Adaptation of Rejection Algorithms for a Radar Clutter

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Abstract: In this paper, the algorithms for adaptive rejection of a radar clutter are synthesized for the case of a priori unknown spectral-correlation characteristics at wobbulation of a repetition period of the radar signal. The synthesis of algorithms for the non-recursive adaptive rejection filter (ARF) of a given order is reduced to determination of the vector of weighting coefficients, which realizes the best effectiveness index for radar signal extraction from the moving targets on the background of the received clutter. As the effectiveness criterion, we consider the averaged (over the Doppler signal phase shift) improvement coefficient for a signal-to-clutter ratio (SCR). On the base of extreme properties of the characteristic numbers (eigennumbers) of the matrices, the optimal vector (according to this criterion maximum) is defined as the eigenvector of the clutter correlation matrix corresponding to its minimal eigenvalue. The general type of the vector of optimal ARF weighting coefficients is de-termined and specific adaptive algorithms depending upon the ARF order are obtained, which in the specific cases can be reduced to the known algorithms confirming its authenticity. The comparative analysis of the synthesized and known algorithms is performed. Significant bene-fits are established in clutter rejection effectiveness by the offered processing algorithms compared to the known processing algorithms.

Keywords: Adaptation, Rejection Algorithms, Wobbulation of Repetition Period, Clutter.

1. Introduction

At design and exploitation of radar systems, the problem of signal detection from the moving target on the clutter background invariably remains the one of the most important, relevant, and difficult problems. The passive interference (clutter) in the form of undesirable reflections from fixed of slowly moved objects: the local objects, dry land or sea surfaces, the hydrometeors (clouds, rain, hail, snow) and metal reflectors dropping for target masking (so-called, chaff) essentially destroy the normal operation of radar systems of various purposes [1, 2]. Clutter intensity may significantly exceed the level of the proper receiver noises that leads to overload of the reception section (radar “blindness”) and, as a consequence, to useful signal missing. Nevertheless, even at overload absence, the useful signal can be lost or not detected at all, on the background of intensive undesirable interference. The main processing operation for received data is the rejection of the interference spectral components at extraction the signals from the moving targets on the clutter background, which is caused by undesirable reflections [3]. However, effective selection of the signal is impossible for so-called target blind velocities, when the spectral lines of signals and interference coincide. The intended variation (or wobbulation) of the pulse repetition period is the one of the known method for blind velocity elimination [1, 4]. The wobbulation improves the conditions of target detection, which are moving at previous blind velocities, but it leads to narrowing of the RF rejection band that significantly decreases the effectiveness of the clutter rejection. In order to eliminate this, the time-variable weighting coefficients are used according to the wobbulation law [1].

Besides, the absence of a priori information about the spectral-correlation interference properties as well as its non-uniformity and non-stationarity in the scanned area, causes trouble for implementation of the limited possibilities of clutter rejection, which assumes the adaptive RF structure, similar to suggested in [5] at wobbulation absence. In this connection, a synthesis and an analysis of adaptive rejection algorithms for the clutter at repetition period wobbulation is interesting and relevant, and it is performed in this paper.

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2. Description of radar wobbulated sequence

At repetition period wobbulation, the sequence of processed samples forms the wob-bulation core consisting of p non-equidistant or non-equal time intervals T_1, T_2, ..., T_i, ..., T_p and repeating with a constant period T_w, which is called the wobbulation period [1]:

$$T_{\mathrm{w}} = \sum_{i=1}^{p} T_i \,. \tag{1}$$

As a rule, variation of inter-pulse intervals within the limit of wobbulation core is per-formed in accordance with a some law, which is called the wobbulation law and can be represented via variation of the repetition period with regard to the minimal period T_{min} by the value multiple to some time discrete value

$$\Delta T = T_{\min} / M \,, \tag{2}$$

where M is a integer scale multiplier.
In particular, at the linear law, the consequent variation of the T_i interval occurs from a pulse to the next by the value ΔT according to a rule

$$T_i = T_{\min} + (i-1)\Delta T \,, \quad i = \overline{1, p} \,. \tag{3}$$

The cross law can be obtained as follows:

$$\begin{aligned} &T_{2i-1} = T_{\min} + (i-1)\Delta T \,, \\ &T_{2i} = T_{\max} - (i-1)\Delta T \,, \quad i = \overline{1, p/2} \,, \end{aligned} \tag{4}$$

where the maximal repetition period within the limits of wobbulation core is

$$T_{\max} = T_{\min} + (p-1)\Delta T \,. \tag{5}$$

RF characteristics essentially depends on the choice of quantities P, ΔT(or M) and the wobbulation law. With a growth of wobbulation range for repetition period, we must ex-pect improvement of RF velocity characteristics; however, from a point of view of radar prob-lems under solution, it is necessary to impose the following limitations:
– The minimal period T_{min} must meet the condition of unambiguous determination of a given range;
– The maximal period T_{max} must satisfy the condition $T_{max} \leq 1.5\, T_{min}$ from energy considerations.
The depth or wobbulation index is the one of the main quantitative index of the wob-bulated sequence

$$\mathrm{mod} = \left(\frac{T_{\max}}{T_{\min}} - 1 \right) 100\% \,. \tag{6}$$

Taking into consideration a non-stationarity of (T_1, T_2, ..., T_p) intervals within the limits of the wobbulation period T_w, the interference properties is expedient to describe by the p correlation sub-matrices R_l, which elements are equal to

$$R_{jk}^{(l)} = \rho_{jk}^{(l)} \exp(\mathrm{i}\psi_{jk}^{(l)}) \,, \tag{7}$$

where $\rho_{jk}^{(l)} = \rho(t_{l-j} - t_{l-k})$ are coefficients on the inter-period correlation, $\psi_{jk}^{(l)} = \psi(t_{l-j} - t_{l-k})$ are the Doppler phase shifts, j, $k = \overline{0, m}$, $l = \overline{(m+1), (m+p)}$, m is the RF order. Here and further, boundaries of l value variations are displaced by m , to not to take into account an effect of the transient in the filter.

3. The adaptation Criterion and the Algorithm Synthesis

The synthesis of required algorithms for the non-recursive adaptive rejection filter (ARF) of the given order consists in determination of the weighting coefficients vector G={G_k}, $k = \overline{0, m}$, which realizes the best effectiveness for extraction of moving target sig-nals on the background of the received clutter. As the effectiveness criterion, we consider the μ coefficient of signal-to-clutter ratio (SCR) improvement [5], which is averaged over the Doppler signal phase shift. Then, during RF adaptation process, in general case, the **G** vector realizing the maximum value of μ should be formed. And, at repetition period wobbulation during RF adaptation, for each from p correlation sub-matrices $\boldsymbol{R_l}$ of the clutter, the own optimal sub-vector $\mathbf{G}_l = \{G_k^{(l)}\}$ of weighting coefficients should be formed. Taking this into consideration, the above-mentioned criterion can be written as

$$\begin{aligned} &\mu_l = \max_{\mathbf{G}_l} (\mathbf{G}_l^{*\mathrm{T}} \mathbf{G}_l / \mathbf{G}_l^{*\mathrm{T}} \mathbf{R}_l \mathbf{G}_l) \,, \\ &\qquad l = \overline{(m+1), (m+p)} \,, \end{aligned} \tag{8}$$

where symbols * and T designate a complex conjugation and a transposition.
On the base of extreme properties of the matrix eigenval-

ues α, the optimal vector $\mathbf{G}_l$ is determined as the matrix eigenvector $\mathbf{R}_l$ [6] corresponding to its minimal eigen-value $\alpha_{\min}^{(l)}$ from the following matrix equation:

$$(\mathbf{R}_l - \alpha_{\min}^{(l)}\mathbf{I})\mathbf{G}_l = 0\,, \tag{9}$$

where I is the unitary matrix, and the value $\alpha_{\min}^{(l)}$ is the least root of the characteristic equa-tion

$$\det(\mathbf{R}_l - \alpha\,\mathbf{I}) = 0\,. \tag{10}$$

Overcoming of a priori uncertainty of interference param-eters is based on the adaptive Bayesian approach [7] ac-cording to which the unknown correlation sub-matrices $\mathbf{R}_l$ of inter-ference are replaced by their estimation values $\hat{\mathbf{R}}_l$.

In the general case the equation (9) is satisfied by the vec-tor of ARF optimal weight-ing coefficients, which can be represented as

$$\hat{\mathbf{G}}_l = \{\hat{G}_k^{(l)}\} = \left\{\hat{g}_k^{(l)} \exp\left(\mathrm{i}\sum_{i=1}^{k}\hat{\psi}_{l-i}\right)\right\},\quad k=\overline{0,m}\,, \tag{11}$$

where $\hat{g}_k^{(l)}$ are coefficients determined by estimations $\hat{\rho}_{jk}^{(l)}$ and $\hat{\alpha}_{\min}^{(l)}$ in accordance with specific (depending on RF order m) adaptive algorithms; $\hat{\psi}_l$ is an estimate of the Doppler phase shift of the clutter over the period T_l (evi-dently, $T_{l+np}=T_l$, $n=0, 1, 2, ...$).

To determine coefficients $\hat{g}_k^{(l)}$, as it follows from (9), it is necessary to solve the sys-tem of (m+ 1) autonomous lin-ear equations with (m+ 1) unknown variables

$$\sum_{j=0}^{m}(\hat{\rho}_{jk}^{(l)} - \hat{\alpha}_{\min}^{(l)}\delta_{jk})\hat{g}_k^{(l)} = 0\,,\quad k=\overline{0,m}\,. \tag{12}$$

This system has the following solutions, which differ from the trivial (zero) one [8]:

$$\hat{g}_k^{(l)} = C\hat{A}_{Row,\,k}^{(l)}\,,\quad k=\overline{0,m}\,, \tag{13}$$

where C is the arbitrary constant; $\hat{A}_{Row,\,k}^{(l)}$ is the algebraic compliment of the appropriate element in the determinant $\det[\hat{\rho}_{jk}^{(l)} - \hat{\alpha}_{\min}^{(l)}\delta_{jk}]$, in which the expansion line with the number is chosen so that at least one of the compliment $\hat{A}_{Row,\,k}^{(l)}$ differs from zero; δ_{jk} is the Kronecker symbol.

Under the limiting condition $\hat{g}_0^{(l)} = g_0 = 1$, we have for the optimal weighting coeffi-cients

$$\hat{g}_k^{(l)} = \hat{A}_{Row,\,k}^{(l)} \Big/ \hat{A}_{Row,\,Col}^{(l)}\,,\quad k,\,Row=\overline{0,m}\,, \tag{14}$$

where the value of expansion element (a column) Col corresponds to a number of weighting coefficient, which is equaled to unit, i.e., in this case, Col=0 .

Solutions of equation system (12) obtained at different values of a number of expan-sion row Row are identical on the final result (the μ_l value). Supposing for distinct-ness Row=1, we finally obtain for optimal weighting co-efficients

$$\hat{g}_k^{(l)} = \hat{A}_{1k}^{(l)} \Big/ \hat{A}_{10}^{(l)}\,,\ k=\overline{0,m}\,. \tag{15}$$

The specific view of adaptive algorithms from (15) should be found out in the follow-ing specific cases:

for m=1 ⇨ g_0=1, g_1=-1;

for m=2 ⇨ g_0=1, calculation values of $\hat{A}_{10}^{(l)}$, $\hat{A}_{11}^{(l)}$ and $\hat{A}_{12}^{(l)}$, we obtain

$$\hat{g}_1^{(l)} = -\frac{(1-\hat{\alpha}_{\min}^{(l)})^2 - (\hat{\rho}_{02}^{(l)})^2}{(1-\hat{\alpha}_{\min}^{(l)})\hat{\rho}_{01}^{(l)} - \hat{\rho}_{12}^{(l)}\hat{\rho}_{02}^{(l)}}\,,$$

$$\hat{g}_2^{(l)} = \frac{(1-\hat{\alpha}_{\min}^{(l)})\hat{\rho}_{12}^{(l)} - \hat{\rho}_{01}^{(l)}\hat{\rho}_{02}^{(l)}}{(1-\hat{\alpha}_{\min}^{(l)})\hat{\rho}_{01}^{(l)} - \hat{\rho}_{12}^{(l)}\hat{\rho}_{02}^{(l)}}\,; \tag{16}$$

for $m=3 \;\Rightarrow\; g_0=1$,

$$\hat{A}_{10} = -(1-\hat{\alpha}_{\min}^{(l)})^2\hat{\rho}_{01}^{(l)} + (1-\hat{\alpha}_{\min}^{(l)})(\hat{\rho}_{02}^{(l)}\hat{\rho}_{12}^{(l)} + \hat{\rho}_{03}^{(l)}\hat{\rho}_{13}^{(l)}) +,$$

$$+\hat{\rho}_{01}^{(l)}(\hat{\rho}_{23}^{(l)})^2 - \hat{\rho}_{02}^{(l)}\hat{\rho}_{13}^{(l)}\hat{\rho}_{23}^{(l)} - \hat{\rho}_{12}^{(l)}\hat{\rho}_{03}^{(l)}\hat{\rho}_{23}^{(l)}\,,$$

$$\hat{A}_{11} = (1-\hat{\alpha}_{\min}^{(l)})^3 - (1-\hat{\alpha}_{\min}^{(l)})[(\hat{\rho}_{02}^{(l)})^2 + (\hat{\rho}_{03}^{(l)})^2 + (\hat{\rho}_{23}^{(l)})^2] +$$

$$+2\hat{\rho}_{12}^{(l)}\hat{\rho}_{03}^{(l)}\hat{\rho}_{23}^{(l)}\,,$$

$$\hat{A}_{12} = -(1-\hat{\alpha}_{\min}^{(l)})^2\hat{\rho}_{12}^{(l)} + (1-\hat{\alpha}_{\min}^{(l)})(\hat{\rho}_{01}^{(l)}\hat{\rho}_{02}^{(l)} + \hat{\rho}_{13}^{(l)}\hat{\rho}_{23}^{(l)}) +$$

$$+\hat{\rho}_{12}^{(l)}(\hat{\rho}_{03}^{(l)})^2 - \hat{\rho}_{01}^{(l)}\hat{\rho}_{23}^{(l)}\hat{\rho}_{03}^{(l)} - \hat{\rho}_{02}^{(l)}\hat{\rho}_{13}^{(l)}\hat{\rho}_{03}^{(l)}\,,$$

$$\hat{A}_{13} = -(1-\hat{\alpha}_{\min}^{(l)})^2\hat{\rho}_{13}^{(l)} + (1-\hat{\alpha}_{\min}^{(l)})(\hat{\rho}_{01}^{(l)}\hat{\rho}_{03}^{(l)} + \hat{\rho}_{12}^{(l)}\hat{\rho}_{23}^{(l)}) +$$

$$+\hat{\rho}_{13}^{(l)}(\hat{\rho}_{02}^{(l)})^2 - \hat{\rho}_{01}^{(l)}\hat{\rho}_{23}^{(l)}\hat{\rho}_{02}^{(l)} - \hat{\rho}_{12}^{(l)}\hat{\rho}_{02}^{(l)}\hat{\rho}_{03}^{(l)}\,. \tag{17}$$

For m=3 , adaptive algorithms depend on estimates of six correlation coefficients and turn out as extremely bulky, therefore, in this case, it is expedient to build ARF in the form of cascade connection of chains of 1st and 2nd orders to simplify the adaptation procedures.

Now we note a connection of above-mentioned algorithms with the already known ones [1, 5]. With this goal, at m=2 for algorithms (16) we find the following limits:

$$\lim_{\Delta f \to 0}(\hat{g}_1^{(l)}) = -1 - \left(\frac{T_{l-1}}{T_{l-2}}\right), \quad \lim_{\Delta f \to 0}(\hat{g}_2^{(l)}) = \frac{T_{l-1}}{T_{l-2}}; \quad (18)$$

$$\lim_{\mathrm{mod} \to 0}(\hat{g}_1^{(l)}) = -\frac{2\hat{\rho}_{12}^{(l)}}{1-\alpha_{\min}^{(l)}}, \quad \lim_{\mathrm{mod} \to 0}(\hat{g}_2^{(l)}) = 1; \quad (19)$$

where Δf is the spectral width of the interference.

In the case of strongly-correlated interference (i.e., at $\rho_{jk} \to 1$ or $\Delta f \to 0$), algorithms (16) at arbitrary wobbulation deepness , as it follows from (18), are completely coincided with known algorithms basing on the time-varying coefficients according to the wobbulation law [1].

At mod→0, we obtain $\rho_{12}^{(l)} \cong \rho_{23}^{(l)} \cong \rho$, and algorithms (16), as it follows from (19), completely coincide with algorithms of [5]. In addition, at $\rho \to 1$, they transform to the clas-sical algorithms with binomial weighting coefficients $g_k = (-1)^k C_m^k$. The convergence of synthesized algorithms to known ones in the specific cases confirms their authenticity.

The ARF system (transfer) function in -plain is defined as a superposition of p specific system functions by the following equation:

$$H(\{z_l\}) = \frac{1}{p}\sum_{l=m+1}^{m+p}\sum_{k=0}^{m}\hat{g}_k^{(l)} z_l^{-k}\exp\left(\mathrm{i}\sum_{i=1}^{k}\hat{\psi}_{l-i}\right), \quad (20)$$

where $z_l = \exp(\mathrm{i}\,\omega T_l)$.

In accordance with the given system function, we can synthesize the ARF structural circuit, which differs from described in [5] by a presence of an additional weighting unit cor-responding to unequal to unit at the coefficient $\hat{g}_m^{(l)}$ of repetition period wobbulation, by im-plementation of the calculation unit for weighting coefficients, which realizes (for instance, at m=2) the condition $\hat{\rho}_{23}^{(l)} = \hat{\rho}_{12}^{(l-1)}$ by means of estimate delay of inter-period correlation coefficients and then calculating weighting coefficients according to adaptive algorithms (16), and by peculiarities of ARF units synchronization, taking into account the repetition period wobbulation.

4. The Adaptive Algorithm Analysis

Let us perform an analysis of synthesized algorithms basing on the effectiveness crite-rion following from (8). As resulting averaged improvement coefficient of AFR at p-multiple wobbulation of the repetition period, we take a superposition of p specific improvement coefficients:

$$\mu = \frac{1}{p}\sum_{l=m+1}^{m+p}\mu_l = \sum_{l=m+1}^{m+p}(\mathbf{G}_l^{*\mathrm{T}}\mathbf{G}_l / \mathbf{G}_l^{*\mathrm{T}}\mathbf{R}_l\mathbf{G}_l). \quad (21)$$

We assume that the wobbulation law is crossed, the Doppler interference phase have been already compensated (ψ_l=0), and the interference correlation function can be approx-imated by the Gaussian curve:

$$\rho_{jk} = \exp\{-\pi^2[\beta(t_j - t_k)/T_{\min}]^2/2.8\}, \quad (22)$$

where $\beta = \Delta f T_{\min}$ is normalized spectral width of interference.

$$\text{At that, } R_{jk}^{(l)} = \rho_{jk}^{(l)} = \rho_{l-j,\,l-k}. \quad (23)$$

Let us analyze benefits achieved by offered algorithms and defining by expression

$$\Delta\mu = \mu/\mu_{\mathrm{kn}}, \quad (24)$$

where μ is the improvement coefficient of ARF on the base of synthesized algorithms, μ_{kn} is the improvement coefficient of AFR on the base of known algorithms.

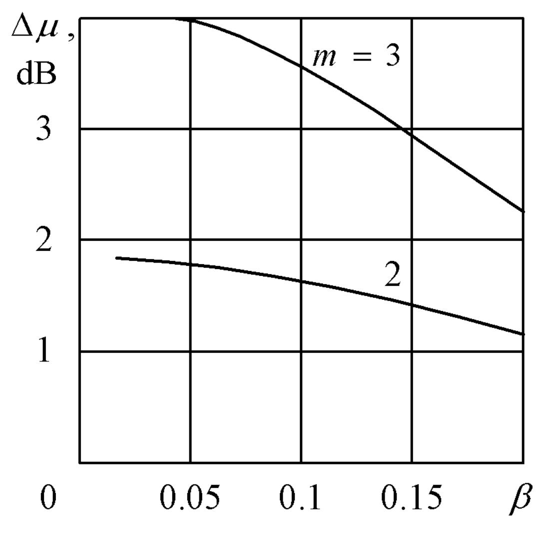

Fig. 1. The improvement coef-ficient benefit vs. the clutter parameter

At eight-multiple (p=8) wobbulation of the repetition period and the wobbulation deepness mod=25% , figure 1 shows functions of benefit $\Delta\mu$ in ARF improvement coefficient μ vs. normalized spectral width of interference β basing on synthesized algo-rithms compared with RF basing on non-adaptive time-varying algorithms [1]. From curves we can see that offered adaptation to clutter correlations characteristics at wobbulation of the repetition period allows obtaining essential benefits in clutter rejection effectiveness, which achieve 1.8 and 4.2 dB, relatively, at ARF order m=2 and 3.

Figure 2 shows the curves at m=3 and β= 0.05 illustrating the effect of wobbulation parameters on the benefit in ARF effectiveness basing on offered algorithms compared to ARF with stationary algorithms [5]. We see that at variation of wobbulation deepness within the limits of mod≤50% (depending on the wobbulation parameters), significant (up to 15 dB) are achieved, which correspond to the wobbulation cross-law. At the linear wobbulation law the similar benefit value does not exceed 5 dB.

These benefits can be explained as follows. In ARF with stationary algorithms the var-iation on an inter-pulse interval leads to deformation of ARF velocity characteristics in the rejection zone, which essentially decreases the clutter rejection effectiveness. The processing algorithm offered here combines adaptation to clutter correlation characteristics and variation in time of the weighting vector due to which additional benefits may be achieved in the clut-ter rejection effectiveness.

The analysis of ARF velocity characteristics on the base of offered algorithms shows that at $m < p$,together with maximization of the clutter rejection effectiveness, application of adaptive algorithms (16) and (17) for calculation of weighting coefficients gives the smoothed enough ARF characteristic in the pass-band at any placing of repetition periods in the group. In addition, ARF of $m = p$ -order is invariant according to chosen effectiveness criterion (8) with respect to various placing of repetition periods within the limits of the wobbulation pe-riod. This allows elimination of contradiction between requirements to increase the effective-ness of clutter rejection and to improve uniformity of the velocity characteristic at choice of repetition periods alteration in the group.

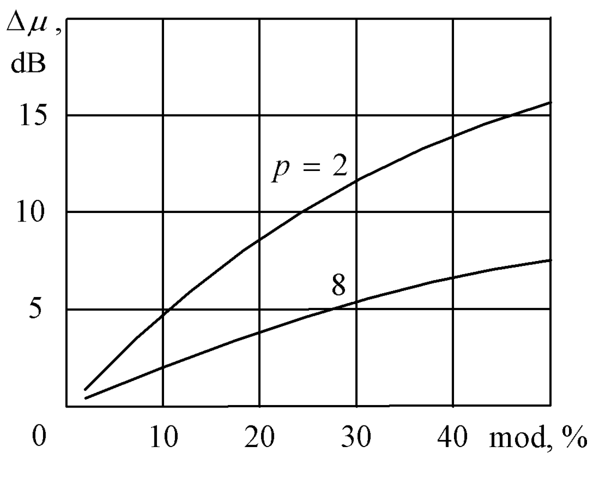

Fig. 2. The improvement coefficient ben-efit vs. wobbulation parameters

5. Conclusions

Algorithms synthesized in suggested paper, under conditions of a priori ambiguity of the spectral-correlation clutter characteristics, allow adaptation to an argument and a modulus of the relevant correlation function without approximation of its shape, taking into account wobbulation laws and parameters for repetition periods.

Application of synthesized algorithms allows obtaining essential benefits (compared to known algorithms of radar signal processing) in effectiveness of signal extraction of moving targets on the clutter background under conditions of a priori uncertainty of interference characteristics at repetition period wobbulation allowing elimination of blend target velocities. Achievement of this benefit is caused by combination of processing algorithm adaptation to unknown interference parameters with the time adjustment in accordance with the wobbula-tion law.

Application of algorithms obtained at ARF designing allows effectiveness increase of radar signal extraction from moving targets in much wider range of their radial velocities on the clutter background with known spectral-correlation properties. At that, the complication of the hardware-software implementation of ARF and growth of processing time of arrived data are required in accordance with more complicated offered algorithms compared to known ones.

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