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Signal processing in recursive rejection filters in the transient mode

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Abstract: A recursive rejection filter (REF) oriented to the radar signal extraction from the moving targets on a background of passive interference in the form of undesired reflections from fixed or slowly moving objects (so-called clutter) is the object under investigation. By means of the state variable method, which gives the adequate filter description in the time domain, the REF structure in the transient mode is synthesized, which is improved with the aim of transient acceleration with the clutter edge arriving. The REF structure's improvement in the transient mode is achieved by its reconfiguration, which is made by REF output and feedback switching. The steady-state values of decorrelated rejection residues from the nonrecursive REF part are passed to the REF output and to feedback circuits, which practically eliminates a “ring” in the feedback circuits, which is caused by the mean value and fluctuations of the clutter samples, and significantly accelerates the transient at the REF output. The structure diagram of the reconfigurable RF in the transient mode by means of recursive couplings switching is offered. A solution of transient acceleration problems for recursive REFs allows substantive utilization of required characteristics of REFs and their flexible control. A comparative analysis of clutter REF rejection effectiveness of fixed and reconfigurable structures is performed in the transient mode. It is shown that REF structure reconfiguration by means of recursive coupling switching essentially reduces the transient duration in the filter and increases the clutter rejection effectiveness in the transient operation mode.

Key words: Efficiency analysis, acceleration, clutter edge, structure reconfiguration, rejection filter, state variable, transient

1. Introduction

Passive interferences in the form of undesired reflections from fixed or slowly moving objects – local obstacles, land and sea surfaces, hydrometeors (clouds, rain, hail, snow) (so-called clutter), and metallic reflectors dropped for target masking (so-called chaff) – essentially destroy the normal operation of different radar systems (RSs) [1–4]. The clutter intensity may significantly exceed the level of the proper receiver noise, which leads to receiver overloading (“radar blinding”) and, as a consequence, to loss of the useful signal. Nevertheless, even for the absence of overloads, the useful signal may be lost or not detected at all on the background of the intensive clutter.

Protection methods against clutter depend on the RS type and on the probing signal used. This problem is most effectively solved in so-called pulse-Doppler RSs with small all-duty factors of the transmitted signal [1,2]. Processing of the received data is provided in the multichannel system in range and Doppler frequency.

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Due to differences of the Doppler frequency of the interference and the useful signal, the observation of the useful signal is carried out in the Doppler filters, which are free from interference. This provides the best selection of moving targets on the clutter background. Unambiguous measurement of the radial target velocity is achieved with high resolution and accuracy. Nevertheless, the range measurement is connected with an ambiguity, which may be eliminated by special methods that complicate the signal processing [1].

The unambiguous range measurement of a large number of targets by simple means and with high resolution is achieved in coherent-pulse RSs with probing pulses of large duty-off factors, which ensures the wide application of such RSs in practice [3]. The low pulse repetition frequency chosen from the condition of unambiguous range measurement leads to close location of the comb spectral components, which complicates the signal selection on the clutter background, which exceeds the power of the useful radar signal. In this case, the main operation of received data processing is rejection of interference spectral components, and the rejection filter (REF) is the main unit of the appropriate processing system [1,3].

Utilization of digital signal processing techniques allowed implementation of underoptimal processors on the base of digital filters for interference suppression and also led to REF structures with adaptation to the Doppler phase of the clutter [5–9]. Development of digital methods and devices for digital signal processing proceeded with discussions in the modern scientific and technological literature [10–16].

Among nonrecursive and recursive REFs, the recursive REFs have known advantages in the steady-state mode, which opens the wide possibilities of required features formation and its flexible control [1,3]. However, the prolonged transient caused by recursive couplings precedes the steady-state mode. Noncompensated interference residues at the RF output in the transient mode create a powerful background, masking the useful signal and leading to false alarms.

At discrete scanning of an antenna beam in radar systems with phased antenna arrays and also at linear scanning, in the case of signal detection on the discrete interference background and on the background of the forward edge of the lengthy interference, the duration of the radar signal samples processed, as a rule, is commensurable to the time of the transient being established in the recursive filters, and the transient is the main operation mode of recursive REFs.

2. The problem formulation

In this connection, the actual problem is modernization of the REF structure with the aim to accelerate its transient and increase the clutter rejection effectiveness in the transient mode as well as the required analysis of recursive REF characteristics in the transient mode.

3. The synthesis of the modernized REF

For a synthesis of the recursive REF modernized structure in the transient mode we use the state variable method giving the adequate REF description in the time domain. As with any discrete system, the discrete recursive REF of the mth order in the kth time moment is described by a state vector $\mathbf{X}(k) = [x_n(k)]$, where $x_n(k)$ is the state variable corresponding to the output quantity of the REF nth delay unit in the kth step, $k = \overline{0,\ N-1}$, $n = \overline{1,\ m}$, and N is a sample volume.

Connection between REF states at the kth and $(k+1)$th steps and between the state and input impact is described by the difference matrix equation of the REF state, which in the standard form is [17]:

$$\mathbf{X}(k+1) = \mathbf{A}\mathbf{X}(k) + \mathbf{B}u(k), \tag{1}$$

where $\mathbf{A}$ is a square matrix defining the connection between states at the kth and $(k+1)$th steps, and $\mathbf{B}$ is a vector-column describing the dependence between the state and the input impact $u(k)$.

The following state vector at the kth step is the solution of the difference equation in Eq. (1):

$$\mathbf{X}(k) = \mathbf{A}^k\mathbf{X}(0) + \sum_{l=0}^{k-1} \mathbf{A}^{k-1-l}\mathbf{B}\,u(l), \tag{2}$$

which depends on parameters of the REF and the initial state vector $\mathbf{X}(0)$ and permits determination of the REF output quantity from the matrix equation of the type "input – state – output":

$$y(k) = \mathbf{C}\mathbf{X}(k) + du(k) = \mathbf{C}\mathbf{A}^k\mathbf{X}(0) + \mathbf{C}\sum_{l=0}^{k-1} \mathbf{A}^{k-1-l}\mathbf{B}\,u(l) + du(k), \tag{3}$$

where $\mathbf{C}$ is a vector-line describing the connection between the REF state and the output quantity, and d is a scalar characterizing the connection between input and output.

The synthesis of the REF modernized structure with the aid of transient acceleration supposes the formation of the initial state vector $\mathbf{X}(0)$. The criterion of transient acceleration is based on the assumption that the REF output quantity is constant and hence the constancy of the state beginning with the clutter arrival:

$$\mathbf{X}(k+1) = \mathbf{X}(k) = \mathbf{X}(0) \text{ or } \mathbf{X}(k+1) - \mathbf{X}(k) = 0 \text{ for } k \geq 0. \tag{4}$$

To satisfy the criterion of Eq. (4), we require squareness of the clutter sample envelope, which occurs in the discrete observation mode and with combination with the known arrival time of the sample open opportunities to accelerate the REF transient. If the envelope shape differs from the rectangular one, e.g., at linear (continuous) scanning, we must fix the clutter arrival moment and apply the preliminary sample weighting to ensure the envelope's squareness.

The value of the initial state vector $\mathbf{X}(0)$, at which the DC clutter component compensation is achieved at the REF output in the transient mode, which corresponds to the zero response on the nonmodulated group of deterministic samples [i.e. $y(0) = y(k) = y(k+1) = 0$ at $u(0) = u(k) = u(k+1)$], according to the criterion of Eq. (4), is determined by the following equation:

$$\mathbf{A}^k(\mathbf{A} - \mathbf{I})\mathbf{X}(0) + \mathbf{A}^k\mathbf{B}\,u(0) = 0. \tag{5}$$

The solution of Eq. (5), as it follows from Eq. (2), is the initial state vector

$$\mathbf{X}(0) = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{B}\,u(0), \tag{6}$$

where $\mathbf{I}$ is a unitary matrix.

The form of the $\mathbf{X}(0)$ vector, in accordance with Eq. (6), assumes an introduction of the weighted values of the first clutter sample $u(0)$ at the moment of its arrival at the outputs of the REF delay units, which leads to constancy of the state and REF output values at arrival of the clutter sample group with constant amplitude. In the case of actual samples, application of the first sample of $u(0)$ does not lead straight away to the steady-state operation mode, but somewhat accelerates the transients.

Taking into consideration the fluctuating character of the sample, we can achieve more effective transient acceleration if we use the initial state that is proportional not only to the quantity of the single first sample but to the combination of the first samples of $u(k)$, $k = \overline{0,\ m-1}$. For this, in a manner similar to Eq. (2), we use the expression of the state vector to the moment of the mth sample arrival:

$$\mathbf{X}(m) = \mathbf{A}^m \mathbf{X}(0) + \sum_{l=0}^{m-1} \mathbf{A}^{m-1-l} \mathbf{B}\, u(l). \tag{7}$$

Processing of m samples by REF direct connections only without taking into account RF feedback circuits will correspond to the criterion of Eq. (4), which assumes that $\mathbf{X}(m) = \mathbf{X}(0)$. Under such a condition, the following relation resulting from Eq. (7) is true:

$$\mathbf{X}(m) = \sum_{l=0}^{m-1} \mathbf{A}^{m-1-l} \mathbf{B}\, u(l) = \mathbf{X}(0). \tag{8}$$

Application in Eq. (3) of vector $\mathbf{X}(m)$ as the initial state vector leads to a modified equation for the output quantity:

$$y(k) = \mathbf{C}\mathbf{A}^k \mathbf{X}(m) + \mathbf{C} \sum_{l=m}^{k-1} \mathbf{A}^{k-1-l} \mathbf{B}\, u(l) + du(k), k \geq m. \tag{9}$$

Thus, formation of the initial state, according to Eq. (8), requires utilization of the REF direct connections during arrival of m samples and it can be achieved by reconfiguration of the REF structure, which is done by switching of the REF output and feedbacks.

Let us illustrate the synthesis of the modernized REF structure in the transient mode based on the most interesting example for the radar practice case: the cascade connection of the nonrecursive 1st-order unit and the recursive 2nd-order unit (NRU_1-RU_2) with weighting coefficients of the recursive unit in direct connections of $a_0 = a_2 = 1$, $a_1 = a$; and in the feedbacks – b_1 and b_2. According to Eq. (8), the initial state vector has the following form:

$$\mathbf{X}(3) = \begin{bmatrix} au(2) + (1-a)u(1) - u(0) \\ u(2) - u(1) \\ u(2) \end{bmatrix}. \tag{10}$$

Formation of the $\mathbf{X}(3)$ vector results in processing of the first input samples in the REF's nonrecursive part. The filter output is switched on the fourth sample step only. Simultaneously, the feedbacks are switched, which corresponds to REF structure reconfiguration.

After substitution of the $\mathbf{X}(3)$ vector into Eq. (9) for $k = 3$, we obtain for the output quantity the following:

$$y(3) = u(3) - (1-a)u(2) + (1-a)u(1) - u(0). \tag{11}$$

As we see, the steady-state quantities of decorrelated rejection residues from the nonrecursive REF part pass to the REF output and to the feedback circuits, which practically eliminates "rings" in feedback circuits, which is caused by the mean value and fluctuations of the clutter samples, and essentially accelerates the transients at REF output.

4. The structural diagram of the modernized REF

As an initial structure, we use the fixed structure of the recursive REF shown in Figure 1.

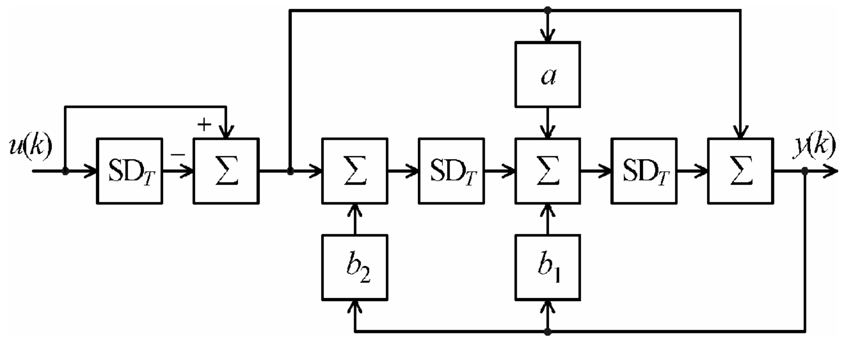

Figure 1. Structural diagram of reconfigurable recursive RF.

This block-diagram represents the cascade connection of the 1st-order nonrecursive chain and the 2nd-order recursive chain and contains storage devices SD_T by the repetition period T of samples under processing, the summers (Σ), and weighting blocks a, b_1, and b_2. The noncompensated residuals of the interference rejection $y(k)$ are passed into the REF output and into recursive connections, which correspond to transients of the nonrecursive REF part, which essentially increases the transient time for output clutter samples masking the target signal.

Transient acceleration, as is shown above, is achieved by REF structure reconfiguration. The structural diagram of the reconfigurable REF presented in Figure 2 additionally contains a control block (CB) and a switcher (Sw). Reconfiguration of the REF structure is implemented by recursive connections switching (b_1 and b_2). To the 4th sample (pulse) arrival corresponding to transient being established in the REF's nonrecursive part, the switcher (Sw), which was in the open state, now closes according to a command from the control block (CB). The residues of clutter rejection corresponding to the steady-state mode of the REF's nonrecursive part now pass to recursive connections and to the REF output, which essentially reduces the transient time at compensation of clutter samples.

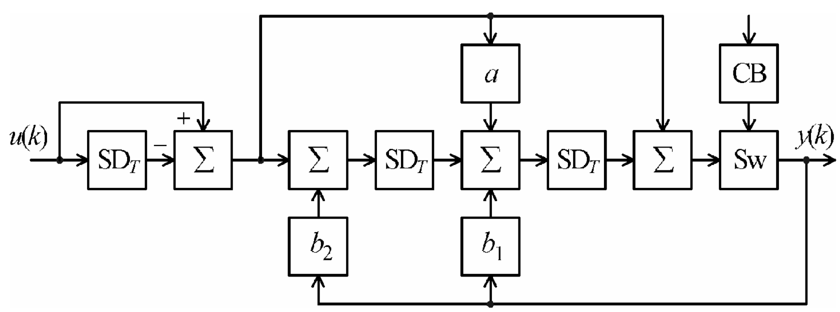

Figure 2. The block-diagram of the recursive REF of rearrangeable structure.

The further sample processing of the signal and clutter mixture occurs in the usual manner: samples sequentially pass to SD_T, weighting blocks (a, b_1, and b_2), and adders (Σ). Samples of the mixture of signals and decorrelated (over the arrived number of periods) clutter residues are formed at the REF output. Echoes from moving targets, which differ from the narrowband interference by the Doppler modulation, are not compensated and pass to the REF output.

We should note that the REF structure reconfiguration can be most easily arranged at the known start of the sequence process, which occurs at discrete scanning of an antenna beam.

In the linear (continuous) observation mode, modernization of the REF structure with the goal of acceleration of its transient has its own peculiarities, caused by modulation of clutter pulses at its edges by the antenna pattern. First the detection of the clutter forward edge occurs over all modulated edge pulses at the pulse arrival moment, which corresponds to the flat portion of the clutter envelope. Then the delayed clutter edge samples are weighted with a goal of recovering its envelope squareness, which allows effective extraction of Doppler signals without waiting for the pulse arrival of the envelope flat portion at processing, similar to Figure 2. At arrival and detection of the rear clutter edge, also by means of sample weighting, the recovering of the squareness of its envelope occurs.

Practical implementation of the REF considered can be done with modern hardware and software by means of digital signal processing.

5. An analysis of REF effectiveness in the transient mode

A system function in the z-plane of the recursive REF in the form of the cascade connection of the nonrecursive 1st-order unit and the recursive 2nd-order unit has the following form [5]:

$$H(z) = \frac{(z-1)\,(z^2 + a\,z + 1)}{z\,(z^2 - b_1\,z - b_2)} = \frac{z^3 - (1-a)\,z^2 + (1-a)\,z - 1}{z\,(z^2 - b_1\,z - b_2)} = \sum_{k=0}^{\infty} g_k\,z^{-k}, \tag{12}$$

where $z = e^{i\omega T}$; g_k are coefficients of the pulse response corresponding to the REF of fixed structure and determined for $k \leq 3$ from the following relations:

$$g_0 = d_0, \quad g_1 = d_1 + b_1 g_0,$$

$$g_k = d_k + \sum_{j=1}^{2} b_j g_{k-j}, \tag{13}$$

and for $k > 3$

$$g_k = \sum_{j=1}^{2} b_j g_{k-j}, \tag{14}$$

where $d_0 = -d_3 = 1,\ d_1 = -d_2 = -(1-a)$.

The following system function corresponds to the REF's nonrecursive part:

$$H_1(z) = 1 - (1-a)\,z^{-1} + (1-a)\,z^{-2} - z^{-3} = \sum_{k=0}^{3} g_k^{(1)} z^{-k}, \tag{15}$$

and coefficients of the pulse response are

$$g_0^{(1)} = -g_3^{(1)} = d_0 = -d_3 = 1,$$

$$g_1^{(1)} = -g_2^{(1)} = d_1 = -d_2 = -(1-a), \tag{16}$$

and the REF recursive part the system function is

$$H_2(z) = \left(1 - b_1 z^{-1} - b_2 z^{-2}\right)^{-1} = \sum_{k=0}^{\infty} g_k^{(2)}\, z^{-k}, \tag{17}$$

and coefficients of the pulse response are

$$g_0^{(2)} = 1, \quad g_1^{(2)} = b_1, \tag{18}$$

and for $k \geq 2$

$$g_k^{(2)} = b_1 g_{k-1}^{(2)} + b_2 g_{k-2}^{(2)}. \tag{19}$$

Let us consider the effectiveness of clutter rejection in the transient mode by the recursive REF of the fixed and reconfigurable structure. We assume that digital samples $U_j = x_j + iy_j$ of the complex envelope of the Gaussian narrowband interference are described by the following correlation moments at the noncompensated Doppler velocity:

$$R_{jk} = \overline{U_j U_k^*}/2 = \sigma_{cl}^2\, \rho_{jk} + \sigma_n^2 \delta_{jk}, \tag{20}$$

where σ_{cl}^2, σ_n^2 are dispersions of the clutter and the receiver proper noise, respectively; ρ_{jk} are coefficients of the clutter interperiod correlation; and δ_{jk} is the Kronecker symbol.

Now we have at the RF output of the fixed structure implemented in two quadrature channels in the transient mode:

$$V = \sum_{j=0}^{k-1} g_j\, U_{k-j}. \tag{21}$$

The clutter dispersion at the RF output is defined as follows:

$$\sigma_{Vcl}^2 = \frac{1}{2}\overline{VV^*} = \sigma_{cl}^2 \sum_{j,k=0}^{k-1} g_j\, g_k\, \rho_{jk} + \sigma_n^2 \sum_{j=0}^{k-1} g_j^2. \tag{22}$$

We shall evaluate REF effectiveness according to the normalized coefficient of clutter suppression with regard to the passage of the noncorrelated proper noise [18]:

$$\mu = h_0 / \left(\sigma_{Vcl}^2 / \sigma_{cl}^2\right), \tag{23}$$

where $h_0 = \sigma_{Vn}^2 / \sigma_n^2 = \sum\limits_{j=0}^{k-1} g_j^2$ is the normalized coefficient determining the passage through the REF of the noncorrelated proper noise of the receiver.

For the REF of fixed structure, taking into account Eqs. (22) and (23), we obtain

$$\mu(k) = \sum_{j=0}^{k-1} g_j^2 \Bigg/ \left(\sum_{j,k=0}^{k-1} g_j\, g_k\, \rho_{jk} + \lambda \sum_{j=0}^{k-1} g_j^2\right), \tag{24}$$

where $\lambda = \sigma_n^2 / \sigma_{cl}^2$ is the noise/interference ratio.

Representing the output quantity for the REF of reconfigurable structure and taking into consideration the switching of recursive couplings in the form:

$$V = \sum_{j=0}^{k-4} g_j^{(2)} \sum_{l=0}^{3} g_l^{(1)} U_{4+j-l}, \tag{25}$$

we obtain as a result of calculations similar to the previous ones:

$$\mu(k) = \sum_{l,p=0}^{3} \sum_{j=|l-p|}^{k-4} g_j^{(2)} g_{j-|l-p|}^{(2)} g_l^{(1)} g_p^{(1)} \Bigg/ \left(\sum_{j,k=0}^{k-4} \sum_{l,p=0}^{3} g_j^{(2)} g_{k|}^{(2)} g_l^{(1)} g_p^{(1)} \rho_{j-l,\,k-p} + \right.$$
$$\left. + \lambda \sum_{l,p=0}^{3} \sum_{j=|l-p|}^{k-4} g_j^{(2)} g_{j-|l-p|}^{(2)} g_l^{(1)} g_p^{(1)} \right). \tag{26}$$

Calculation results for rejection effectiveness in the transient mode for Gaussian approximation of the clutter correlation coefficients $\rho_{jk} = \exp\{-[\pi(j-k)\beta]^2/2.8\}$, for normalized clutter spectrum width $\beta = \Delta fT = 0.05$ and $\lambda = 10^{-6}$, are presented in Figure 3. Curve *1* corresponds to the RF of fixed structure and curve *2* corresponds to the RF of reconfigurable structure. Curve *1* for the REF of fixed structure is calculated in accordance with Eq. (24), in which coefficients g_k of the impulse characteristic are determined by Eqs. (13) and (14). Curve *2* for the REF of reconfigurable structure is calculated in accordance with Eq. (26), in which coefficients $g_k^{(1)}$ of the nonrecursive REF part are determined by Eq. (16) and coefficients $g_k^{(2)}$ of the recursive REF by Eqs. (18) and (19). In both cases, the weighting coefficients are $a = -1.9375$, $b_1 = -0.6875$, and $b_2 = -0.5625$. As we see, the transients being established in the REF of reconfigurable structure occur practically to the 5th sample leading to essential (up to tens of decibels) benefit in effectiveness of the clutter rejection in the transient mode compared to the REF of fixed structure.

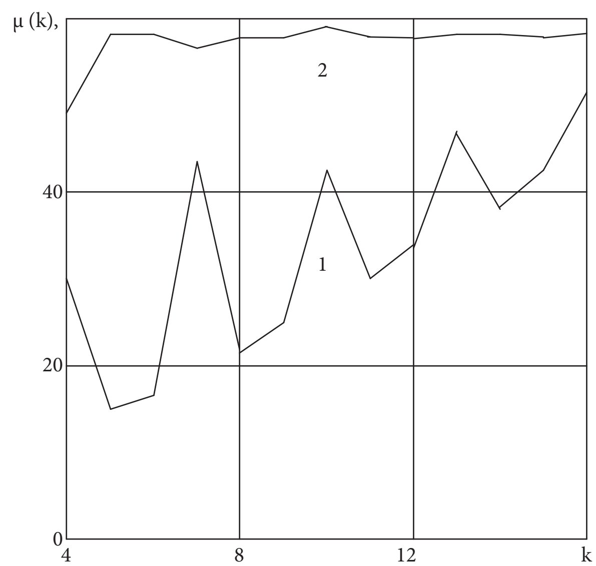

Figure 3. Effectiveness of clutter rejection in the transient mode.

Taking into account the problem of transient acceleration, recursive REFs allow wide utilization of required characteristic formation and its flexible control, which creates favorable conditions for appropriate RF adaptation under a priori ambiguity of the spectral-correlation clutter characteristics.

6. Conclusions

The improved recursive REF, which was synthesized by the state variable method, allows implementation of transient acceleration by means of its structure reconfiguration. The steady-state values of noncorrelated residuals of rejection of the nonrecursive REF part are passed to the REF output and in feedback, which practically eliminates the “ring” in feedbacks, which is caused by the interference samples’ fluctuations.

The block diagram of the improved REF is offered, in which the reconfiguration of the REF structure is implemented by switching of recursive couplings after transients in the nonrecursive REF part. The passage of interference rejection residuals into the REF output and into recursive couplings, which correspond to the steady-state mode of the nonrecursive REF part, essentially reduce the transient time for compensation of the clutter sample compensation.

The comparative analysis of the RF of the fixed structure shows that the RF structure reconfiguration by means of recursive connections switching significantly reduces the transient duration resulting in essential (up to tens of decibels) benefits in effectiveness of the clutter rejection in transients compared to the REF of fixed structure.

The solution of the transient acceleration problem of the recursive REF factually allows the use of wide opportunities of required feature formations of these REFs and their flexible control, which creates favorable conditions for appropriate REF adaptation under conditions of a priori ambiguity of clutter spectral-correlation characteristics.

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