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MATHEMATICAL MODELING OF MTI AND MTD EFFICIENCY IN SHIPBORNE RADAR SYSTEMS

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Abstract. In this article we investigate the effectiveness of Moving Target Indication (MTI) and Moving Target Detection (MTD) technologies in enhancing the performance of ship-based aerial surveillance radars under conditions influenced by hydrometeors. The aim is to develop a comprehensive methodology that assesses the quality of radar target detection while addressing the unique operational challenges faced by shipboard radars, such as limited antenna size and specific scanning requirements. The research employs a modified methodology that evaluates radar performance across various frequency ranges (3–25 cm). It includes a mathematical model to characterize target detection against hydrometeor backgrounds, incorporating factors like signal-to-noise ratios and Doppler frequency shifts. The study utilizes simulation data to analyze the performance of MTI and MTD processing techniques, focusing on their ability to suppress clutter caused by hydrometeors. Simulation results indicate that MTD processing generally outperforms MTI processing in most scenarios, particularly in the decimeter wave band. However, for wavelengths exceeding 10 cm, MTI processing may yield better results due to its effectiveness in managing clutter frequencies. The analysis reveals that the fluctuation caused by hydrometeor movement significantly impacts detection quality, with decimeter wave band radars demonstrating superior performance compared to centimeter wave band systems. In conclusion, the findings underscore the importance of selecting appropriate processing techniques based on operational conditions and radar specifications. Enhanced signal-to-noise ratios can be achieved through spatial and polarization selection methods, although limitations exist due to antenna size constraints on shipboard radars.

Keywords: MTI; MTD; radar station; passive clutter; clutter removal; hydrometeors; frequency selection; selection of moving targets; notch filter; Doppler filter..

Introduction

The operation of a surveillance radar station (radar) under the influence of natural clutter is a normal (typical) mode of the station operation. An increase in the energy potential has little effect on the probability of detecting targets located in the hydrometeor cloud, therefore, processing issues are the primary determinants in the design process of the station [1,2]. There are known methods of protection against passive clutter based on frequency, spatial and polarization selection. In literature [3], the effectiveness of various types of selection to protect ground-based surveillance radars from clutter caused by the presence of hydrometeors in the resolving volume is considered. A hypothetical number of air traffic control radars (ATC radars) operating in various wave ranges have been accepted as objects for analysis. The quality indicator characterizing the effectiveness of detecting a large passenger aircraft in a cloud of hydrometeors, expressed in terms of the coefficient of improvement of processing equipment and compared with the threshold (required) value, was numerically evaluated. Unlike ATC radars, shipboard radars have their own characteristics that should be taken into account during the research process, for example, as below:

1. The overall dimensions of the antenna aperture are strictly limited by the possibilities of placement on the carrier;
2. The scan rate, as well as the type of detected target, must be consistent with the typical tasks of ship stations. In addition to this, in the course of research, the research methodology given in [3] should be developed, namely: to revise the methodology for evaluating the effectiveness and range of operation of the studied radars [4], expand the range of quasi-optimal processing methods, expand the number of destabilizing factors under consideration, update the parameters of the emitted signals and the achievable characteristics of the receiver-detector. Taking into account the above features and technical aspects, the purpose of the article is a comprehensive assessment of the effectiveness of the use of MTI and MTD to reduce the influence of hydrometeors in ship-based aerial surveillance radars.

1. Problem analysis

Shipboard surveillance radars are designed to detect and track the air and above-water targets [5]. Consequently, these stations should be characterized by high information content in terms of the task of viewing space, namely, a circular viewing area and high resolution with unambiguity in range. Therefore, most of these radars belong to the class of coherent pulse stations (coherent pulse radars of long range). Taking into account a number of technical and economic reasons, a circular view of the space is provided by a mechanical method of scanning with a beam (rotation of the antenna web) [6]. Methods and techniques of scanning (as well as the station channel) in the vertical plane can be any, if the condition is met, that a packet of reflected pulses with a length sufficient for optimal processing is formed. Thus, the objects of research are coherent pulse radars with a sequential overview in the horizontal plane. Let's consider the most typical case – the detection of an aerodynamic target of medium size moving uniformly and rectilinearly in a cloud of hydrometeors. As the basis of the research methodology, we will take the methodology set out in [3], supplemented and modified as follows:

1. A hypothetical series of radars operating in the wavelength ranges of 3...25 cm is analyzed, which corresponds to the operating ranges of ship stations [7, 8].
2. The size of the antenna aperture for the entire range of radars under consideration is assumed to be constant [9]. This condition makes practical sense due to the actual shortage of space for the location of radar antennas on ships of modern construction and the corresponding restrictions on the size of the aperture [10, 11]. Moreover, the relevance of this problem is increasing due to the widespread introduction of stealth technologies in shipbuilding [12, 13].
3. We will assume that quasi-optimal signal processing at the video frequency takes place in the radars under consideration, based on MTI (Moving Target Indication) technology (fig. 1, a) and MTD (Moving Target Detection) technology (fig. 1, b). And that the MTI-processing is organized using the simplest notch filters based on delay line cancellers devices, and the MTD-processing is a set of Doppler filters with a finite impulse response (i.e. FIR filters) [5] synthesized using FFT [14]. The presence of a limiter and other nonlinearities in the path is neglected [15].

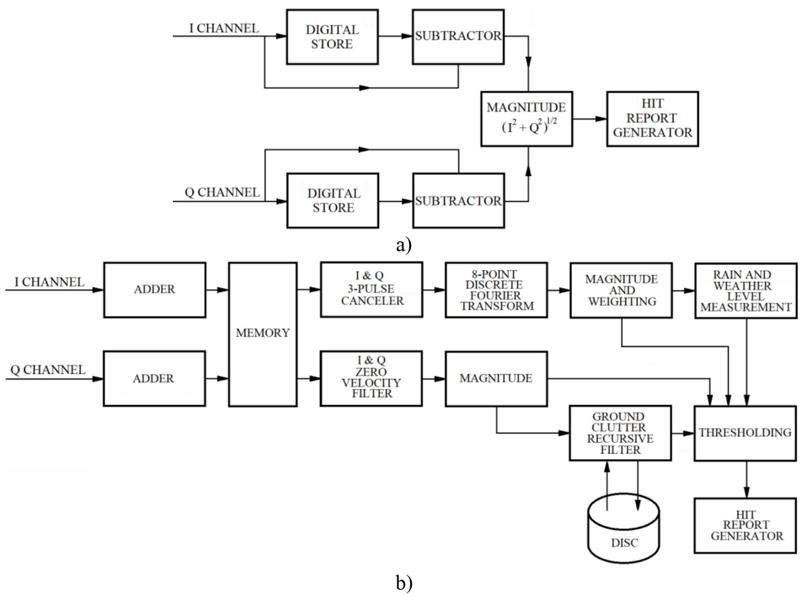

Figure 1. Block diagram of typical digital MTI (a) and MTD (b) signal processor

4. We will evaluate the quality of processing taking into account a number of destabilizing factors that cause both the expansion of the spectrum of external clutter and the appearance of additional ones. The filtration quality will be evaluated numerically in the spectral region. The extremely laconic formula expressions used in [3] for the improvement coefficients obtained by D. Barton [16] are unacceptable in our case due to a noticeable error. Since a linear approximation of the trigonometric function was used in the process of outputting these expressions [17], then these expressions are valid for the case when the width of the clutter spectrum is negligibly less than $\frac{2F}{\pi}$ (where F is a pulse repetition frequency (PRF)), which is not always the case.

5. To assess the quality of detection, we will use a differential estimation method in the field of Doppler frequencies. The classical integral method of quality assessment, expressed in terms of a single coefficient of improvement, has little practical significance, since filters (in particular, notch filters) have a rugged frequency response (up to zeros in the areas of notch) [18]. Therefore, in order to update the quality indicator for comparative assessments, it is necessary to abandon the single (integral) value of the quality indicator, and the quality assessment itself should be carried out separately for each conditionally accepted sub-band of Doppler frequencies.

2. Mathematical model

Let's consider a mathematical model that characterizes the fact of target detection. A condition for detecting a target against the background of hydrometeors for the *i*-th sub-band of the Doppler shift of the signal (where $i = 0, 1, \ldots, (N-1)$, N is the number of sub-bands) at the output of the phase detector we will consider:

$$\overline{I_i} > \overline{K_r},$$

where $\overline{I_i}$ is the signal-to-noise ratio improvement coefficient for the i-th sub-band; $\overline{K_r} = (\gamma_\Sigma \overline{\sigma_h}/\overline{\sigma})$ is the required signal-to-noise ratio for target detection against hydrometeors; γ_Σ is the distinctness coefficient; $\overline{\sigma_h}$ is the average radar cross-section (RCS) of hydrometeors in the radar resolution volume; $\overline{\sigma}$ is the target RCS.

The values of $\overline{I_i}$ and $\overline{K_r}$ are estimated for a target at distance D in moderate rain conditions (with precipitation rate $w = 10$ mm/h and wind speed $\sigma_v = 4$ m/s, following [3]). First, we calculate the reflectivity factor Z and specific RCS of hydrometeors $\overline{\sigma_{00}}$ [19]:

$$Z = 200 w^{1{,}6} \quad (\text{mm}^6/\text{m}^3),$$

$$\overline{\sigma_{00}} = \frac{0{,}93\pi^5}{\lambda^4} Z \quad (\text{mm}^2/\text{m}^3),$$

where λ is the radar wavelength in millimeters.

The average RCS of hydrometeors in the resolution volume is:

$$\overline{\sigma_h} = \overline{\sigma_{00}} \frac{c\tau}{2B} \frac{\pi D^2}{4} \theta_1 \theta_2,$$

where τ is the pulse width, B is the pulse compression ratio, and θ_1, θ_2 are the horizontal and vertical beamwidths respectively. For a fixed aperture size D d_1xd_2 the width of radiation pattern can be calculated according to the expressions: $\theta_1 = 1{,}25\lambda/d_1$, $\theta_2 = 1{,}25\lambda/d_2$, where d_1 and d_2 are maximum aperture sizes in horizontal and vertical planes (measured in meters). We will evaluate the limiting value of the spectral processing improvement coefficient $\overline{K_{SCi}}$. The width of the clutter spectrum at the input is determined by the fluctuation of the reflecting surface of meteorological formations, the modulation of signals when viewing space with a beam and internal instabilities of the station. In this case, the energy spectrum of passive clutter $S_c(f)$ near the zero spectral line, can be approximated by a bell-shaped (Gaussian) function of the following type [16, 19]:

$$S_c(f) = S_{c0} \exp\left(-\frac{f^2}{2(\sigma_c^2 + \sigma_a^2 + \Delta F_{sys}^2 + \Delta F_{mov}^2)}\right), for -\frac{F}{2} \leqslant f \leqslant \frac{F}{2},$$

where S_{c0} is the power density at zero frequency (normalizing coefficient) of the energy spectrum; f is frequency; $\sigma_c = \frac{\Omega_A}{3{,}78\theta_1}$ is the width of the spectrum of signals reflected from meteorological formations; is the magnitude of the spectrum expansion caused by the rotation of the antenna with angular velocity Ω_A; ΔF_{sys} is absolute value of frequency instability of radar receiving and transmitting devices; $\Delta F_{mov} = \frac{v_{mov}}{\lambda\sqrt{2}\theta_1}$ – characterizes the maximum expansion of the spectrum (i.e. for the traverse directions of the radiation pattern) caused by the movement of the radar carrier (the phase center of the antenna) at a speed of v_{mov}. Then to find the improvement coefficient $\overline{K_{SCi}}$ of processing devices, it's necessary to find the coefficient of passive clutter suppression k_C and coefficient of the power gain the of the required signal $\overline{K_i}$ for i-th frequency sub-band:

$$k_C = \frac{\int\limits_{-\frac{F}{2}}^{\frac{F}{2}} S_C(f)df}{\int\limits_{-\frac{F}{2}}^{\frac{F}{2}} S_C(f)K^2(f)df}, \tag{1}$$

$$\overline{K_i} = \frac{\int\limits_{f_i}^{f_i+\Delta f} S_S(f)K^2(f)df}{\int\limits_{f_i}^{f_i+\Delta f} S_S(f)df}, \tag{2}$$

where $i = 0, 1, ...(N-1)$; $K(f)$ is a frequency response of the processing device; f_i and Δf – the initial frequency and width of the i-th sub-band: $f_i = f_0 + i * \Delta f$, $f_0 = -\frac{F}{2}$, $\delta f = \frac{F}{N}$; $S_S(f)$ – spectral density of the radial velocity distribution of the target. Usually, the value of the Doppler shift of the signal frequency is assumed to be equally probable, then $S_S(f) = N_0$, where N_0 is spectral density of a white noise. Frequency response of processing devices $K(f)$, when using MTI processing based on the delay line cancellers of the *n*-th multiplicity, corresponds to the expression [20]:

$$K_{MTI}(f) = 2^n \left(\left|\sin\left(\frac{\pi f}{F}\right)\right|\right)^n.$$

For the case of MTD processing [21], there is a set of filters, the frequency characteristics of which overlap the frequency band of the signals, which allows not only to separate the signals by Doppler frequency increment, but also to improve the ratio of the useful signal to noise (due to the narrowness of the Doppler filters). Frequency response of k-th filter is defined by the following expression [2]:

$$K_{DFk}(f) = \left|\frac{\sin\left(N_{DF}\pi\left(\frac{f}{F} - \frac{k}{N_{DF}}\right)\right)}{\sin\left(\pi\left(\frac{f}{F} - \frac{k}{N_{DF}}\right)\right)}\right|, \tag{3}$$

where $k = 0, 1, ...(N_{DF}-1)$. According to 3, central (k=0) the Doppler filter corresponds to the zero Doppler offset of the signals, which may make practical sense, for example, when forming a clutter map, or for detecting low-speed targets [22]. The issues of building a radar detector, as well as the selection of low-speed and sedentary targets [23] are not considered here. Given that it is advisable to choose the value equal to an integer power of 2 (and therefore even), it makes sense to arrange the passbands of the filter set symmetrically relative to the zero Doppler offset point (point of f=0). In addition to this, in order to preserve the generality of research, we give the expression 3 to the above-accepted research frequency band:

$$K_{DFk}(f) = \left| \frac{\sin\left(N_{DF}\pi\left(\frac{2f-\frac{F}{N_{DF}}}{2F} + \frac{1}{2} - \frac{k}{N_{DF}}\right)\right)}{\sin\left(\pi\left(\frac{2f-\frac{F}{N_{DF}}}{2F} + \frac{1}{2} - \frac{k}{N_{DF}}\right)\right)} \right| .$$

Frequency response $K_{DFk}(f)$ and $K_{MTI}(f)$, and also the energy spectrum of passive clutter $S_C(f)$ conventionally shown on fig. 2 Directly, the value of the improvement coefficient in spectral signal processing for the i-th sub-band is determined using 1 and 2 according to the following expression: The value of the improvement coefficient, taking into account

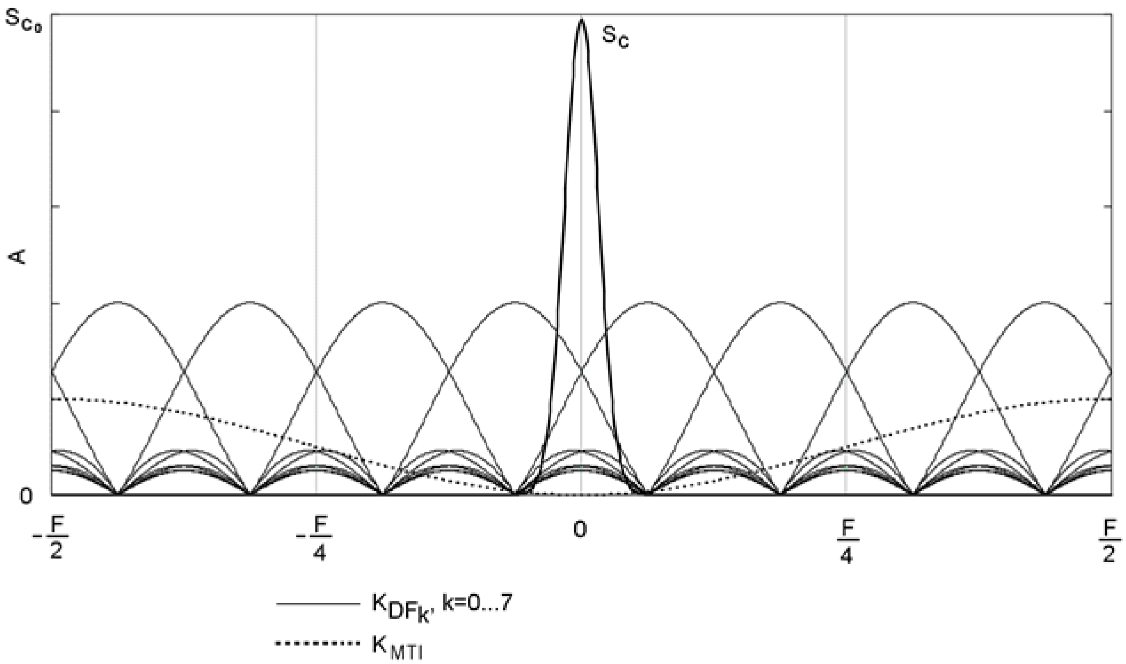

Figure 2. Frequency response and the energy spectrum of passive clutter

all limiting factors, is determined by the expression:

$$\overline{I_i} = \left(\frac{1}{\overline{K_{SCi}}} + \sum_{j=1}^{5} \frac{1}{I_j} \right)^{-1} .$$

where I_j stands for limit values of the improvement coefficient limited by various instability factors and features of the processing equipment. The frequency instability of the receiving and transmitting equipment (frequency and phase of the transmitter, local and coherent heterodynes) was taken into account above by the value ΔF_{sys} (see expression for $S_c(f)$). Other destabilizing factors are expressed in terms of a variety of values I_j, namely:

1. *Fluctuations in the time position of probing pulses* (time jitter) of Δt value leads to a deterioration in the suppression of the leading and trailing edges of the pulse and the corresponding limitation for improvement factor: $I_1 = \frac{\tau}{2B(\Delta t)^2}$ or $I_1 = \frac{\tau}{2B^2(\Delta t)^2}$ – for pulse compression with linear frequency modulation and pulse compression with phase modulation signals respectively.

2. *Fluctuations in pulse duration* Δt lead to residuals that make up half of the remainder of the time jitter with an equal fluctuation value. Thus, to calculate the corresponding limit on improvement factor I_2 one can use the expression for I_1, taking into account that $\Delta t = \frac{\Delta\tau}{\sqrt{2}}$.

3. *The amplitude* jitter causes the improvement factor to be limited to the level of: $I_3 = (\frac{\Delta A}{A})^{-2}$, where $\frac{\Delta A}{A}$ is a relative change in amplitude as a result of fluctuations.

4. *Quantization noise*, caused by the limited size of the ADC bit depth N. For the case of two independently fluctuating quadrature channels I and Q (see fig. 1) noise leads to the following value of the maximum improvement factor: $I_5 = 0{,}75(2^N - -1)^2$.

Influence of the pulse repetition period wobble (respectively, value of F), what leads to additional expansion of the spectrum of clutter, during scanning, and random (uncorrelated) movements of hydrometeors are not considered here. The quality of the detector and the detection statistics are taken into account through the value of γ_Σ.

3. Modelling Results

We assume that a target with the radar cross-section of $\overline{\sigma} = 10\ m^2$ value is located at a distance of $D = 50\ km$ from radar in a cloud of hydrometeors with the above parameters corresponding to medium-intensity rain conditions. Let's take the following data values of the station parameters formed on the basis of [7, 16]: the size of the aperture of the radar antenna d_1xd_2=2x2m^2, relative frequency instability $\frac{\Delta F_{sys}}{f_R}$=$10^{-8}$ (where f_R is carrier frequency of the signal), the coefficient of distinguishability γ_Σ=8. The target is probed by a coherent sequence of complex (B=10) pulse signals with a duration of τ=1 µs, with repetition rates of F=2 kHz. For a well-designed system, we can confidently assume that the following expression will be valid for any values of i and j: $I_j << \overline{K_{SC_i}}$ [24,25]. Antenna rotation speed $\Omega_A = 12\ min^{-1}$. Vehicle speed (we neglect rolling) is $v_{mov} = 30\ kn$ [8]. When considering delay line cancellers (for MTI processing), we will limit ourselves to devices with a multiplicity of *n* not higher than 2. The use of a higher multiplicity leads to a significant narrowing of the frequency response of a filter and the deterioration in the speed characteristics. For MTD processing, we assume the dimension of Doppler filtering to be equal to the number of sub-bands of frequency analysis: N_{DF}=8, N=8. In this case, the zero value of the Doppler frequency offset is located on the border of the sub-bands with numbers of i equal to 3 and 4. The results of mathematical modeling (value of $\frac{\overline{I_i}}{K_r}$, calculated in dB, rounded to integer) for various carrier frequencies and processing methods are summarized in Tables 1 (for MTI processing) and 2 (for MTD processing). Positive values (in dB) characterize the possibility of detecting a target against the background of hydrometeors. Values greater than +10 dB and less than -10 dB are replaced by the signs "+" and "-" respectively.

Table 1. Simulation results for MTI processing

λ, cm	n	Sub-band number, i							
		0	1	2	3	4	5	6	7
3	1	-5	-7	-	-	-	-	-7	-5
	2	-1	-4	-	-	-	-	-4	-1
5	1	2	1	-2	-	-	-2	1	2
	2	+	7	1	-	-	1	7	+
10	1	+	+	+	1	1	+	+	+
	2	+	+	+	4	4	+	+	+
25	1	+	+	+	+	+	+	+	+
	2	+	+	+	+	+	+	+	+

Table 2. Simulation results for MTD processing

λ, cm	Sub-band number, $i (i = k)$							
	0	1	2	3	4	5	6	7
3	4	-1	-6	-	-	-6	-1	4
5	+	8	1	-6	-6	1	8	+
10	+	+	+	-1	-1	+	+	+
25	+	+	+	7	7	+	+	+

The analysis of the simulation results showed that the use of MTD processing, in comparison with MTI processing, in most of the considered cases gives the best result. There will be an exception for the case when the wavelength is more than 10 cm. In this case, the bandwidth of the clutter frequencies is significantly narrowed and ensuring a high level of signal suppression with a Doppler shift close to zero comes out on top in terms of efficiency (what is better provided by the equipment of delay line cancellers). Additionally, it is worth considering the possibility of supplementing the MTI notch filter with a set of MTD Doppler filters. Analysis of the simulation results indicates that this construction for the above conditions makes sense in terms of energy (in terms of increasing the signal-clutter ratio) only in the UHF frequency range (λ=10…25 cm).

Conclusion

The article presents a comprehensive methodology for assessing the quality of target detection, taking into account the energy and spectral characteristics of passive clutter, as well as the characteristics of radiation pattern formation, processing equipment, signal formation and radar survey. Of all the considered factors that cause the expansion of the clutter spectrum, the fluctuation caused by the movement of hydrometeors has the greatest influence. As the result of above, there is a strong dependence of the quality of frequency selection on the wavelength. Decimeter wave band radars offer better detection quality in hydrometeor conditions compared to centimeter-range stations. However, they do not always possess satisfactory characteristics for resolving targets and providing a smaller viewing area, which limits their potential use for detecting a wide range of aerial targets. To improve the signal-to-noise ratio at the input of the processing device, it is necessary to additionally use spatial and polarization selection [26], as well as use signals with a larger base. It is worth noting that the possibilities of spatial selection for shipboard radars are limited by the permissible size of the antenna aperture. And when using polarization selection (using, for example, circular polarization of radiation instead of linear), simultaneously with the suppression of the signal from raindrops by 25 dB, the level of the useful signal decreases by 6-8 dB [8, 16]. Overall, the presented article eliminates inaccuracies, clarifies and complements the conclusions of the scientific work [27].

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МАТЕМАТИЧЕСКОЕ МОДЕЛИРОВАНИЕ ЭФФЕКТИВНОСТИ MTI И MTD-ОБРАБОТКИ КОРАБЕЛЬНЫХ РАДИОЛОКАЦИОННЫХ СИСТЕМ

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Аннотация. В настоящем исследовании изучается эффективность методик индикации движущихся целей (MTI) и обнаружения движущихся целей (MTD) для повышения эффективности работы корабельных радаров воздушного наблюдения в условиях, зависящих от гидрометеорологической обстановки. Цель заключается в разработке комплексной методологии, позволяющей оценивать качество обнаружения целей с помощью радиолокатора и одновременно учитывать уникальные эксплуатационные проблемы, с которыми сталкиваются судовые радары, такие как ограниченный размер антенны и особые требования к сканированию. В исследовании используется модифицированная методология, которая оценивает характеристики радара в различных частотных диапазонах (3–25 см). Она включает математическую модель для характеристики обнаружения цели на фоне гидрометеорологических условий, учитывающую такие факторы, как отношение сигнал/шум и доплеровские сдвиги частоты. В исследовании используются данные моделирования для анализа эффективности методов обработки данных MTI и MTD, с акцентом на их способность устранять помехи, вызванные гидрометеорологическими факторами. Результаты моделирования показывают, что обработка MTD в целом превосходит обработку MTI в большинстве сценариев, особенно в дециметровом диапазоне волн. Однако для длин волн, превышающих 10 см, обработка MTI может дать лучшие результаты благодаря своей эффективности в управлении частотами помех. Анализ показывает, что колебания, вызванные перемещением гидрометеора, существенно влияют на качество обнаружения, при этом радары дециметрового диапазона волн демонстрируют более высокую производительность по сравнению с системами сантиметрового диапазона волн. Полученные данные подчеркивают важность выбора подходящих методов обработки, основанных на условиях эксплуатации и технических характеристиках радара. Улучшения отношения сигнал/шум можно достичь с помощью методов пространственного и поляризационного выбора, хотя существуют ограничения, связанные с размерами антенны судовых радаров.

Ключевые слова: MTI; MTD; радар; пассивная помеха; устранение помех; гидрометеоры; выбор частоты; выбор движущихся целей; режекторный фильтр; доплеровский фильтр .

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