *Schematic diagram of criterion processing*

They are located to the left of the standard characteristics of the conventional correlator calculated for the fully known signal. This is a result of combining signals from two repetition periods in OR scheme (in this case, it operates as a multiplier), this procedure is identical to the accumulation.

5. Moving Target

If a target is moving the problem is concerned with its passing from one resolution cell to another during pulse repetition period emerges. We can solve this problem by using a multi-channel scheme similar to Doppler filtration system, which provides optimal detection of moving targets. The similar multichannel scheme can be used for selection of optimal integration time T while detecting target with various physical lengths L. The losses resulted from the multi-cannel configuration of the scheme can be calculated using the conventional methods that are valid for the similar multi-cannel digital Doppler systems.

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ПРИЁМ СВЕРХШИРОКОПОЛОСНЫХ РАДАРНЫХ СИГНАЛОВ, РАССЕЯННЫХ СЛОЖНЫМИ ЦЕЛЯМИ

И.Я. Иммореев, Д.В. Федотов

Обсуждаются вопросы приема радарных сигналов сопровождения, параметры которых неизвестны. Рассмотрен метод обнаружения радарных сигналов с неизвестными параметрами. Метод основан на корреляционной обработке принятых в смежные периоды зондирования сигналов – межпериодной периодической корреляционной обработке сигналов (IPCP).

ПРИЙМАННЯ НАДШИРОКОСМУГОВИХ РАДАРНИХ СИГНАЛІВ, РОЗСІЯНИХ СКЛАДНИМИ ЦІЛЯМИ

І.Я. Іммореєв, Д.В. Федотов

Обговорено питання приймання радарних сигналів супроводження з невідомими параметрами. Розглянуто метод виявлення радарних сигналів з невідомими параметрами. Метод базується на кореляційній обробці прийнятих сигналів у суміжних періодах зондування – міжперіодна періодична кореляційна обробка сигналів (IPCP).