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Overview of radar detection methods for low altitude targets in marine environments

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Abstract: In this paper, a comprehensive overview of radar detection methods for low-altitude targets in maritime environments is presented, focusing on the challenges posed by sea clutter and multipath scattering. The performance of the radar detection methods under sea clutter, multipath, and combined conditions is categorized and summarized, and future research directions are outlined to enhance radar detection performance for low–altitude targets in maritime environments.

Keywords: radar, sea clutter, multipath scattering, detection, low altitude target.

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1. Introduction

When radars are used to detect low-altitude targets over sea surface, issues stemming from sea clutter and multipath scattering interference may occur in radar systems. Intensive sea clutter can impact the detection of target echoes, increasing the difficulty of radar target detection. Moreover, it can lead to a higher occurrence of false alarms, complicating the identification of real targets. Furthermore, echoes from multipath scattering may attenuate the radar target echoes, which further complicates radar target detection.

To enhance the performance of radar systems in detecting low-altitude targets over sea surface, the effects of sea clutter and multipath scattering must be mitigated. Consequently, researchers worldwide have explored radar target detection methods tailored to various scenarios, including sea clutter, multipath scattering, and combined conditions. In this paper, radar target detection methods used in each of these scenarios are synthesized and categorized. Under sea clutter conditions, radar detection methods include clutter suppression methods, target signal enhancement methods, and radar detector design methods. Under multipath scattering conditions, radar detection methods include temporal diversity, spatial diversity, frequency diversity, and polarization diversity methods. For scenarios involving both sea clutter and multipath scattering, the radar detection methods are summarized according to the signal processing techniques and systemic innovation. Finally, future research directions for radar detection involving low-altitude targets over sea surface are proposed.

2. Research on radar detection methods in scenarios with sea clutter

Efforts to improve radar target detection performance in the presence of sea clutter have considered three main aspects: sea clutter suppression, target signal enhancement, and detector design. These aspects are elaborated on in the following subsections.

2.1 Sea clutter suppression methods

The effective suppression of sea clutter can enhance the radar signal-to-noise ratio (SNR), consequently enhancing the radar target detection performance. Sea clutter suppression methods include many methods in the time domain, frequency domain, space domain, polarization domain and joint domain.

In the time domain, the main idea of sea clutter suppression methods is to weight the radar signals received at different moments to mitigate the influence of sea clutter. Typical time-domain clutter suppression methods include moving target indication (MTI) and clutter map [1]. In addition to the linear weighting of the received radar signals, the nonlinear weighting of the received radar signals based on multiple observations has been explored to suppress the influence of sea clutter [2,3]. For instance, researchers at the University of Calgary employed a recursive nonlinear weighting strategy to predict and suppress the influence of sea clutter [3]. Additionally, signal averaging or position consistency checks

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across multiple observations can effectively be performed to identify false alarms caused by sea clutter [4,5].

The sea clutter suppression methods in the frequency domain are similar to those in the time domain. The main idea of these methods is to weight the multiple observed radar signals and filter the signals in the frequency domain to suppress the influence of sea clutter. The weighting is based on the sea clutter spectrum characteristics. Adaptive finite impulse-response (FIR) or infinite impulse-response (IIR) filters are commonly used for frequency-domain filtering [6]. At the University of Electronic Science and Technology of China, an adaptive weighting method for radar signal spectra was proposed to suppress skywave over-the-horizon radar (OTHR) sea clutter based on prior information and theoretical ionospheric perturbation models [7]. Moreover, sea clutter can be suppressed by zeroing spectral signals at estimated clutter spectral positions and widths [8].

The fundamental principle underlying sea clutter suppression in the spatial domain involves leveraging the similarity among adjacent distance units of the sea clutter and estimating the sea clutter in the tested range cell according to the sea clutter in the reference range cells, ultimately suppressing the influence of sea clutter. Notably, techniques such as the singular value decomposition (SVD) method [9], orthogonal projection method [10], and oblique projection method [11] have been employed to mitigate the influence of sea clutter. For instance, researchers at the University of Delaware, United States, used the spatial correlations inherent in sea clutter and applied the SVD method to reduce the sea clutter by approximately 15 dB in OTHR scenarios [9]. A sea clutter suppression technique based on orthogonal projection was introduced, reducing the sea clutter by more than 5 dB [10], as graphically illustrated in Fig. 1.

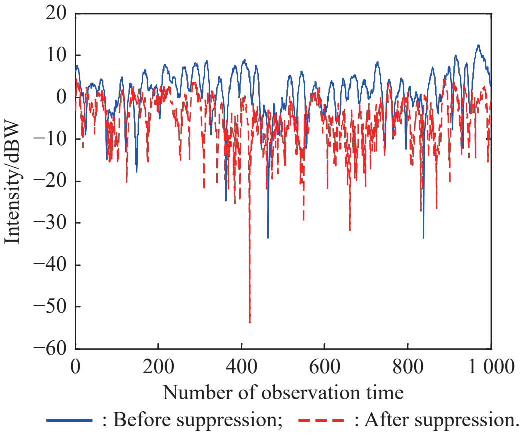
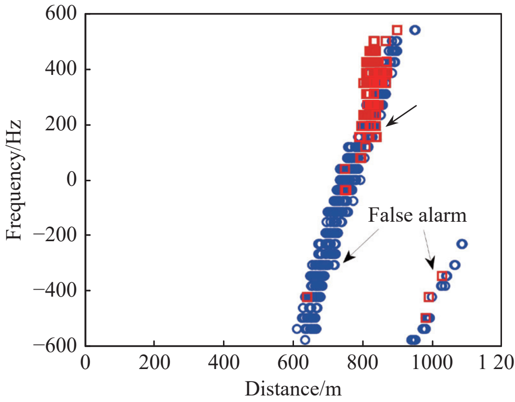
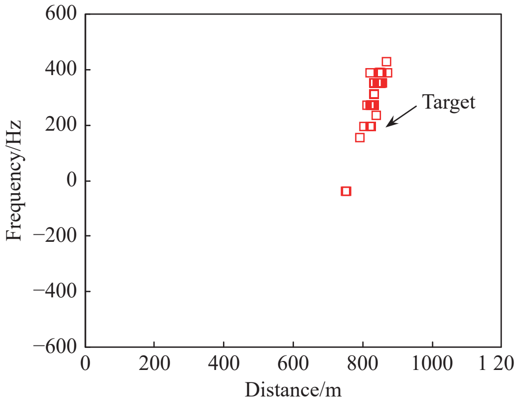


Fig. 1 Sea clutter suppression results based on orthogonal projections

For low-speed targets, the target signal is submerged by fierce sea clutter in both the temporal and spectral domains. In this case, polarization filtering methods can be applied for sea clutter suppression. Polarization filtering methods utilize the polarization characteristics differences between sea clutter and target echoes. By assigning weights to signals across various polarization channels, these methods effectively suppress the sea clutter [12,13]. In this context, researchers at Harbin Institute of Technology introduced a multi-notch polarization filter [14] and a slant-projection polarization filter [15], successfully achieving sea clutter suppression for high-frequency ground-wave radar. We also proposed a polarization matching method for eliminating false alarms caused by sea clutter, reducing radar false alarms by 1 to 2 orders of magnitude [16], as depicted in Fig. 2. The circles and squares represent the result in the horizontal-horizontal (HH) and horizontal-vertical (HV) channels, respectively.



(a) Radar detection results



(b) Radar detection results after polarization matching

Fig. 2 Effect of our proposed polarization matching method for radar sea clutter false alarm rejection

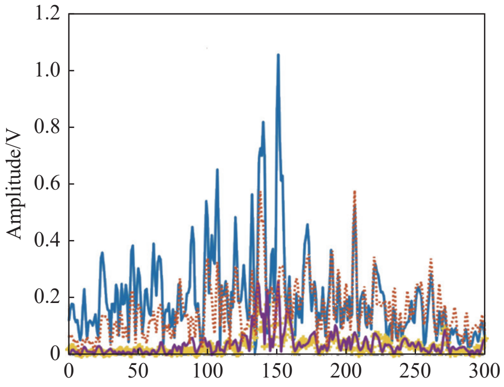
Similarly, researchers at the University of Helsinki, Finland, considered the differences in co-polarization channel correlation coefficients, differential reflectivity, and differential phase between meteorological targets and sea clutter, and their approach involves using polarization spectral decomposition to identify sea clutter, which are subsequently suppressed through polarization spectral filtering [12]. To effectively suppress sea clutter, methods that focus on only one domain often exhibit limited effects. To address this issue, scholars have proposed various multiple-domain joint filtering methods, such as space-time joint filtering [17], time-frequency joint filtering [18–20], and polarization-space-time domain joint filtering [21,22]. Space time adaptive processing (STAP), for example, is effective in suppressing airborne radar sea clutter. The sea clutter suppression performance is determined by the estimation accuracy of the clutter covariance matrix. For time-frequency joint filtering, techniques such as time-frequency analysis [18], short-time Fourier transform (STFT) [19], and wavelet transform [20] have good sea clutter suppression performance. Similarly, for polarization-space-time joint filtering, US researchers have introduced methods that combine polarization-space-time domain information [21] and polarization filtering with STAP techniques [22]. These methods offer varying degrees of improvement in sea clutter suppression compared to space-time joint processing approaches but with increased engineering complexity.

In summary, sea clutter suppression methods primarily utilize the distinct characteristics of sea clutter and target echoes in different domains, such as the time, frequency, space, and polarization domains, which is accomplished through weighted signal processing within one or multiple domains. Previous studies have proposed numerous single- and multiple-domain joint sea clutter suppression methods. These methods address distinct scenarios and exhibit varying sea clutter suppression efficacy. Considering algorithmic feasibility, the development of effective sea clutter suppression methods merits further exploration. Moreover, the comprehensive exploitation of multiple domain information, including temporal, spectral, spatial, and polarization information, for deep sea clutter suppression to enable the detection of weak sea surface target echoes merits further investigation.

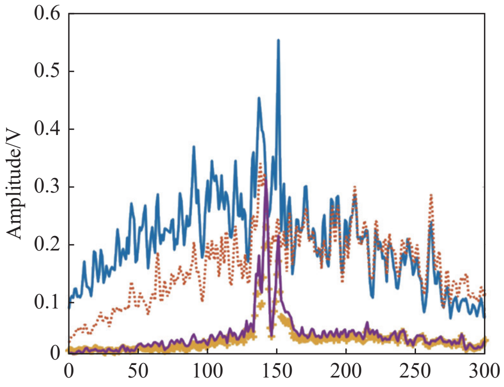
2.2 Target echo enhancement methods

In addition to sea clutter suppression, enhancing the target echo signal can increase the SNR, thereby improving the radar target detection performance. Target echo enhancement methods mainly weight multiple observation signals to increase the SNR based on the characteristics of the target echo signal in the temporal, spatial, polarization, and time-frequency domains.

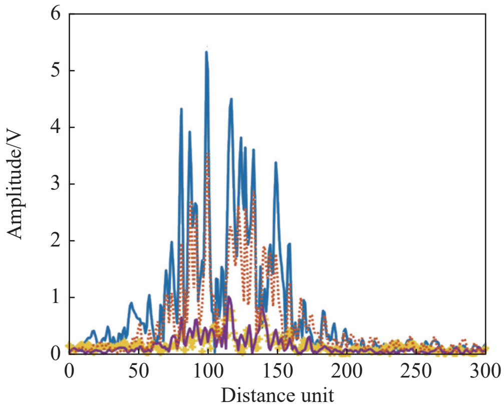
In the time domain, several classic methods for enhancing target signals include matched filtering, coherent integration, and noncoherent integration techniques. Coherent integration is realized by direct summing multiple complex radar signals or obtaining the fast Fourier transform (FFT) of these signals [23]. The former approach is suitable for enhancing the signals of stationary and low-speed moving targets. The latter is usually employed for enhancing the signals of fast-moving targets. Noncoherent integration techniques are implemented by summing the power of the received radar signals. These methods can also improve the radar SNR, but the improvement is less than that achieved with coherent integration. Fig. 3 shows the target echo enhancement effects of noncoherent integration and coherent integration approaches, where the target is a boat located between 61 and 181 distance units, VH means vertical-horizontal, and VV means vertical-vertical. Additionally, averaging the multiple received radar signals or selecting the largest values from multiple received signals can enhance the SNR of the target signal [4].



(a) Amplitude of radar monopulse echoes



(b) Amplitude of radar echoes after noncoherent integration



(c) Amplitude of radar echoes after coherent integration

—— : HH; ✦ : HV; —— : VH; ······ : VV.

Fig. 3 Amplitude of echoes before and after coherent/noncoherent integration (polarimetric radar target detection-based methods for sea clutter)

In the spatial domain, array antenna and array adaptive processing methods are commonly used to enhance the target signal, where the signals received by multiple array elements are weighted to coherently integrate the spatially distributed received signals. Scholars have proposed several array adaptive weighting methods [24].

In the polarization domain, the correlation among the signals collected in multiple polarization channels is primarily utilized for target signal enhancement. These methods mainly weight multiple signals in different polarization channels to enhance the target signal according to various criteria. Typical polarization-based target signal enhancement methods include polarization matched filtering [13], polarization whitening filtering [25], polarization span [26], and polarization power synthesis [27]. Additionally, target echo signals can be effectively enhanced by designing radar transmitting and receiving polarization modes based on target polarization scattering characteristics [28].

In addition to enhancing target echoes with signal processing techniques applied in individual domains, target echoes can be enhanced with joint domain processing approaches. The Radon transform, fractional-order Fourier transform (FrFT), STFT, and other methods are commonly used for target echo enhancement in the time-frequency domain [29]. Scholars at the Beijing Institute of Technology proposed an adaptive Radon-Fourier transform method by integrating the Radon transform and Fourier transform techniques, which accumulates target echo energy in the time-frequency map while suppressing clutter [30].

In summary, the rational weighting of the multiple received radar signals can lead to target echo enhancement. These signals may be received signals with different times, array elements, polarization channels, or different signals in a certain domain. The determination of the weighting coefficients is crucial and depends on the characteristics of the target signal. Sea clutter suppression methods can significantly improve the SNR, while the SNR improvement with target signal enhancement methods is usually limited in theory. Target echo enhancement and sea clutter suppression are not mutually exclusive. The two types of methods can be combined effectively to further improve the radar SNR.

2.3 Radar detector design

After clutter suppression or target echo enhancement, the output signal is processed further to obtain test statistics for radar detection. Different processing methods applied to the output signal will yield different test statistics, leading to varied detection performance. Thus, to achieve better detection performance, the test statistic should be designed according to the characteristics of the output signal after clutter suppression or target echo enhancement.

Radar detector designs can be broadly classified into two categories: detector designs based on classic statistical theory [31,32] and detector designs based on signal characteristics [33].

Radar detector design methods based on classic statistical theory primarily consider two scenarios concerning the sea clutter amplitude distribution: those conforming to Gaussian or non-Gaussian distributions. Within each scenario, further differentiation is made between situations in which the sea clutter and target parameters are known or unknown. Consequently, detector designs can be tailored to different scenarios and conditions. A summary of the pertinent research is depicted in Fig. 4. In the case of sea clutter following Gaussian distributions, when the covariance matrices of both the target and sea clutter are known, the test statistics and statistical distributions obtained from the likelihood ratio test can be analytically expressed. This leads to optimal radar target detection performance [31]. In practice, it is often desired for the radar to have a low and constant false alarm rate. Achieving a constant false alarm rate (CFAR) requires the radar detection threshold to adapt to changes in the power of the sea clutter, which is challenging in practical applications. Scholars have thus proposed adaptive threshold detectors to address this issue [34]. Subsequently, considering the temporal and spatial variations in sea clutter, scholars have introduced various detectors, including the cell-averaged CFAR (CA-CFAR) detector and its improved versions [35,36]. When the covariance matrix of either the sea clutter or target signal is unknown, generalized likelihood ratio tests (GLRT) or Bayesian tests can be used to make decisions [31]. The performance of the GLRT method is influenced by the amount of observed data and the accuracy of the estimated unknown parameters. On the other hand, the performance of the Bayesian test method relies mainly on the accuracy of prior information. Scholars in Wuhan Electronic Information Institute conducted in-depth analysis and summarized the multi-channel adaptive signal detection basic theory and methods [32].

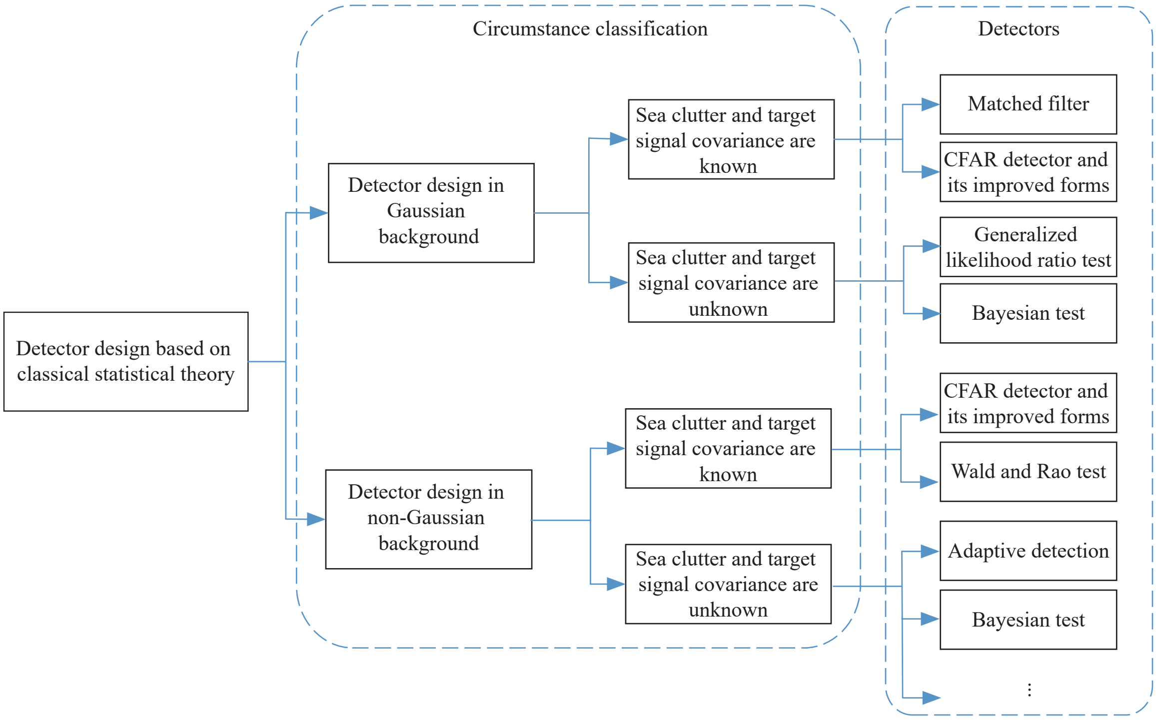


Fig. 4 Detector design based on classic statistical theory

As the radar range resolution improves, sea clutter amplitudes often follow non-Gaussian distributions. Consequently, the performance of detectors designed under Gaussian sea clutter backgrounds degrades. To address this issue, scholars have developed radar detectors for non-Gaussian sea clutter backgrounds according to various distributions [37–51]. Among these, detectors designed for composite Gaussian distribution clutter backgrounds, such as the Weibull distribution [37–39], K distribution [40–42], CG distribution [43–49], and CG-GIG distribution [50,51], have been extensively studied. However, deriving the theoretical detection performance of these detectors is complex, and analytical expressions can rarely be obtained.

In the case of non-Gaussian sea clutter, when either the sea clutter or target covariance matrix is known, scholars have introduced the Wald test, the Rao test, and their improved detectors to address the challenge of determining the test statistic and deriving the statistical distribution [52–55]. These detectors are comparatively straightforward to implement and exhibit minor performance degradation compared to optimal detectors. When the sea clutter and target covariance matrices are unknown, auxiliary data are needed to adaptively estimate the sea clutter and target covariance matrices. Then, the estimated covariance matrices are used to obtain quasi-optimal detection.

The performance of radar detection methods based on classic statistical theory has an upper limit. To further improve the detection performance, feature-based radar detector design methods have been investigated in the past decade. The fundamental principle of these methods is to identify characteristic differences in the received radar signals when the target signal is present or absent. These differences are subsequently used to make test decisions. Research in this area has progressed from initial single-domain single-feature detector designs to encompass single-domain multiple-feature and multiple-domain multiple-feature detector designs. The features employed by existing detectors are summarized in Table 1.

Table 1 Various features used for detector designs

Signal domain	Signal feature
Time domain	Amplitude distribution, Relative mean amplitude [56], Information entropy [57], Hurst index [57]
Frequency domain	Relative Doppler peak height [56], Relative Doppler entropy [56], Spectral peak-to-mean ratio [57], Frequency domain Hurst index [58], Relative Doppler coefficient of variation [59]
Polarization domain	Relative volume scattering power [60], Relative dihedral scattering power scattering mechanism [60], Relative surface scattering power [60], Polarization entropy [61], Polarization anisotropy [61]
Transform domain	Fractal features [62−66], Chaotic features [67], Fractional order Fourier transform features [68−71]
Time frequency domain	Micro-Doppler [72,73], Time frequency accumulation [74], Number of connected regions in time frequency biplot [74], Maximum connected region size [74]

Single-feature-based detection have similar principles to detection methods based on classic statistical theory that involve selecting a specific feature as a test statistic and then comparing this statistic with a detection threshold. Detection methods based on classic statistical theory mainly use the magnitude distribution characteristic.

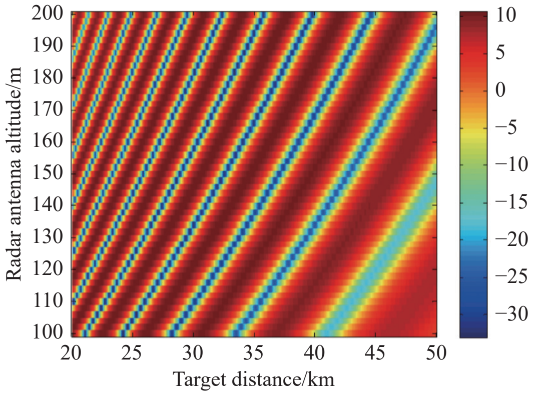
Detection methods based on multi-feature discrimination primarily leverage multiple features within a single domain or features across multiple domains to collaboratively construct a detector [56,75]. The main principle of the multiple-feature-based detection method involves identifying multiple features with distinct differences, with the challenge of determining the detection threshold to maintain a CFAR. Three main approaches exist for identifying feature differences: (i) analyzing various radar echo features with and without target signals according to measured data [56,75]; (ii) employing deep learning techniques based on abundant measured data [76−79]; (iii) analyzing the features of radar received signals with and without target signals with theoretical modeling approaches [67]. The determination of the detection threshold requires a case-specific approach. For one- or two-dimensional feature dimensions, theoretical derivations suffice. For three-dimensional feature dimensions, a convex packet learning algorithm is applicable [56,60]. In cases where the feature dimension is equal to or greater than three, support vector machines (SVM) [57], decision tree algorithms [58], isolation forest [59] for dimensionality reduction, or deep learning [76−79] techniques can be employed to calculate the detection threshold.

The performance of detectors designed based on multiple-feature approaches can exceed the detection performance limits set by the Neyman-Pearson (NP) criterion. However, this necessitates ample training data and comprehensive scene coverage. For untrained and unfamiliar scenarios, the detection performance can significantly decline. Furthermore, the integration of multidimensional features such as polarization, space, time, and frequency features is a potential direction for the future advancement of feature-based detector designs. And How to apply feature-based detectors in engineering still needs to be further explored.

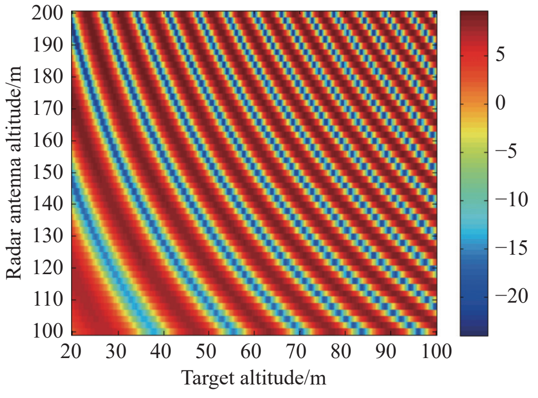
In conclusion, the core concepts underlying classic statistical theory-based detector design methods and feature-based detector design methods are similar. Both strategies harness statistical regularities within signals to design detectors, resulting in good research outcomes. Nevertheless, the joint utilization of these two methodologies remains unexplored. The radar detection performance can potentially be enhanced through their combined application, which warrants further study. Additionally, it is essential to address key questions surrounding the integration of detector design methods with sea clutter suppression and target echo enhancement methods to optimize radar detection performance.

3. Research on radar detection methods in scenarios with multipath scattering

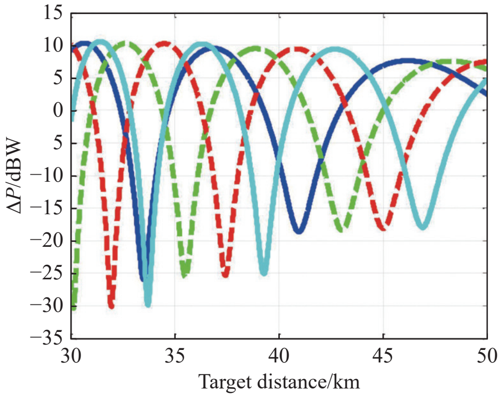
Multipath scattering includes both specular reflection and diffuse reflection. Generally, specular reflection significantly affects the radar detection performance, whereas diffuse reflection has a weaker impact on the radar detection performance [80]. Consequently, within the literature [81−83], efforts to analyze the effects of multipath scattering on radar detection mainly consider specular reflection. Specular reflection can either enhance or attenuate radar target echoes. The influence of specular reflection on the radar target echo relies on factors such as the radar antenna height, operating frequency, polarization mode, target height, sea state, and distance between the radar and the target. Thus, the impact of specular reflection on radar detection performance is related to radar operational parameters and circumstances. In addition, it exhibits a certain degree of stochasticity. Fig. 5 illustrates a chart depicting variations in the power of the received radar signal with alterations in the target height, target distance, and radar altitude in a low-altitude detection scenario. In this illustration, the radar’s transmission power is 50 kW, and the transmitting and receiving antennas both have a maximum gain of 43 dB. Their half power beam width is 4°, the radar wavelength is 0.03 m, the target radar cross section is 0.1 m^2, and the standard deviation of fluctuation in the sea surface height is 0.1 m. Notably, radar clutter and thermal noise were not considered in this case. The power difference in the received radar signal caused by specular reflection is represented as $\Delta P(\mathrm{dB}) = P_1(\mathrm{dB}) - P_0(\mathrm{dB})$, where P_1 and P_0 denote the power of the received radar signals with and without specular reflection, respectively. Both are expressed in decibels (dB).



(a) Target altitude 50 m



(b) Target distance 45 km



(c) Target altitude 20 m

: h_r=100 m; : h_r=110 m; : h_r=120 m;
: h_r=130 m.

Fig. 5 Variations in the radar received signal power in different scenarios

To mitigate the detrimental impact of specular reflection on radar detection performance, researchers have proposed radar target detection methods for addressing specular reflection based on distance super-resolution [84], spatial diversity [85,86], frequency diversity [87], and polarization diversity [88−90]. For low-altitude radar target detection, the path difference between the radar direct echo and the reflected echo typically ranges on the order of decimeters or centimeters. In theory, if the radar's distance resolution is sufficiently high, the target's direct and specular reflection echoes will fall into different range resolution cells, preventing interference between the two and thus circumventing the specular reflection effect. However, achieving decimeter- or centimeter-level distance resolution is a major challenge for low-altitude surveillance radar systems; thus, range super-resolution techniques are not applicable in practice.

Fig. 6 shows that the enhancement and attenuation effects of specular reflection on radar target echoes are correlated with the radar height, target height, and radar-target spacing. In scenarios where the target height and radar-target spacing are fixed, the powers of the target signals received by the radar antenna at different heights vary. Inspired by this result, multiple antennas with different heights are usually employed to collect the target echo signals. Through the meticulous design of these multiple antennas, the received target echo power across antennas can be complementary [91]. Subsequently, processing methods such as averaging or selecting the largest signal among the signals received by multiple antennas can be utilized to diminish or eliminate the attenuation effect caused by specular reflection on radar target echoes. The utilization of multiple antennas to address multipath scattering leverages the concept of spatial diversity. Furthermore, the application of multiple-input multiple-output (MIMO) radar systems for multipath scattering mitigation considers the principles of spatial diversity. Employing a single-transmitter multiple-receiver antenna configuration, we introduced anti-specular-reflection detection methods employing three or more antennas, leading to obvious enhancement in the radar target detection performance under specular reflection conditions [92,93].

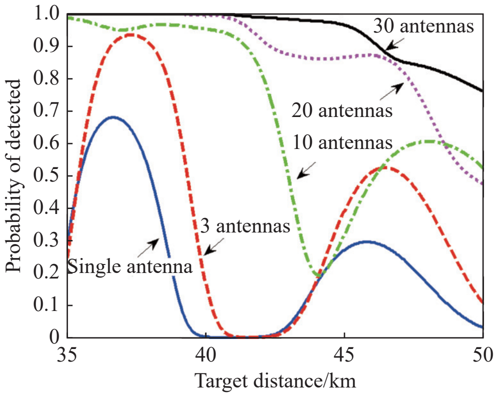


Fig. 6 Radar detection performance of single-transmitter multiple-receiver antenna under multipath conditions

The phase difference between the direct echo of the target and the specular reflected echo is determined by the path difference and the radar wavelength. The wavelength, in turn, is determined by the frequency. Consequently, altering the radar frequency leads to a change in the phase difference between the direct echo of the target and the specular reflected echo. As a result, when the radar employs transmission signals of different frequencies, the phase difference between the direct echo and the reflected echo varies across different frequency channels. Leveraging this characteristic, through processes such as averaging and selecting the strongest signals among multiple frequency channels, the detrimental impact of specular reflection on the target echoes received by radar antennas can be addressed. According to the principle of frequency diversity, scholars have utilized orthogonal frequency division of multiple signals to enhance the radar's performance in detecting targets in environments with multipath interference [94–97].

An alternative approach for addressing multipath scattering is to combine time accumulation methods with frequency diversity approaches. For instance, in an earlier study [98], the adoption of the M/N detection method for frequency diversity radar was proposed, effectively enhancing radar target detection performance under multipath scattering conditions. Based on this, we examined the optimal selection of the M value for frequency diversity radar systems using the M/N detection approach under different conditions [99]. Additionally, researchers at Xidian University introduced a sequential statistical detection algorithm based on multi-frequency techniques [100], which involves sorting the amplitude of the target echoes received at multiple frequency points and subsequently accumulating non-phase parameters for several signals with stronger amplitudes. These accumulated values are then utilized as test statistics to facilitate target detection under multipath conditions.

In theory, polarization diversity methods can also be used to address specular reflection effects in radar detection. However, to our knowledge, articles on addressing multipath scattering using polarization diversity approaches are rare at present. Researchers adopted VV polarization and utilized the Brewster effect to effectively mitigate multipath interference when detecting sea-skimming ultra-low-altitude targets at a grazing angle of approximately 7° [101].

The fundamental principles of spatial diversity, frequency diversity, and polarization diversity methods to address specular reflection are consistent, involving the manipulation of the phase difference between the direct echo and the multipath reflection echo. Therefore, spatial diversity, frequency diversity, and polarization diversity methods can be jointly employed. MIMO radar leverages both frequency and spatial diversity methods to effectively enhance radar target detection by addressing specular reflection effects. A similar concept can also be applied to polarization MIMO radar, which is not discussed here.

In conclusion, the phase difference between the target direct echo and the reflected echo from multipath scattering is the key factor influencing multipath interference effects. Diverse phase differences can be achieved through spatial diversity, frequency diversity, and polarization diversity methods, yielding radar target echoes with varying strengths. Proper optimization or processing of these distinct radar target echo channels can mitigate or eliminate the adverse impact of multipath scattering on radar target detection. Spatial diversity, frequency diversity, and polarization diversity methods operate within distinct dimensions. Moreover, these three methods can be jointly employed. Currently, spatial diversity and frequency diversity methods have been applied in radar systems. Investigating the integration of polarization diversity methods with diversity approaches to propose cost-effective and feasible anti-multipath interference detection techniques is a worthy research direction.

4. Research on radar detection methods in scenarios with sea clutter and multipath scattering

In practice, radar detection of low-altitude targets on sea surfaces is influenced by interference from both sea clutter and multipath scattering. Sea clutter adversely affects radar target detection, while the impact of multipath scattering on radar target detection performance can be either advantageous or disadvantageous. To mitigate the adverse effects of sea clutter and multipath scattering, researchers have proposed several anti-clutter-and-multipath detection methods. The radar target detection methods for use in scenarios with both sea clutter and multipath scattering can be divided into two main categories: using traditional radar systems to design methods for suppressing sea clutter and multipath scattering interference; and designing radar detectors based on new system configurations.

Analyzing the influence of sea clutter and multipath scattering on radar detection performance is crucial for developing methods for simultaneously mitigating the effects of sea clutter and multipath scattering. In the 1990s, scholars at the Royal Signals and Radar Establishment modeled sea clutter and target multipath echoes as K distributions and Rice-squared distributions, respectively. They analyzed the SNR needed for radar target detection under different clutter and multipath scattering conditions with fixed false alarm and detection probabilities [102]. Through theoretical analysis, they derived mathematical expressions for the radar detection probability and false alarm probability in environments with sea clutter and multipath scattering characterized by *K*-distributions [80,103]. Based on this analysis, the effects of clutter, specular reflections, and diffuse reflections on the radar detection performance were investigated, which revealed that multipath scattering can be advantageous for detecting low SNR targets. However, the performance improvement with this approach was limited. Conversely, multipath scattering may adversely affect the detection of high SNR targets, leading to potentially severe performance degradation. In environments with moderate to high sea states, multipath scattering has a relatively minor impact on the radar detection performance, with clutter being the primary factor influencing the detection performance of low SNR targets, as shown in Fig. 7. In Fig. 7, $\varphi_f = \pi$, $\varphi_f = \varphi_s + \varphi_l$, φ_s is the phase of the specular reflection coefficient, and φ_l is the phase difference caused by the path difference between the primary reflected echo and the direct echo.

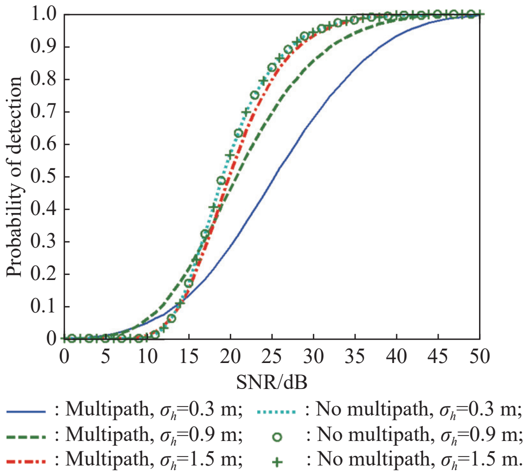


Fig. 7 Radar target detection performance in scenarios with sea clutter and multipath scattering

In conventional radar systems, sea clutter and multipath scattering interference can be directly suppressed to simultaneously address both issues. The common sea clutter and multipath interference suppression methods can be categorized into three primary classes: (i) initially suppressing multipath scattering, followed by clutter suppression; (ii) initially suppressing clutter, followed by multipath scattering suppression; (iii) simultaneously suppressing clutter and multipath interference. Among these, techniques that prioritize multipath scattering suppression before addressing clutter include methodologies such as weight vector interpolation, extrapolation and updating [104], filter design [104], and beam space selection [104,105]. Approaches that first suppress clutter, followed by multipath scattering mitigation, include strategies such as clutter prefiltering [104] and blind channel equalization [106]. Methods for simultaneously addressing clutter and multipath interference include spatial adaptive processing [104,107,108], adaptive matched filtering [109,110], and deep learning methodologies [111].

In scenarios where the geometric information of the low-altitude detection environment is known, multipath scattering can be effectively utilized to enhance the radar detection performance for low-altitude targets. For instance, researchers at Georgia Institute of Technology achieved long-range detection and stable tracking of moving vehicles within urban settings using airborne radar and leveraged multipath scattering based on a priori knowledge of urban building geometries [112]. The corresponding results are shown in Fig. 8.

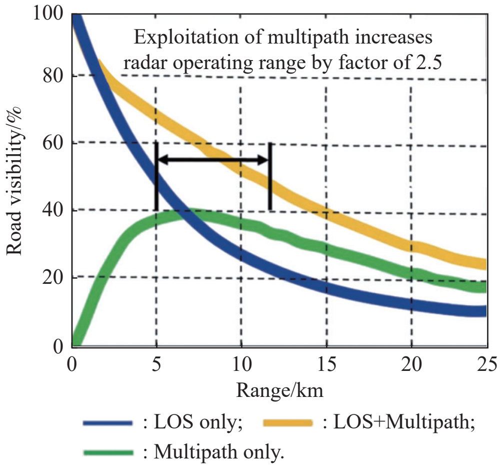


Fig. 8 Comparison between radar detection ranges before and after the utilization of multipath scattering methods [112]

In addition, the application of the time inversion technique can effectively enhance radar detection performance in scenarios with clutter and multipath scattering. Scholars at Carnegie Mellon University successfully employed the time inversion technique to enhance the radar detection performance for stationary targets in environments with clutter and multipath scattering [113,114]. However, it should be noted that the time inversion technique is less effective in improving the detection performance of moving targets [115].

Notably, new generation radar systems, such as ultra-wide-band [116] (UWB), frequency diversity [87], and MIMO systems, have inherent advantages in addressing clutter and multipath interference. As a result, their performance in detecting low-altitude targets surpasses that of conventional radars. For example, the Senrad radar developed by researchers at the US Naval Research Laboratory, with a bandwidth of approximately 550 MHz, can achieve long-range detection and stable tracking for low-altitude targets [116].

In general, clutter and multipath scattering affect the background and target signals of the received radar signal, respectively. The key challenge in clutter and multipath radar target detection research lies in suppressing clutter while utilizing multipath scattering to enhance target signals. The effectiveness of theoretical methods proposed by Chinese and foreign scholars has been verified through simulations and experiments. However, in engineering, simultaneously addressing sea clutter and multipath scattering remains a complex issue that requires further research for low-altitude radar target detection.

5. Conclusions

In this paper, a comprehensive overview of recent research on techniques for radar target detection in scenarios with sea clutter, multipath scattering, and both developed in China and abroad is presented. Radar detection techniques that address sea clutter are relatively independent of those for addressing multipath scattering. These techniques cannot be directly applied in environments with clutter and multipath scattering. Research on detection techniques in environments with clutter and multipath scattering is still in the preliminary stage. Further investigations are needed to explore low-altitude radar target detection techniques considering clutter and multipath scattering simultaneously, as well as practical engineering implementations. In particularly, detection methods using both statistical theory and machine learning with small samples worth investigation in some special scenarios.

References

[1] DING L F, GENG F L, CHEN J C. Principle of radar. 6th ed. Beijing: Publishing House of Electronic Industry, 2020. (in Chinese)

[2] LEUNG H. Nonlinear clutter cancellation and detection using a memory-based predictor. IEEE Trans. on Aerospace and Electronic Systems, 1996, 32(4): 1249–1256.

[3] LEUNG H, YOUNG A. Small target detection in clutter using recursive nonlinear prediction. IEEE Trans. on Aerospace and Electronic Systems, 2000, 36(2): 713–718.

[4] PANAGOPOULOS S, SORAGHAN J J. Small-target detection in sea clutter. IEEE Trans. on Geoscience and Remote Sensing, 2004, 42(7): 1355–1361.

[5] CRANE M K, MOORADD D C, RAMIREZ M D. A polarization technique for mitigating low-grazing-angle radar sea clutter. Proc. of the IEEE MTT-S International Microwave Symposium, 2017: 333–335.

[6] CHEONG J W, SOUTHWELL B J, DEMPSTER A G. Blind sea clutter suppression for spaceborne GNSS-R target detection. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 2019, 12(12): 5373–5378.

[7] HU J F, JIAN C, ZHUO C, et al. Knowledge-aided ocean clutter suppression method for sky-wave over-the-horizon radar. IEEE Geoscience and Remote Sensing Letters, 2018, 15(3): 355–358.

[8] HUANG Y, PENG Y N, WANG X T, et al. Adaptive clutter suppression method for airborne radar based on frequency domain processing. Systems Engineering and Electronics, 2000, 22(12): 4–6. (in Chinses)

[9] POON M W Y, KHAN R H, LE-NGOC S. A singular value decomposition (SVD) based method for suppressing ocean clutter in high frequency radar. IEEE Trans. on Signal Processing, 1993, 41(3): 1421–1425.

[10] YANG Y, XIAO S P, WANG X S. Radar detection of small target in sea clutter using orthogonal projection. IEEE Geoscience and Remote Sensing Letters, 2018, 16(3): 382–386.

[11] YI C L, JI Z Y, KIRUBARAJAN T, et al. An improved oblique projection method for sea clutter suppression in shipborne HFSWR. IEEE Geoscience and Remote Sensing Letters, 2016, 13(8): 1089–1093.

[12] ALKU L, MOISSEEV D, AITTOMÄKI T, et al. Identification and suppression of nonmeteorological echoes using spectral polarimetric processing. IEEE Trans. on Geoscience and Remote Sensing, 2015, 53(7): 3628–3638.

[13] NOVAK L M, SECHTIN M B, CARDULLO M J. Studies of target detection algorithms that use polarimetric radar data. IEEE Trans. on Aerospace and Electronic Systems, 1989, 25(2): 150–165.

[14] WANG J, ZHANG Q Y, CAO B. Multi-notch polarization filtering based on oblique projection. Proc. of the Global Mobile Congress, 2009. DOI: 10.1109/GMC.2009.5295831.

[15] MAO X P, LIU A J, HOU H J, et al. Oblique projection polarisation filtering for interference suppression in high-frequency surface wave radar. IET Radar, Sonar & Navigation, 2012, 6(2): 71–80.

[16] YANG Y, WANG X S, SHI L F, et al. A method for radar-based fixed-wing UAV and clutter identification using dual polarization characteristics. China: ZL201910801086.0. 2021−08−24. (in Chinese)

[17] MCDONALD M K, CERUTTI-MAORI D. Coherent radar processing in sea clutter environments, part I: modelling and partially adaptive STAP performance. IEEE Trans. on Aerospace and Electronic Systems, 2016, 52(4): 1797–1817.

[18] YASOTHARAN A, THAYAPARAN T. Time-frequency method for detecting an accelerating target in sea clutter. IEEE Trans. on Aerospace and Electronic Systems, 2006, 42(4): 1289–1310.

[19] WANG W P, FENG Y, SHAN T. A sea clutter suppression method using improved time-frequency filtering method. Journal of Signal Processing, 2019, 35(2): 208–216. (in Chinses)

[20] DUK V, ROSENBERG L, NG B W H. Target detection in sea-clutter using stationary wavelet transforms. IEEE Trans. on Aerospace and Electronic Systems, 2017, 53(3): 1136–1146.

[21] PARK H R, KWAK Y G, WANG H. Efficient joint polarisation-space-time processor for nonhomogeneous clutter environments. Electronics Letters, 2002, 38(25): 1714–1715.

[22] PARK H R, WANG H. Adaptive polarisation-space-time domain radar target detection in inhomogeneous clutter environments. IEE-Radar, Sonar & Navigation, 2006, 153(1):

35–43.
[23] SKOLNIK M I. Radar handbook. 3rd ed. Columbus: McGraw Hill, 2008.
[24] WANG Y L, DING Q J, LI R F. Adaptive array processing. Beijing: Tsinghua University Press, 2009. (in Chinese)
[25] NOVAK L M, BURL M C. Optimal speckle reduction in polarimetric SAR imagery. IEEE Trans. on Aerospace and Electronic Systems, 1990, 26(2): 293–305.
[26] ZEBKER H A, VAN ZYL J J, HELD D N. Imaging radar polarimetry from wave synthesis. Journal of Geophysical Research: Solid Earth, 1987, 92(B1): 683–701.
[27] BOERNER W M, KOSTINSKI A B, JAMES B D. On the concept of the polarimetric matched filter in high resolution radar imaging: an alternative for speckle reduction. Proc. of the International Geoscience and Remote Sensing Symposium, 1988: 69–72.
[28] LI Y Z, CHENG X, LI M Q, et al. A study on polarization gain for radar targets detection. Modern Radar, 2013, 35(2): 35–39. (in Chinese)
[29] TAO R, MA J M, DENG B, et al. Fractional Fourier transform and its application. 2nd ed. Beijing: Tsinghua University Press, 2022. (in Chinese)
[30] XU J, YAN L, ZHOU X, et al. Adaptive Radon-Fourier transform for weak radar target detection. IEEE Trans. on Aerospace and Electronic Systems, 2018, 54(4): 1641–1663.
[31] KAY S M. Fundamental of statistical signal processing volume II: detection theory. Upper Saddle River: Prentice Hall. 1998.
[32] LIU W J, LIU J, HAO C P, et al. Multichannel adaptive signal detection: basic theory and literature review. Science China (Information Sciences), 2022, 65: 121301.
[33] XU S W, BAI X H, GUO Z X, et al. Status and prospects of feature-based detection methods for floating targets on the sea surface. Journal of Radars, 2020, 9(4): 684–714. (in Chinese)
[34] ROBEY F C, FUHRMANN D R, KELLY E J, et al. A CFAR adaptive matched filter detector. IEEE Trans. on Aerospace and Electronic Systems, 1992, 28(1): 208–216.
[35] SABAHI M F, HASHEMI M M, SHEIKHI A. Radar detection based on Bayesian estimation of target amplitude. IET Radar, Sonar & Navigation, 2008, 2(6): 458–467.
[36] KRONAUGE M, ROHLING H. Fast two-dimensional CFAR procedure. IEEE Trans. on Aerospace and Electronic Systems, 2013, 49(3): 1817–1823.
[37] SCHLEHER D C. Radar detection in Weibull clutter. IEEE Trans. on Aerospace and Electronic Systems, 1976, 12(6): 736–743.
[38] POURMOTTAGHI A, TABAN M R, GAZOR S. A CFAR detector in a nonhomogenous Weibull clutter. IEEE Trans. on Aerospace and Electronic Systems, 2012, 48(2): 1747–1758.
[39] CHEN Z R, CHEN A L, LIU W J, et al. CFAR detection in nonhomogeneous Weibull sea clutter for skywave OTHR. IEEE Geoscience and Remote Sensing Letters, 2023, 20: 3508005.
[40] DONG Y H. Optimal coherent radar detection in a K-distributed clutter environment. IET Radar, Sonar & Navigation, 2012, 6(5): 283–292.
[41] SHI S N, SHUI P L. Optimum coherent detection in homogenous K-distributed clutter. IET Radar, Sonar & Navigation, 2016, 10(8): 1477–1484.
[42] SHUI P L, LIU M, XU S W. Shape-parameter-dependent coherent radar target detection in K-distributed clutter. IEEE Trans. on Aerospace and Electronic Systems, 2016, 52(1): 451–465.
[43] XUE J, XU S W, LIU J, et al. Bayesian detection for radar targets in compound-Gaussian sea clutter. IEEE Geoscience and Remote Sensing Letters, 2022, 19: 4020805.
[44] XUE J, LI H E, PAN M Y, et al. Adaptive persymmetric detection for radar targets in correlated CG-LN sea clutter. IEEE Trans. on Geoscience and Remote Sensing, 2023, 61: 5108212.
[45] SANGSTON K J, GINI F, GRECO M S. Coherent radar target detection in heavy-tailed compound-Gaussian clutter. IEEE Trans. on Aerospace and Electronic Systems, 2012, 48(1): 64–77.
[46] XUE J, LIU J, XU S W, et al. Adaptive detection of radar targets in heavy-tailed sea clutter with lognormal texture. IEEE Trans. on Geoscience and Remote Sensing, 2021, 60: 5108411.
[47] XUE J, YAN J L, PAN M Y, et al. Knowledge-aided adaptive Gradient test for radar targets in correlated compound Gaussian sea clutter with lognormal texture. IEEE Geoscience and Remote Sensing Letters, 2023, 20: 3509105.
[48] XUE J, XU S W, SHUI P L. Near-optimum coherent CFAR detection of radar targets in compound-Gaussian clutter with inverse Gaussian texture. Signal Processing, 2020, 166: 107236.
[49] GAO Y C, LIAO G S, ZHU S Q. Adaptive signal detection in compound-Gaussian clutter with inverse Gaussian texture. Proc. of the 14th International Radar Symposium, 2013, 2: 935–940.
[50] XUE J, XU S W, LIU J, et al. Model for non-Gaussian sea clutter amplitudes using generalized inverse Gaussian texture. IEEE Geoscience and Remote Sensing Letters, 2018, 16(6): 892–896.
[51] XU S W, WANG Z X, BAI X H, et al. Optimum and near-optimum coherent CFAR detection of radar targets in compound-Gaussian clutter with generalized inverse Gaussian texture. IEEE Trans. on Aerospace and Electronic Systems, 2021, 58(3): 1692–1706.
[52] KONG L J, CUI G L, YANG X B, et al. Rao and Wald tests design of polarimetric multiple-input multiple-output radar in compound-Gaussian clutter. IET Signal Processing, 2011, 5(1): 85–96.
[53] XUE J, MA M S, LIU J, et al. Wald- and Rao-based detection for maritime radar targets in sea clutter with lognormal texture. IEEE Trans. on Geoscience and Remote Sensing, 2022, 60: 5119709.
[54] SUN M R, LIU W J, LIU J, et al. Rao and Wald tests for target detection in coherent interference. IEEE Trans. on Aerospace and Electronic Systems, 2021, 58(3): 1906–1921.
[55] LIU J, MASSARO D, ORLANDO D, et al. Radar adaptive detection architectures for heterogeneous environments. IEEE Trans. on Signal Processing, 2020, 68: 4307–4319.
[56] SHUI P L, LI D C, XU S W. Tri-feature-based detection of floating small targets in sea clutter. IEEE Trans. on Aerospace and Electronic Systems, 2014, 50(2): 1416–1430.
[57] LI Y Z, XIE P C, TANG Z S, et al. SVM-based sea-surface small target detection: a false-alarm-rate-controllable approach. IEEE Geoscience and Remote Sensing Letters, 2019, 16(8): 1225–1229.
[58] ZHOU H K, JIANG T. Decision tree based sea-surface

weak target detection with false alarm rate controllable. IEEE Signal Processing Letters, 2019, 26(6): 793–797.
[59] XU S W, ZHU J N, JIANG J Z, et al. Sea-surface floating small target detection by multifeature detector based on isolation forest. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 2020, 14: 704–715.
[60] XU S W, ZHENG J B, PU J, et al. Sea-surface floating small target detection based on polarization features. IEEE Geoscience and Remote Sensing Letters, 2018, 15(10): 1505–1509.
[61] CHEN S C, GAO H T, LUO F. Target detection in sea clutter based on combined characteristics of polarization. Journal of Radars, 2020, 9(4): 664–673. (in Chinese)
[62] LO T, LEUNG H, LITVA J, et al. Fractal characterisation of sea-scattered signals and detection of sea-surface targets. IEE Proceedings F-Radar and Signal Processing, 1993, 140(4): 243–250.
[63] GUAN J, LIU N B, HUANG Y, et al. Fractal characteristic in frequency domain for target detection within sea clutter. IET Radar, Sonar & Navigation, 2012, 6(5): 293–306.
[64] HU J, TUNG W W, GAO J B. Detection of low observable targets within sea clutter by structure function based multifractal analysis. IEEE Trans. on Antennas and Propagation, 2006, 54(1): 136–143.
[65] LIU N B, HUANG Y, GUAN J, et al. Fractal analysis of real sea clutter in frequency domain. Journal of Electronics & Information Technology, 2012, 34(4): 929–935. (in Chinese)
[66] GAO J B, YAO K. Multifractal features of sea clutter. Proc. of the IEEE Radar Conference, 2002: 500–505.
[67] HAYKIN S, LI X B. Detection of signals in chaos. Proceedings of the IEEE, 1995, 83(1): 95–122.
[68] LIU N B, WANG G Q, BAO Z H, et al. Multifractal property of sea clutter FRFT spectrum for target detection. Journal of Signal Processing, 2013, 29(1): 1–9. (in Chinese)
[69] GU Z M, ZHANG X G, WANG Q. Multifractal property and target detection of sea clutter in FRFT domain. Journal of Nanjing University (Natural Science), 2017, 53(4): 731–737. (in Chinese)
[70] TIAN Y F, JI G R, YIN Z Y, et al. Weak targets detection in sea clutter based on modified fractal character differences. Periodical of Ocean University of China, 2013, 43(3): 92–97. (in Chinese)
[71] LIU N B, GUAN J, WANG G Q, et al. Target detection within sea clutter based on multi-scale Hurst exponent in FRFT domain. Acta Electronica Sinica, 2013, 41(9): 1847–1853. (in Chinese)
[72] CHEN X L, LIU N B, WANG G Q, et al. Gaussian short-time fractional Fourier transform based detection algorithm of target with micro-motion at sea. Acta Electronica Sinica, 2014, 42(5): 971–977. (in Chinese)
[73] CHEN X L, GUAN J, YU X H, et al. Radar micro-Doppler signature extraction and detection via short-time sparse time-frequency distribution. Journal of Electronics & Information Technology, 2017, 39(5): 1017–1023. (in Chinese)
[74] SHI S N, SHUI P L. Sea-surface floating small target detection by one-class classifier in time-frequency feature space. IEEE Trans. on Geoscience and Remote Sensing, 2018, 56(11): 6395–6411.
[75] BAI X, XU S W, ZHU J N, et al. Floating small target detection in sea clutter based on multi-feature angle variance. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 2023, 16: 9422–9436.
[76] SU N Y, CHEN X L, GUAN J, et al. Detection and classification of maritime target with micro-motion based on CNNs. Journal of Radars, 2018, 7(5): 565–574. (in Chinese)
[77] QU Q Z, LIU W J, WANG J X, et al. Enhanced CNN-based small target detection in sea clutter with controllable false alarm. IEEE Sensors Journal, 2023, 23(9): 10193–10205.
[78] QU Q Z, WANG Y L, LIU W J, et al. A false alarm controllable detection method based on CNN for sea-surface small targets. IEEE Geoscience and Remote Sensing Letters, 2022, 19: 1–5.
[79] SU N Y, CHEN X L, CHEN B X, et al. Dual-channel convolutional neural networks feature fusion method for radar maritime target intelligent detection. Modern Radar, 2019, 41(10): 47–52. (in Chinese)
[80] YANG Y, FENG D J, WANG X S, et al. Performance analysis of low-altitude radar seeker detecting sea surface target. Journal of Electronics & Information Technology, 2011, 33(8): 1779–1785. (in Chinese)
[81] BARTON D K. Low-angle radar tracking. Proceedings of the IEEE, 1974, 62(6): 687–704.
[82] WHITE W D. Low-angle radar tracking in the presence of multipath. IEEE Trans. on Aerospace and Electronic Systems, 1974, 10(6): 835–852.
[83] YANG Y. Study on the theories and methods of low altitude target detection for radar seeker. Changsha: National University of Defense Technology, 2014. (in Chinese)
[84] YU K B. Recursive super-resolution algorithm for low-elevation target angle tracking in multipath. IEE-Radar, Sonar & Navigation, 1994, 141(4): 223–229.
[85] SHI J P, HU G P, LEI T. DOA estimation algorithms for low-angle targets with MIMO radar. Electronics Letters, 2016, 52(8): 652–654.
[86] SEN S, NEHORAI A. Adaptive OFDM radar for target detection in multipath scenarios. IEEE Trans. on Signal Processing, 2010, 59(1): 78–90.
[87] ZHAO J H, YANG J Y. Frequency diversity to low-angle detecting using a highly deterministic multipath signal model. Proc. of the CIE International Conference on Radar, 2006. DOI: 10.1109/ICR.2006.343202.
[88] GIULI D. Polarization diversity in radars. Proceedings of the IEEE, 1986, 74(2): 245–269.
[89] VALENZUELA-VALDES J F, GARCIA-FERNANDEZ M A, MARTINEZ-GONZALEZ A M, et al. The role of polarization diversity for MIMO systems under Rayleigh-fading environments. IEEE Antennas and Wireless Propagation Letters, 2006, 5: 534–536.
[90] ZHANG M Q, PENG L, LIANG Y, et al. Radar polarization diversity technology for low-altitude targets. Proc. of the CIE International Conference on Radar, 2021: 2326–2330.
[91] ZHANG Y, ZENG H, WEI Y M, et al. Marine radar antenna height design under multipath effect. Proc. of the IET International Radar Conference, 2013. DOI: 10.1049/cp.2013.0115.
[92] YANG Y, XIAO S P, FENG D J, et al. Single-transmit three-receive antenna radar anti-multipath scattering detection method. China: ZL201610190745.8. 2018–01–09. (in Chinese)
[93] YANG Y, XIAO S P, LI C, et al. A method for radar target detection under multipath conditions. China: ZL201810082853.2. 2020−05−05. (in Chinese)
[94] XIA Y. Research on detection and tracking of low altitude

target based on OFDM radar. Changsha: National University of Defense Technology, 2016.

[95] YUAN H F, JIANG C S. Performance of OFDM-MIMO radar for multipath suppression. Signal Processing, 2012, 28(7): 1000–1005. (in Chinese)

[96] LI J, LIU H M, MIAO J H. Analysis of the dynamic range and the detection performance of weak target for orthogonal waveform MIMO radar. Signal Processing, 2010, 26(4): 512–516. (in Chinese)

[97] ZHOU H, HU G P, SHI J P, et al. Low altitude target detection performance for OFDM-MIMO radar. Chinese Journal of Radio Science, 2016, 31(5): 988–995. (in Chinese)

[98] WILSON S L, CARLSON B D. Radar detection in multipath. IEE-Radar, Sonar & Navigation, 1999, 146(1): 45–54.

[99] YANG Y, WANG X S, ZHANG W M, et al. Detection technology of low-flying target on the sea in multipath environment. Chinese Journal of Radio Science, 2011, 26(3): 443–449. (in Chinese)

[100] CAO Y H, WANG S H, WANG Y, et al. Target detection for low angle radar based on multi-frequency order-statistics. Journal of Systems Engineering and Electronics, 2015, 26(2): 267–273.

[101] LIU W M, TONG C M, PENG P, et al. Research on grazing incidence scattering characteristics and Brewster effect from ocean surface. Journal of Microwaves, 2017, 33(3): 37–43. (in Chinese)

[102] TOUGH R J A, BAKER C J, PINK J M. Radar performance in a maritime environment: single hit detection in the presence of multipath fading and non-Rayleigh sea clutter. IEE Proceedings F-Radar and Signal Processing, 1990, 137(1): 33–40.

[103] YANG Y, FENG D J, WANG X S, et al. Effects of *K* distributed sea clutter and multipath on radar detection of low altitude sea surface targets. IET Radar, Sonar & Navigation, 2014, 8(7): 757–766.

[104] RABIDEAU D J. Clutter and jammer multipath cancellation in airborne adaptive radar. IEEE Trans. on Aerospace and Electronic Systems, 2000, 36(2): 565–583.

[105] NGWAR M, WIGHT J. Phase-coded-linear-frequency-modulated waveform for low cost marine radar system. Proc. of the IEEE Radar Conference, 2010: 1144–1149.

[106] CHAVANNE R, ABED-MERAIM K, MEDYNSKI D. Target detection improvement using blind channel equalization OTHR communication. Proc. of the Sensor Array and Multichannel Signal Processing Workshop, 2004: 657–661.

[107] LI H D, LIAO G S, XU J W. Robust adaptive clutter suppression approach for missile-borne radar with ΣΔ-beam. Systems Engineering and Electronics, 2019, 41(2): 273–279. (in Chinese)

[108] BIALLAWONS O, ENDER J H G. Multipath detection by using space-space adaptive processing (SSAP) with MIMO radar. Proc. of the International Conference on Radar, 2018. DOI: 10.1109/RADAR.2018.8557221.

[109] KUMBUL U, HAYVACI H T. Knowledge-aided adaptive detection with multipath exploitation radar. Proc. of the Sensor Signal Processing for Defence, 2016. DOI: 10.1109/SSPD.2016.7590605.

[110] GULEN YILMAZ S H, TAHA HAYVACI H. Multipath exploitation radar with adaptive detection in partially homogeneous environments. IET Radar, Sonar & Navigation, 2020, 14(10): 1475–1482.

[111] WU Z Y, PENG Y X, WANG W B. Deep learning-based unmanned aerial vehicle detection in the low altitude clutter background. IET Signal Processing, 2022, 16(5): 588–600.

[112] FERTIG L B, BADEN J M, GUERCI J R. Knowledge-aided processing for multipath exploitation radar (MER). IEEE Aerospace and Electronic Systems Magazine, 2017, 32(10): 24–36.

[113] MOURA J M F, JIN Y W. Detection by time reversal: single antenna. IEEE Trans. on Signal Processing, 2006, 55(1): 187–201.

[114] JIN Y W, MOURA J M F. Time-reversal detection using antenna arrays. IEEE Trans. on Signal Processing, 2008, 57(4): 1396–1414.

[115] ZHANG Z M, CHEN B X, YANG M L. Moving target detection based on time reversal in a multipath environment. IEEE Trans. on Aerospace and Electronic Systems, 2021, 57(5): 3221–3236.

[116] SKOLNIK M, LINDE G, MEADS K. Senrad: an advanced wideband air-surveillance radar. IEEE Trans. on Aerospace and Electronic Systems, 2001, 37(4): 1163–1175.

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