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Radar receiving of long pulse burst when detecting moving targets

The paper introduces an algorithm for detecting a burst of radio pulses. The algorithm takes into account the phase advance due to the Doppler effect at a constant radial velocity of the target, as well as the degree of pulse coherence in the received burst. The algorithm proposed is highly competitive in terms of detection performance with the algorithms of coherent or incoherent integration.

Keywords: radar detection, integration of radio pulse bursts, algorithm for detecting radio pulse bursts

Introduction

Implementation of radar systems with active phased antenna arrays (APAA), employing solid-state devices that do not have high peak power, demands for application of long-duration signals in early-warning radars. In this case, radio-frequency pulse bursts implementing coherent or incoherent integration are used. It should be mentioned that the coherence of radio-frequency pulses is influenced by a number of factors reducing effectiveness of their integration. Those factors include the movement of targets, propagation medium effects, stability of antenna aperture parameters.

The expression defining a single radio-frequency pulse radiated by APAA is:

$$S_{\text{и}}(t) = S(t)e^{j(\omega_0 t+\varphi_0)},$$

where $S(t)$ – square modulation pulse;

ω_0 – circular carrier frequency;

φ_0 – initial phase on the carrier frequency for a transmitted signal.

We presume that the radar uses a radio-frequency pulse burst $S_{\text{п}}(t)$ with repetition period T. The expression defining radio-frequency pulse burst radiated by the transmitter is:

$$S_{\text{п}}(t) = \sum_{i=1}^{N} S\left(t - T(i-1)\right) e^{j[\omega_0 (t - T(i-1)) + \varphi_0]},$$

where N – number of pulses in a burst.

Depending on target movement, signal delay changes.

An assumption is taken that target is moving with constant radial velocity V_r, and signal envelope deformation is not taken into account.

Then the time of receiving a pulse with number i on the leading edge relative to the moment of time when the first pulse in the burst was radiated by the radar is described by the expression

$$t_{\text{з}i} = \frac{2R_0}{c} - \frac{2V_r R_0}{c(c+V_r)} + (i-1)T\left(1 - \frac{2V_r}{c+V_r}\right),$$

where R_0 – range to target at the moment of radiation of the leading edge of the first pulse in the burst;

c – speed of light.

Hence, the repetition period of the received pulses

$$T_{\text{пр}} = T - \Delta T,$$

where $\Delta T = \dfrac{2V_r T}{c+V_r}$.

In this way, the repetition period of the received signals differs from that of the probing signals and from the reference signal. With the repetition period of pulses in the burst amounting to tens of milliseconds, target radial velocity of several thousand metres per second, and the repetition period of the order of ten milliseconds, period change ΔT amounts to units of milliseconds.

In the integration of a pulse burst with carrier frequency f_0 and repetition period T, phase difference between adjacent received pulses, at Doppler frequency $f_{\text{д}}$ on account of target movement, will make

$$\Delta\varphi = 2\pi(f_0 + f_{\text{д}})\Delta T.$$

Hence, under constant radial velocity, without consideration of the effects of radio waves propagation in the medium, phase difference of signals in adjacent pulses of the burst is constant but unknown. For coherent integration it is necessary to take into account the phase advance occurring over the probing period due to Doppler effect.

Principle of the proposed solution

The matrix of matched filter responses to a burst of N radio-frequency pulses, described by complex numbers $\mathbf{Y}_1, \mathbf{Y}_2, \mathbf{Y}_3, \ldots, \mathbf{Y}_N$, has the form

$$\mathbf{M} = \begin{bmatrix} \mathbf{Y}_1\mathbf{Y}_1^* & \mathbf{Y}_1\mathbf{Y}_2^* & \cdots & \mathbf{Y}_1\mathbf{Y}_k^* & \cdots & \mathbf{Y}_1\mathbf{Y}_N^* \\ \mathbf{Y}_2\mathbf{Y}_1^* & \mathbf{Y}_2\mathbf{Y}_2^* & \cdots & \mathbf{Y}_2\mathbf{Y}_k^* & \cdots & \mathbf{Y}_2\mathbf{Y}_N^* \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \mathbf{Y}_k\mathbf{Y}_1^* & \mathbf{Y}_k\mathbf{Y}_2^* & \cdots & \mathbf{Y}_k\mathbf{Y}_k^* & \cdots & \mathbf{Y}_k\mathbf{Y}_N^* \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \mathbf{Y}_N\mathbf{Y}_1^* & \mathbf{Y}_N\mathbf{Y}_2^* & \cdots & \mathbf{Y}_N\mathbf{Y}_k^* & \cdots & \mathbf{Y}_N\mathbf{Y}_N^* \end{bmatrix}. \quad (1)$$

The sum of elements located on the main diagonal of matrix **M** results from the algorithm of incoherent integration of a pulse burst [1] after square-law detection:

$$Y_{\Sigma\text{НО}} = \mathbf{Y}_1\mathbf{Y}_1^* + \mathbf{Y}_2\mathbf{Y}_2^* + \ldots + \mathbf{Y}_N\mathbf{Y}_N^* = \mathbf{Y}_1^2 + \mathbf{Y}_2^2 + \ldots + \mathbf{Y}_N^2,$$

and the sum of all elements of the correlation matrix results from the algorithm of coherent integration of a pulse burst:

$$Y_\Sigma = \left(Y_1 + Y_2 + \ldots + Y_n\right)^2 = Y_{\Sigma\text{НО}} + Y_{\Sigma\text{ПД}},$$

where $Y_{\text{ПД}}$ – sum of matrix **M** elements located on its secondary diagonals, $Y_{\Sigma\text{ПД}} = \sum_{i=1}^{N}\sum_{j=1}^{N} Y_i Y_j^*,\ i \neq j$.

In the proposed algorithm for detecting a pulse burst, with account of inter-period Doppler phase advance, the sums of elements located on each of the diagonals of the matrix of matched filter responses' products are calculated, then supplied to detector, threshold device (TD), and are logically combined according to the "OR" scheme (Fig. 1).

Let us elaborate on the proposed scheme operation.

The sum of matrix **M** elements located on the first secondary diagonal is described by the expression

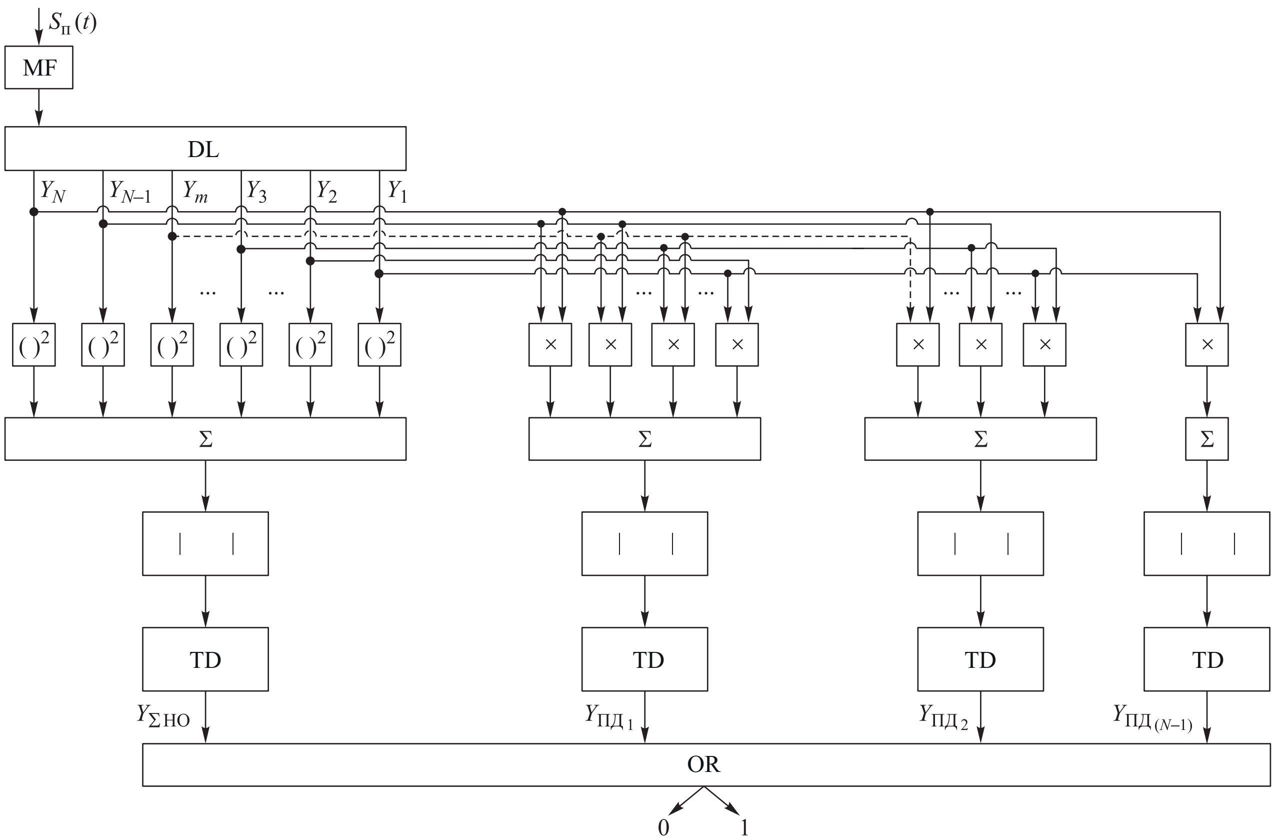

Fig. 1. Block diagram of algorithm for receiving a pulse burst with account of inter-period Doppler phase advance

$$Y_{\Sigma \text{ПД}_1} = \mathbf{Y}_1\mathbf{Y}_2^* + \mathbf{Y}_2\mathbf{Y}_3^* + \mathbf{Y}_3\mathbf{Y}_4^* + \ldots + \mathbf{Y}_{N-1}\mathbf{Y}_N^* = \sum_{k=2}^{N} \mathbf{Y}_{k-1}\mathbf{Y}_k^*,$$

where $\mathbf{Y}_{k-1}\mathbf{Y}_k^* = Y_{k-1}e^{j\varphi_{k-1}}Y_k e^{j\varphi_k} = \mathbf{Y}_{k-1}Y_k^* e^{j(\varphi_k - \varphi_{k-1})}$;

$(\varphi_k - \varphi_{k-1}) = \Delta\varphi_1$ – phase advance between two adjacent pulses in a burst, this advance being a constant magnitude under uniform rectilinear motion of the target, i. e. given the condition that carrier frequency change due to the Doppler effect over a period T is a constant magnitude [2].

Similarly, the sum of matrix **M** elements located on the secondary diagonal with number m is described by the expression

$$Y_{\Sigma \text{ПД}m} = \mathbf{Y}_1\mathbf{Y}_{1+m}^* + \mathbf{Y}_2\mathbf{Y}_{2+m}^* + \mathbf{Y}_3\mathbf{Y}_{3+m}^* + \ldots + \mathbf{Y}_{N-m}\mathbf{Y}_N^* = \sum_{k=1+m}^{N} \mathbf{Y}_{k-m}\mathbf{Y}_k^*,$$

where $\mathbf{Y}_{k-m}\mathbf{Y}_k^* = Y_{k-m}e^{j\varphi_{k-m}}Y_k e^{j\varphi_k} = \mathbf{Y}_{k-m}\mathbf{Y}_k^* e^{j(\varphi_k - \varphi_{k-m})}$;

$(\varphi_k - \varphi_{k-m}) = \Delta\varphi_m$ – phase advance between two pulses in a burst located over m repetition periods, this advance, same as $\Delta\varphi_1$, being a constant magnitude under uniform rectilinear motion of the target.

Hence, for signals reflected from a uniformly moving target, the elements of matrix **M** located on each of its secondary diagonals have phase advances $\Delta\varphi_m$ which are similar, though unknown. This allows to perform coherent summation of the elements of each secondary diagonal of matrix **M**, thus taking into account the unknown value of Doppler frequency variation.

Since in this case the sums of all secondary diagonals of matrix **M** are considered in the final result, the proposed solution by its effectiveness turns out to be close to coherent integration, while at the same time being essentially more economical in terms of computation amounts, as it makes it possible to avoid Doppler multichanneling.

Besides, since the sum of the elements of **M** matrix main diagonal, equivalent to the incoherent integration result, is also involved in the "OR" scheme, the proposed scheme is efficient, without any changes, in processing of an incoherent pulse burst as well, as it considers the coherence degree of the burst pulses.

Evaluation of proposed solution effectiveness

Evaluation of the detection characteristics was performed through mathematical simulation. Signal $S_\text{п}(t)$, in the form of a 12-pulse burst, having passed a matched filter (MF), is supplied via delay line (DL) to the inputs of coherent integrator, incoherent integrator, or to the circuit of pulse train receiving algorithm, with account of the inter-period Doppler phase advance (Fig. 1). In Fig. 1, the following designations of the blocks are used: $(\,)^2$ – squaring, × – multiplying, | | – denoting absolute value. A probability of false alarm is constant for all detection algorithms, being approximately equal to $2 \cdot 10^{-3}$. for all integration algorithms. For setting the detection threshold [1, 3], 30,240 experiments were selected. A probability of correct detection (under fixed false alarm probability) is assessed by the ratio between the number of experiments with the detection threshold exceeded to the total number of experiments.

The detection curves for a radio-frequency pulse burst with different level of coherency for the detection algorithms, after coherent integration of pulses, after incoherent integration, and the proposed algorithm with account of the inter-period Doppler phase advance are given in Figs. 2–5.

In this way, the value of correct detection probability D = 0.9, with arrival of incoherent pulses having inter-pulse correlation coefficient r = 0 at the inputs of three different integration algorithms (see Fig. 2), is achieved at signal-to-noise ratio of 14 dB after their incoherent integration (red curve) and at somewhat smaller signal-to-noise ratio for the proposed algorithm with account of the inter-period Doppler phase advance (dotted curve). It appears impossible to detect a burst of incoherent pulses after passing the coherent integration circuit (green curve).

The value of correct detection probability D = 0.9, with arrival of partly coherent pulses having inter-pulse correlation coefficient r = 0.35 at the inputs of three different integration algorithms (see Fig. 3), is achieved at signal-to-noise ratio of 15 dB after their incoherent integration (red curve) and at somewhat smaller signal-to-noise

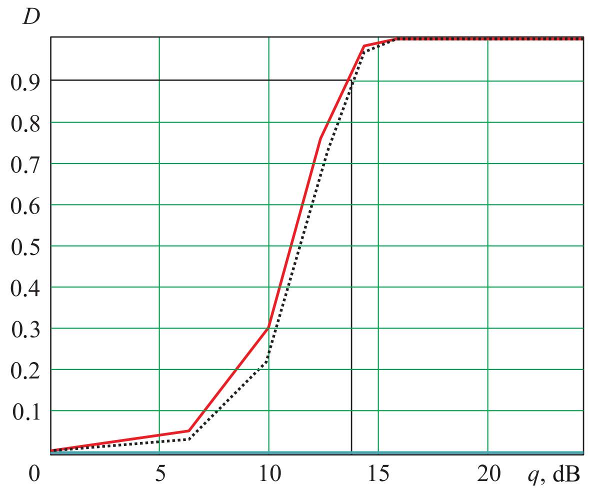

Fig. 2. Detection curves of incoherent pulse burst (with inter-pulse correlation coefficient $r = 0$) after incoherent integration of pulses (———), under processing as per the proposed algorithm with account of inter-period Doppler phase advance (··············), and after coherent integration of pulses (———)

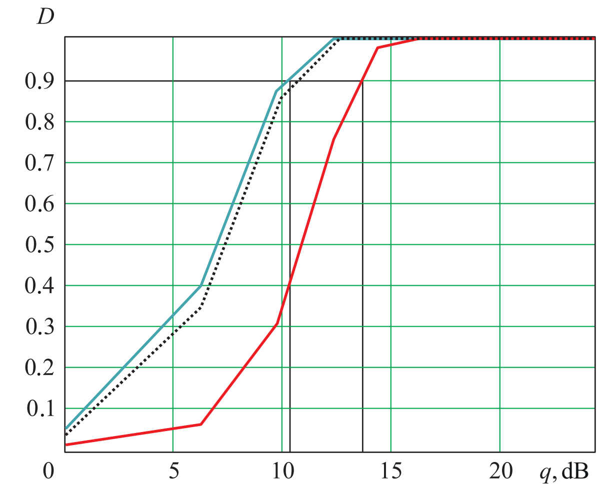

Fig. 4. Detection curves of coherent pulse burst (with correlation coefficient $r = 1$) after incoherent integration of pulses (———), under processing as per the proposed algorithm with account of inter-period Doppler phase advance (··············), and after coherent integration of pulses (———)

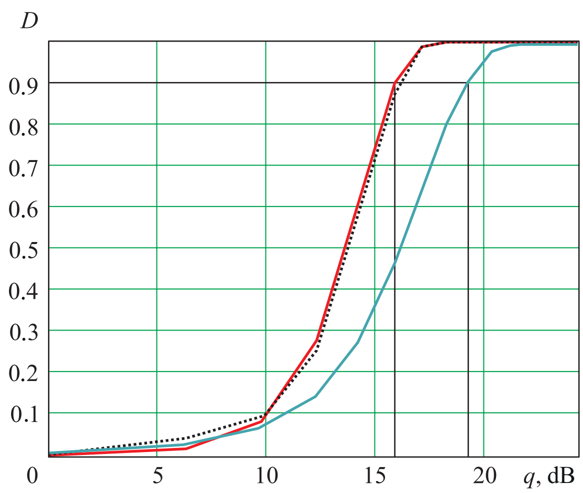

Fig. 3. Detection curves of partly coherent pulse burst (with inter-pulse correlation coefficient $r = 0.35$) after incoherent integration of pulses (———), under processing as per the proposed algorithm with account of inter-period Doppler phase advance (··············), and after coherent integration of pulses (———)

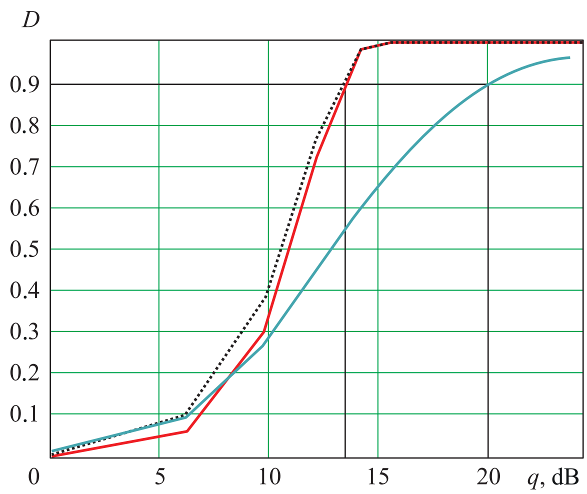

Fig. 5. Detection curves of partly coherent pulse burst consisting of four incoherent sub-bursts (with inter-sub-burst correlation coefficient $r = 0$) after their incoherent integration (———), under processing as per the proposed algorithm with account of inter-period Doppler phase advance (··············), and after their coherent integration (———)

ratio for the proposed algorithm with account of the inter-period Doppler phase advance (dotted curve). A burst of such incoherent pulses is detectable at the coherent integration circuit output with probability $D = 0.9$ at a greater signal-to-noise ratio of 19 dB (green curve).

A burst of coherent pulses (see Fig. 4) is detectable with probability $D = 0.9$ at signal-to-noise ratio of 10 dB after coherent integration of pulses (green curve), at somewhat smaller signal-to-noise ratio for the proposed algorithm with account of the inter-period Doppler phase advance (dotted curve), and at 14 dB at the incoherent integration circuit output (red curve).

A burst of partly coherent pulses consisting of four incoherent sub-bursts (Fig. 5) is detectable with probability $D = 0.9$ at signal-to-noise ratio of 14 dB for the algorithm with account of the inter-period Doppler phase advance (dotted curve), at somewhat smaller signal-to-noise ratio after incoherent integration of pulses (curve 1), and at 23 dB at the coherent integration circuit output. In this case the proposed algorithm has better characteristics as compared with the detection algorithms after coherent or incoherent integration of a pulse burst.

Summing up all of the above, we can state that application of the proposed algorithm makes it possible to detect signals in the form of a pulse burst with different coherence degree, as conditioned by the Doppler phase advance. Now the detection characteristics (the values of signal-to-noise ratio q, reduced to the receiver input, and correct detection probability D) are close to the best (see Figs. 2–4), including those for a long burst of $N = 12$ radio-frequency pulses divided by $K = 4$ sub-bursts; thereat, the sub-bursts are incoherent pair-wise (probability distribution density of the initial phases of sub-bursts is uniform across interval $[-\pi, \pi]$), and pulses in each one of those sub-bursts are coherent.

Conclusion

An algorithm for receiving a pulse burst with account of the inter-period Doppler phase advance, under constant radial velocity of the target, has been developed, based on the use of element sums of a matrix of form (1) featuring products of the received signals located on each one of its diagonals.

The algorithm does not require knowledge of target's radial velocity or application of a multichannel Doppler processing scheme, enabling to successfully process coherent, partly coherent, and incoherent pulse bursts with virtually equal efficiency as compared with the algorithms of, respectively, coherent or incoherent integration.

Algorithm efficiency is confirmed by the mathematical simulation results.

Bibliography

1. Radioelectronic Systems: Fundamentals of Development and Theory. Handbook/ Ed. *Ya. D. Shirman*. M.: Radiotekhnika, 2007. 512 p. (Russian)

2. *Chepkasov A. V.*, *Molchanov F. A.*, *Lyaking E. A.* Otsenka intervala kogerentnogo nakopleniya v radiolokatsionnoy stantsii dalnego obnaruzheniya // Sbornik dokladov VI nauchno-tekhnicheskoy konferentsii molodykh uchenykh i spetsialistov (18–19 sentyabrya 2014 g., FGUP "NPTsAP", Moskva). M.: PAO "NPO "Almaz", 2015. S. 438 – 443. (Russian)

3. Radar Handbook. In 2 vols. Vol. 1 / Ed. *M. I. Skolnik*. M.: Tekhnosfera, 2014. 672 p. (Russian)

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Радиолокационный прием пачки импульсов большой длительности при обнаружении движущихся целей

Предложен алгоритм обнаружения пачки радиоимпульсов, учитывающий набег фаз из-за доплеровского эффекта при постоянной радиальной скорости цели. Данный алгоритм учитывает степень когерентности импульсов в принимаемой пачке и практически не уступает по характеристикам обнаружения алгоритмам когерентного или некогерентного накопления.

Ключевые слова: радиолокационные станции обнаружения, накопление пачки радиоимпульсов, алгоритм обнаружения пачки радиоимпульсов.

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