Hindawi
International Journal of Aerospace Engineering
Volume 2020, Article ID 4673763, 19 pages
https://doi.org/10.1155/2020/4673763

Review Article

Processing Technology Based on Radar Signal Design and Classification

Jianping Ou, Jun Zhang, and Ronghui Zhan

College of Electronic Science and Engineering, National University of Defense Technology, Changsha 410073, China

Correspondence should be addressed to Jianping Ou; oujianping2018@126.com

Received 28 July 2019; Revised 5 September 2019; Accepted 30 December 2019; Published 17 January 2020

Academic Editor: Angelo Cervone

It is well known that the application of radar is becoming more and more popular with the development of the signal technology progress. This paper lists the current radar signal research, the technical progress achieved, and the existing limitations. According to radar signal respective characteristics, the design and classification of the radar signal are introduced to reflect signal's differences and advantages. The multidisciplinary processing technology of the radar signal is classified and compared in details referring to adaptive radar signal process, pulse signal management, digital filtering signal mode, and Doppler method. The transmission process of radar signal is summarized, including the transmission steps of radar signal, the factors affecting radar signal transmission, and radar information screening. The design method of radar signal and the corresponding signal characteristics are compared in terms of performance improvement. Radar signal classification method and related influencing factors are also contrasted and narrated. Radar signal processing technology is described in detail including multidisciplinary technology synthesis. Adaptive radar signal process, pulse compression management, and digital filtering Doppler method are very effective technical means, which has its own unique advantages. At last, the future research trends and challenges of technologies of the radar signals are proposed. The conclusions obtained are beneficial to promote the further promotion applications both in theory and practice. The study work of this paper will be useful for choosing more reasonable radar signal processing technology methods.

1. Introduction

Radar is an electronic system with the advantages of low cost, low-power consumption, and high precision [1], which can be significantly applied in space shuttle topographic missions [2, 3], optics [4], geotechnical mapping [5], meteorological detection [6], and railway ballast evaluation [7]. With the continuous progress of technology [8, 9] and the demand of utilization [10, 11], radar has gradually changed from obtaining the distance [12], azimuth [13], and altitude information [14, 15] from the target to the launching point of electromagnetic wave to gaining more expanded information [16, 17], such as hand-gesture recognition [18], displacement field of the Landers earthquake mapped, and detecting pedestrians with multiple-input multiple-output (MIMO) [19, 20].

All advances and utilities of radar technology are based on reliable and stable radar signal (RS) [21] which affects the detection result of radar directly [22]. RS researches are extensive and professional involving signal-to-noise ratio (SNR) [23], polarization properties [24], micromotion characteristics [25], time-domain convolution [26], and so on. Effects of nonuniform beam filling on the propagation of RS at X-band frequencies were conducted to verify signal attenuation in vertical and horizontal directions. Based on the power law relationship, Gosset and Zawadzki [27] took two mechanisms to investigate the modified action of nonuniform beam filling (NUBF) of the radar beam, which indicates that the apparent two method attenuations often compensate each other by distance owing to overestimating or underestimating a particular attenuation. Furthermore, phase measurement analyzed by examination of differential phase shift and weighted by reflectivity and attenuation in sampling volume will cause negative values in the retrieved specific differential phase shifts except for beam widths of less than 1°, which points out some of the practical problems that may be encountered using rain measurement algorithms at X-band [28].

The RS change is not only related to frequency but also to the propagation process of radar signal, especially in the ionosphere. In order to explore the relationship between the E region ionosphere and the velocity of the electron drift and ion acoustic, Nielsen et al. [29] applied the double-pulse technique to determine the systematic variation trend of Doppler frequency shift with drift velocity and flow angle. The research results show that the ratio of the maximum line-of-sight velocity to the ion acoustic velocity is decreasing from 1.2 to 1.05 when the electron drift speed increases from 600 to 1600 m s^{-1} which can be exploited this new capability in a new joint campaign. Grima et al. [30] valued the influence factors of ionospheric confinement on radio wave propagation with control the evolution of the European ionosphere configuration, which revealed dispersive phase shift and Faraday rotation are the main impacts on RS propagation with a function of the total electron content (up to 4×10^{15} m^{-2}) and the Jovian magnetic field strength at Europa (~420 nT). The scattering or absorption of radar signals by ionization in the atmosphere has been extended to the upper atmosphere of the Mars which was put into effect by Espley et al. [31]. Though the designed instrument MARSIS transmitted a continuous-wave pulse of ~91 μsec duration in 160 frequency steps between 100 kHz and 5.6 MHz, no persistent ionospheric meteorology produced from the solar energetic particles and the daily ionization cycle was found. Namely, part of the high-frequency RS can be scattered or absorbed by the Martian ionosphere which indicates that the radar device can be used in Mars exploration in the future. In order to maintain the time stability of RS for a long time, the deep penetration method is more suitable for velocity mapping which was obtained by the experiment results of Rignot et al. [32]. The conclusion of the study is that the application of long-wave radar in glaciology has important advantages, which was drawn from that C-band penetration is small (1-2 m) on exposed ice, but up to 10 m on cold firn. Close et al. [33] examined the strength relationship among frequency, azimuth of nonspecial meteor trajectories, and RS. With the increase of the angle between the radar beam and the background magnetic field, the signal intensity decreases by 3 to 4 decibels per degree at 160 MHz. The research that focus on aiming to strengthen the radar signals and reduce the attenuation, the penetration depth, wall dispersive [34] and resolution of ultra-wideband, and so on are studied successively [35, 36].

As shown in Figure 1, according to radar signal respective characteristics, the design and classification of the RS are introduced by this paper primarily to reflect signal's differences and advantages. And then the multidisciplinary processing technology of the RS is classified and compared in details referring to adaptive radar signal process, pulse signal management, digital filtering signal mode, Doppler method, and high frequency. In this review, the design and classification of the radar signal are introduced by this paper primarily to reflect signal's differences and advantages according to radar signal respective characteristics. And the multidisciplinary processing technology of the radar signal is classified and compared in details referring to adaptive radar signal process, pulse signal management, digital filtering signal mode, Doppler method, and high frequency. The work done in this paper can effectively help promote the stability of radar signal which is essential to image resolution of coherent imaging, data transmission, and radar receive. Based on the study work of this paper, the researchers can choose more reasonable radar signal processing technology and methods.

2. Radar Signal Transmission

2.1. Transmission Process. Radar technology has been extensively used in practical applications owing to its signal has the characteristics of large bandwidth and time-width for the complex modulation to enhance the antijamming ability of the signal [37, 38], whose signal transmission processes are displayed in Figure 2. The stability and reliability of signals can be optimized and improved from the multidisciplinary aspects of signal generation, amplification, reception, processing, and detection.

As a special equipment, Radar's daily work is carried out with the help of a certain amount of information [39]. Signal reflection can play a role in recognizing objects, which is also the focus of the development of radar technology in the current era [40]. Normalized signal application will exert tremendous influence in practice. Especially in complex combat environment, once the problem of nonstandardized signal recognition is encountered, it will directly restrict radar synthesis ability. The quality of radar signal depends on the signal transmission loss, the interference degree of other signals, and the influence of transmission mode [41, 42].

2.2. Information Screening. Information screening is important function of RS recognition. In the information age, different information sources bring different values, which determine that in the corresponding information application process, information value system is ensured in an active way [41]. The construction and formation of this value system is based on information recognition. Different radars have certain differences in the working band which will directly affect the recognition and feedback of radar signals. Therefore, it should optimize the signal application mode to ensure the validity and authenticity of radar information application in a more active way [42]. Cooper et al. [43] presented the THz imaging radar technology of the Jet Propulsion Laboratory (JPL) with a portable laboratory prototype radar system operating frequency-modulated continuous-wave (FMCW) mode over a 28.8 GHz bandwidth, presently centered at 676.7 GHz. The radar information screening research facilities are showed in Figure 3, and the study finds that the signal to noise ratio of human or clothed mannequin targets typically falls in the range 20-40 dB for a single 100 s FMCW waveform.

In Figure 3, panel (a) is the beam path optic schematic which contains the feed reflector, rotating mirror, subreflector, and the main aperture to transform beam in the range of 660~690 GHz; panel (b) is the radar optic photograph;

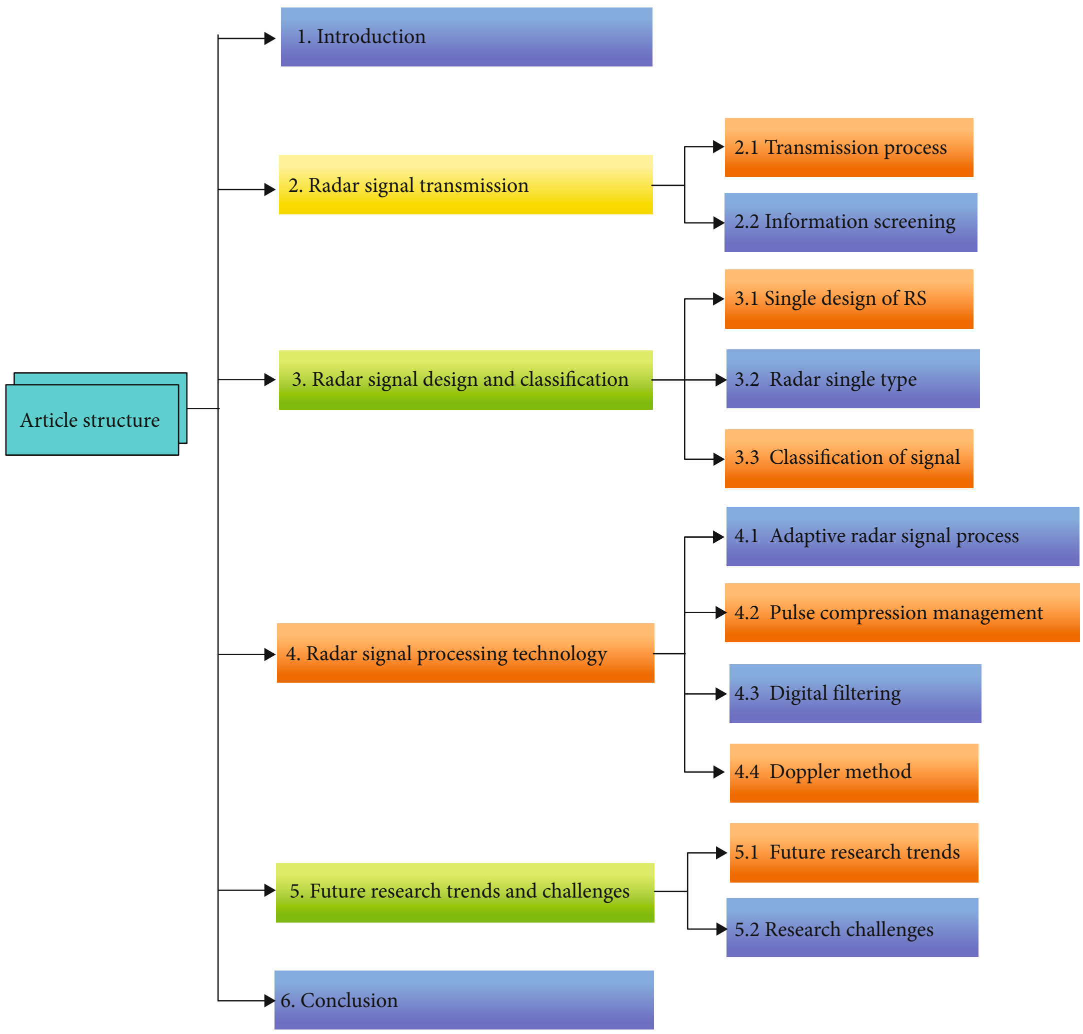


Figure 1: Article structure chart.

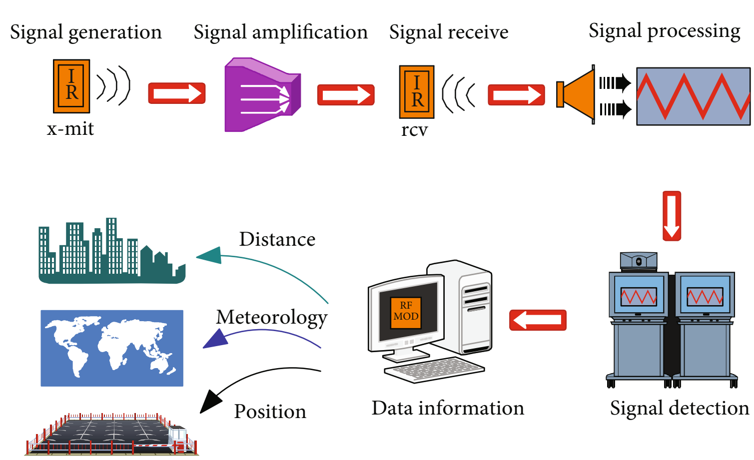


Figure 2: Radar signal transmission process.

panel (c) is the time-delay two-beam multiplexing implemented principle; panel (d) is the additional optical components, panel (e) is the concealed object detection in half the time due to parallel acquisition of the right and left image halves; (f) is the range spectrum of a single radar waveform showing simultaneous radar detection of two different locations on a target. Modelling and computer simulation method were adopted to discuss the radar screening by

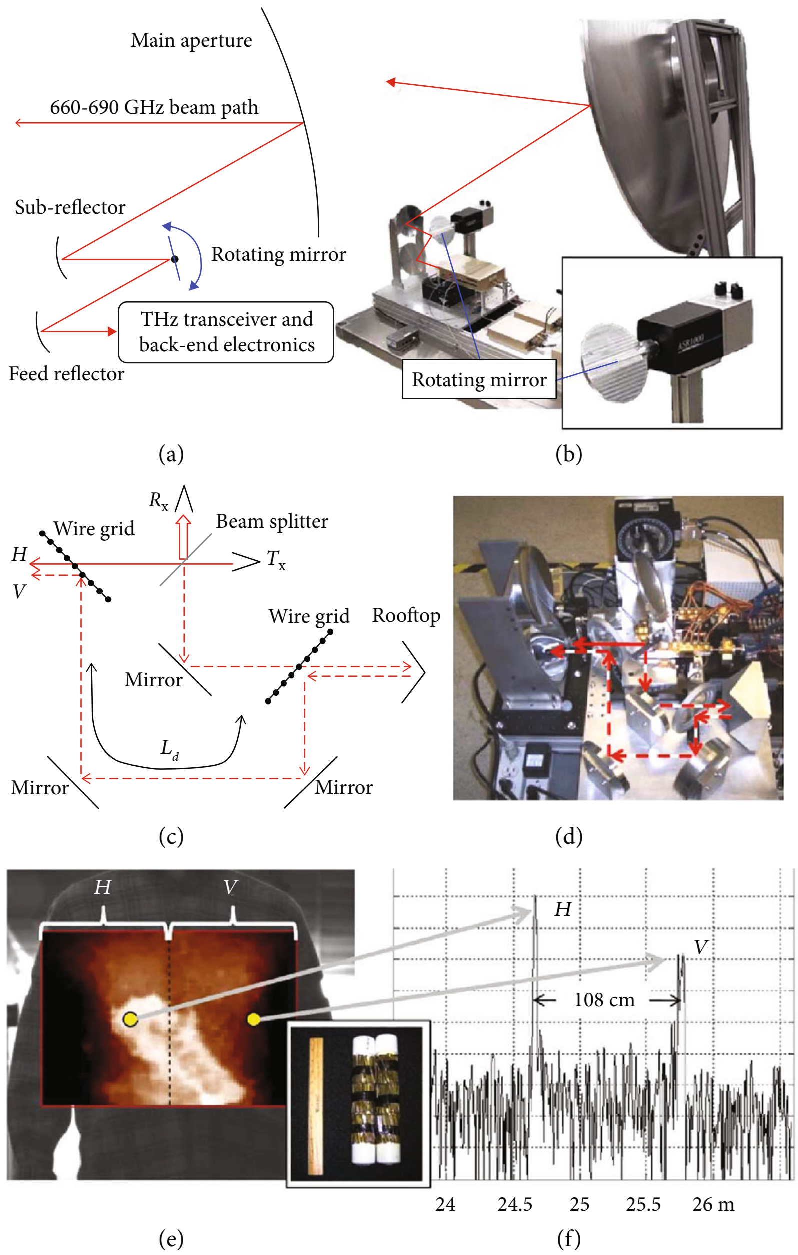


FIGURE 3: Radar information screening device and results [43].

Blackledge [44] through the impulse response functions (IRFs) associated with radar microwave backscattering from a strong and weakly ionized plasma screen. The established model for the RS generated with and without a plasma screen and the screening of the scattered by the plasma is characterized by a simple negative exponential whose decay rate is determined by the conductivity which in turn is proportional to the electron number density. Through the analysis of Bierwagen et al. [45], it can be found that the role of radar signal recognition in the current environment is very important which is one of the effective ways to show the application of mine equipment under the new technology [46, 47]. Exploring the application of radar signal recognition system in an active way is helpful to construct the related recognition application system which becomes an inevitable development [48]. In case of emergencies, we can make better information identification judgment by making corresponding innovations and improving the existing identification application system [49].

3. Radar Signal Design and Classification

3.1. Signal Design of RS. In the field of modern radar signal utilization, the requirements of signal ability and function compatibility are increasingly stringent, which demands not only a large amount of data information [39, 43] but also a good system compatibility timely and punctual [40, 50]. The comprehensively used multidisciplinary radar signal design methods are shown in Figure 4. The design targets include the frequency division multiplexing, stealth targets,

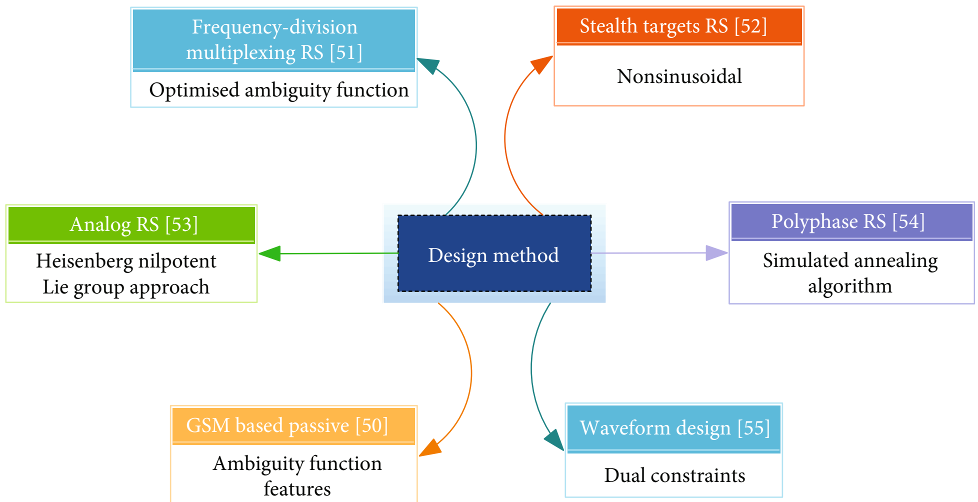


Figure 4: Radar signal design methods.

Table 1: Signal performance comparison of different design methods.

RS design mode	Characteristic	Performance
Orthogonal frequency multiplexing [51]	(1) Optimised ambiguity function (2) Low peak-to-average power ratio	(1) ACF SLL↓ from -15 to -20 dB (2) AF<−10 dB
Nonsinusoidal RS design [52]	(1) Stealth targets (2) Pulse compression with Barker codes	(1) Sidelobe free interval↑ $T_a \geq 2LT$ (2) BCL = 5 with time $t' = 0$
Heisenberg nilpotent Lie group [53]	(1) Phase discontinuity of Fourier (2) Chirp waveforms of microoptics	(1) FEB W = 0.5 Hz recaptured (2) Transmitted at the rate of 2 W/s
Ambiguity function design [50]	(1) Discrete frequency-coded (2) Synthesised polyphase	(1) L increases from 3 to 6 (2) Transmitted at the rate of 2 W/s

polyphase, analog, GSM-based passive, and waveform design. The corresponding objectives are different, and different design methods can be adopted with their respective design focus and highlights.

RS should be based on high range and speed of the resolution and then be designed with multidisciplinary algorithms [49, 51]. The radar signal characteristics and performance of various design methods are synthesized as shown in Table 1. Overall, high-performance radar signals processed by multidisciplinary hybrid algorithm are available.

Multidisciplinary algorithms [51, 52] have been innovatively applied to radar signal design, such as thumbtack range-velocity resolution functions and Hamming scan algorithm [53] which have been achieved significant results. In order to reduce the computational requirements, Nohara [54] completed the design of a space-based radar signal processor through the radar signal processor (RSP) function definitions, sampling correction, frequency alignment, pulse Doppler and compression, monopulse ratio, and noncoherent integration and detection. It leads to a reduction of 25% of the PD function, 20% fewer pulse compression operation of the PC function, and 20% decrease of the peak computational processing requirements after optimizations. Singh and Rao [50] employed the discrete frequency-coded (DFC) to design the RS which achieved very outstanding performance improvement results with the autocorrelation sidelobe peaks (ASP) and cross-correlation peaks (CP) as showed in Figure 5. Figure 5 shows that the value of ASP is much lower than that of CP but their trends are consistent. Compared with polyphase coding sequence set, DFC sequence set with the thumbtack ambiguity function has better correlation and the corresponding values of DFC sequences are much smaller than those of 32-phase sequences.

In order to achieve different technical specifications, the RS design method is also developed towards the trend of multidisciplinary and multimethod combination. To achieve high imaging quality, Song et al. [55] focused on the cognitive waveform optimization design for radar imaging and designed a waveform optimization method maximum the receiving signal-to-clutter ratio under dual constraints including transmitting energy constraint and range profile constraint. The comparison of the different optimization waveforms of the RS is displayed in Figure 6. Among the three waveform power spectra, the TISLR value increases, and more power is concentrated on the frequencies with high signal-to-clutter ratio values. The performance of the optimized design is obviously improved and the solve α values derived from binary searching are 0.3349, 0.4864, and

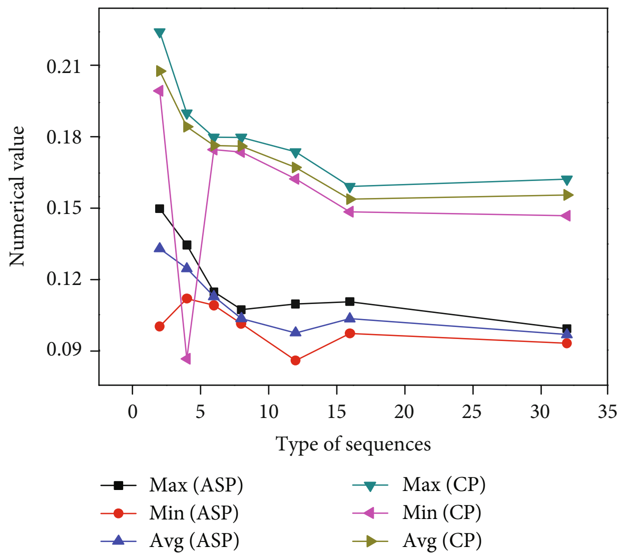


FIGURE 5: Comparison of relevant properties of different types of synthetic sequences (the data were obtained from Ref. [50]).

0.7984 of TISLR1 = 0.008, TISLR2 = 0.0085, and TISLR3 = 0.009, respectively, which are just 0.62, 0.66, and 0.70 times the range profile ISLR of the maximized mutual information-(MMI-) based optimization waveform. When TISLR3 = 0.009, the waveform has the best performance compared with TISLR1 = 0.008 and TISLR2 = 0.0085.

In order to improve the application effect of integrated identification, it will be more complex to do a comprehensive design of new radar. Prediction and management are needed under various conditions to make sure the effect is more real and effective [56]. Setting up new radar types requires comprehensive consideration of various problems, especially the technical means and application methods of competitors. New mode of radar application should be constructed to obtain more information resources in the process of new radar design and used to promote information awareness [57, 58]. Other functions are constantly strengthened and developed to form a more complete database and analytical response methods.

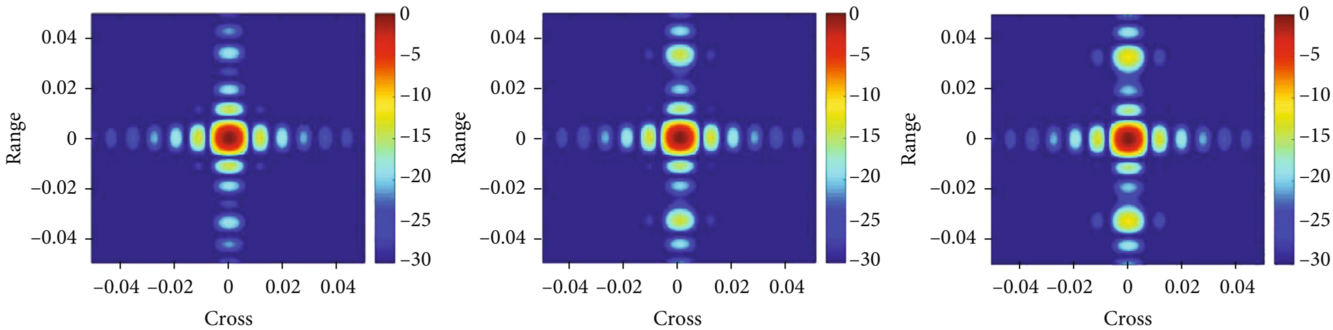
3.2. Radar Signal Type. In the process of signal application, an effective method is to set up new radar classes. In the face of increasingly complex information resources, single signal recognition has become very simple and the actual use effect is not very good [59, 60]. It needs comprehensive technological innovation and optimization to drive a new application of modern radar signals. Hobson et al. [61] used the combination watershed segmentation and k-means clustering algorithm partitioned merged radar reflectivity into multiscale storm clusters which are able to distinguish between smaller-scale features embedded within a larger storm. The comparisons of data acquisition for different radar types at 200 km and 2000 km contingency are listed in Table 2, which show that there are obvious differences between the two kinds of radar types and more in-depth research is needed to distinguish type 1 or 2 is more in line with reality. Observed storm types of RS1 make up of supercell, ordinary, and short-lived which are different from each other. Based on the data of Table 2, the consistency of storm RS2 type prediction is better than RS1.

The Radar Library is relatively perfect from a theoretical view point, but modern warfare is affected by various factors especially the application of information in complex electromagnetic environment, which will become the main direction of development [62]. In practice, whether certain signals to be identified can be accurately judged will be a great test. A phase-modulated surface radar type is presented by Chambers et al. [63] with the comparison of nominal switching frequency displayed in Figure 7. They demonstrate wideband spectral component suppression levels of about 20 dB which is equivalent to reducing the detection range of an electronic support measures receiver by a factor of 10. The code length bits decrease with the nominal switching frequency increasement and the zero-bit sum peak sidelobe level value increases gradually.

Mohamed [64] investigated a high-resolution with no sinusoidal radar whose range resolution is smaller than or equal to target length. The extended target is illuminated by a sequence of short rectangular pulses. The received signal consists of a number of identical target signatures where each provides information about target shape, size, and orientation. As a result, target classification and recognition can be performed at any aspect angle. The radar type based on the feature space trajectory concept was identified by Kim and Jeong [65]. They proposed a systematic approach with the central moments of a range profile and a Bayes classifier to yielding very small dimensional feature vectors, which is an available technique skill to diversity in radar signal processing [66].

3.3. Classification of Signal. Potential applications requiring classification of unknown radar signals include maritime barrier operations aimed at preventing illegal immigration [3, 10], arms and drug smuggling [11, 18], illegal fishing, and piracy [6, 14]. RS classification method is based on diverse radar signals which has been extensively studied and applied in the field of signal classification. Radar signal classification mode is illustrated in Figure 8 which includes the methods of the neural network [67], cluster method [68], similitude entropy [69], support vector machine [70], time-scale characteristics [71], modulation domain [72], basis function neural networks [73], Rihaczek distribution and Hough transform [74], frequency estimation [75], pulse repetition interval [76], bispectrum two dimensions [77], and so on. These classification methods synthesize the research methods of many disciplines, such as system control [67, 73], heat transfer [69], and mathematics [68, 77]. These radar classification methods also reflect the integration of multidisciplines which is helpful to improve the performance of radar signals.

To enable reliable functioning in complex signal environments with multiple radar emitters, modern signal classification must be capable of processing unknown, corrupted, and ambiguous measurements in a robust and reliable manner. For vehicle-type radar classification and speed determination in a computationally cost-effective manner, Cho and



TISLR1 = 0.008

TISLR2 = 0.0085

TISLR3 = 0.009

Figure 6: Comparison of the different optimization waveforms of the RS.

Table 2: Comparison of data acquisition for different radar types at 200 km and 2000 km contingency [61].

	200 km contingency	Observed storm types of RS 1		
		Supercell	Ordinary	Short-lived convective
	Supercell	50	51	5
	Ordinary	31	314	52
	Short-lived	1	39	147
Forecasted storm types of RS 2	2000 km contingency	Observed storm types RS 1		
		Convective line	Unorganized	
	Convective line	66	23	
	Unorganized	33	200	

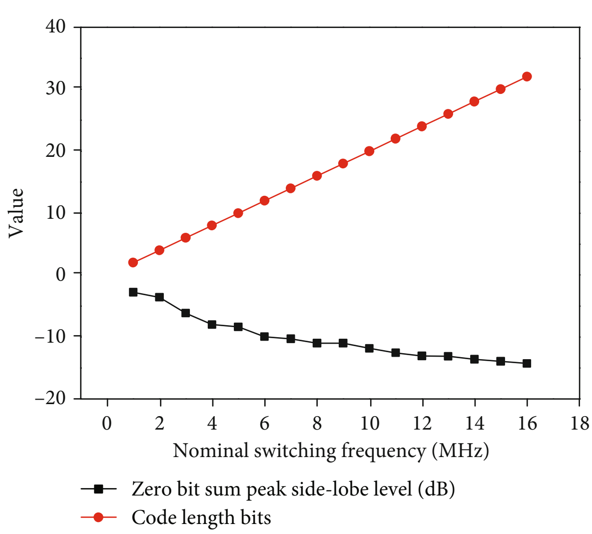


Figure 7: Comparison of nominal switching frequency (the data were obtained from Ref. [63]).

Tseng [70] developed optimization algorithm which will benefit for real-time intelligent transportation systems with 8 categories of radar signal classification mode setting. The recognition rate comparisons of frequency f_m under different linear discriminant analysis (LDA) and support vector machine (SVM) are listed in Figure 9 which suggested support vector machine approach is an effective radar signal classification method with high recognition and correct rate. SVM has the maximum failure rate (≤97%) and the LDA has a lower failure rate (≤94%) which have the same change trend.

It is extremely necessary to classify the modulation type of the intercepted RS for an electronic intelligence receiver in a noncooperative environment (fall detection) with the experimental and simulation methods [71, 72]. The classification of radar signals mainly depends on the improvement of related algorithms [73]. The simulations of the classification algorithm proposed by Zeng et al. [74] showed that the probabilities of successful radar recognition can reach 90% when the SNR is above -4 dB. On the theoretical research of radar signal classification, Gini et al. [75] completed the derivation of the joint maximum likelihood estimator of complex amplitude and Doppler frequency, which used the method of a radar target signal embedding in correlated non-Gaussian clutter modelled as a compound-Gaussian process. It is different from the previous direct classification of radar signals in the past that Kauppi et al. [76] classify the received pulse train with the use of sliding windows to clearly detect submodes. The accuracy, robustness, and reliability of the technology are proved by a large number of static and dynamic simulations of pulse repetition interval modulation modes. With the application and development of large data and related databases [77], a reference library with the single and two aspects library correlations for radar signals is established by Smith et al. [78] to improve the efficiency of radar signal classification. The single and two aspects of library correlations for wheeled and

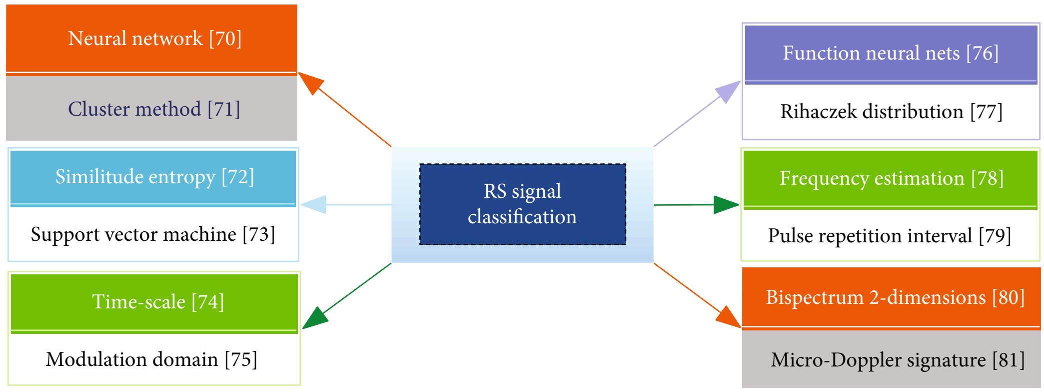


FIGURE 8: Radar signal classification mode.

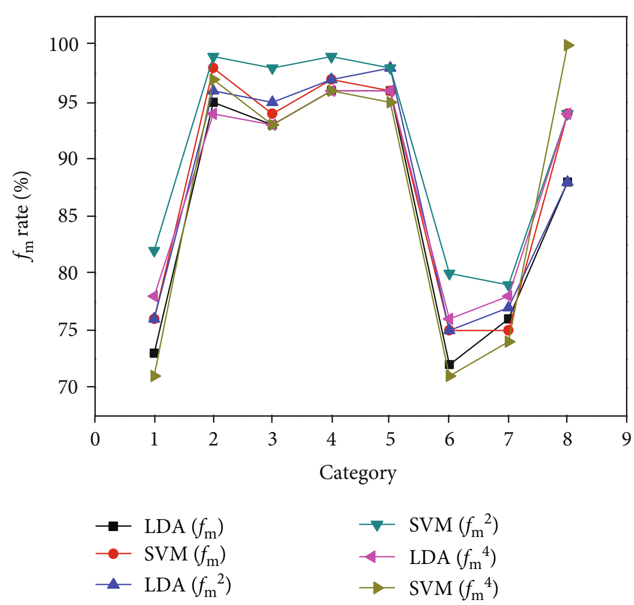


FIGURE 9: Comparison of recognition rate for different classifiers and categories (the data were obtained from Ref. [70]).

tracked vehicles radar signals are displayed in Figure 10 under the angle of 0°, 30°, 60°, 90°, 120°,150°, and 180°. Although there are great errors in the two correction methods, it does promote the establishment and development of radar signal classification database [79, 80].

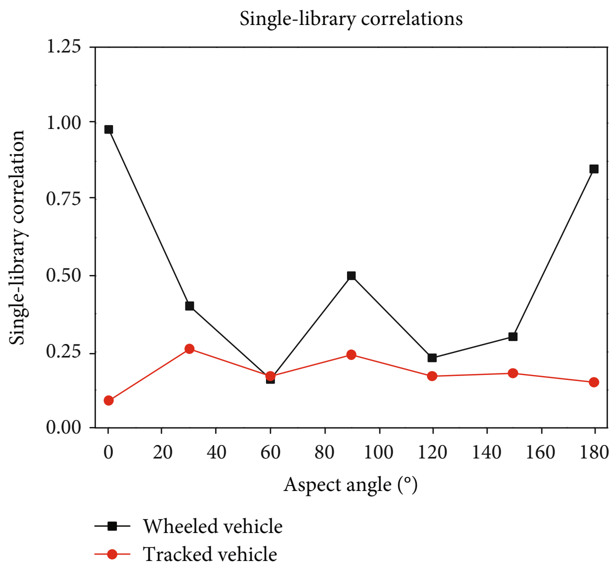
4. Radar Signal Processing Technology

The characteristics of radar signal include carrier frequency [81], its variation characteristics and pulse repetition frequency [82] and its variation characteristics, pulse width and its variation characteristics [83], antenna scanning type, antenna scanning period, signal spectrum, and signal azimuth, and there are a large number of intravenous characteristics of signals [84, 85]. The extraction of features from radar signals is influenced by many factors, which leads to the existence of subjectivity, speculation, and a certain degree of disordered distribution of the extracted features [86]. There are many methods for radar signal processing including the application of single method [87, 88] and the combination of multidisciplinary and multimethod (as shown in Figure 11). In order to eliminate the subjectivity of feature extraction and improve the accuracy of radar signal sorting, recognition, and processing, effective multidisciplinary and multimethods are needed to perform signal processing work [89–91].

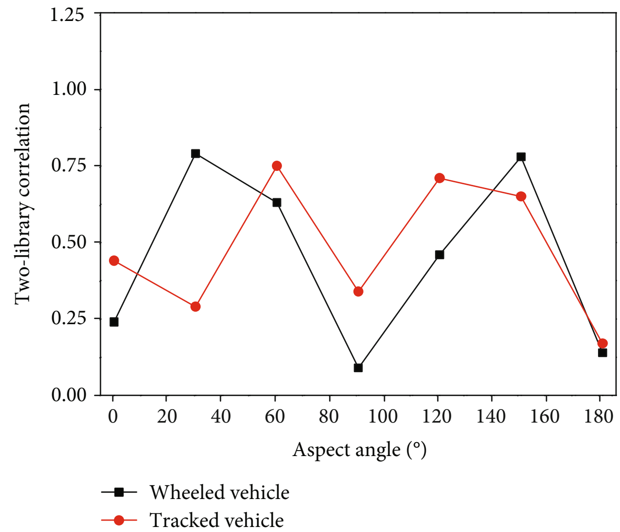
The performance of processed radar signals has been greatly improved in all aspects. Different radar signals adopt varied processing methods in order to improve their special performance requirement. Reconfigurable computing application can significantly improve the working efficiency of high-performance front-end radar signal processor [92]. Frequency subband processing and feature analysis of forward-looking ground-penetrating can remarkably enhance the diagnostic judgment rate of the landmine detection [93]. Radar signal processing for vehicle speed measurements promotes the development of driverless and intelligent transportation [94], and the RS performance improvement aspect through processing is listed in Table 3.

The allocation requirement radar resources must be executed efficiently by a process method to optimize the performance of the overall radar system [95], which forced the research methods of signal processing to develop toward multidisciplinary and multiplan.

4.1. Adaptive Radar Signal Process. Adaptive radar signal process is a self-adaptation method which can adjust the sequence, parameters, boundary conditions, or constraints according to the characteristics of the processing RS data [96], which can make the signal adapt to the statistical distribution and structural characteristics of the processed data to achieve the best processing effect [97]. Bhattacharya et al. [98] are concerned with the Wiener solution of partially adaptive radar arrays using the cross-spectral subspace selection technique. Compared with the performance of principal component techniques, the adaptive radar arrays have better partially adaptive performance and its output signal-to-interference plus noise ratio for the eigen-subspace Wiener filter is 7.65 dB with a loss of 15.63 dB. Owing to the advantages of time-varying null steering in both the temporal and spatial frequency domains, adaptive beamforming methods



(a) Single-library correlations



(b) Two-library correlations

FIGURE 10: Single and two aspects of library correlations for wheeled and tracked vehicles RS.

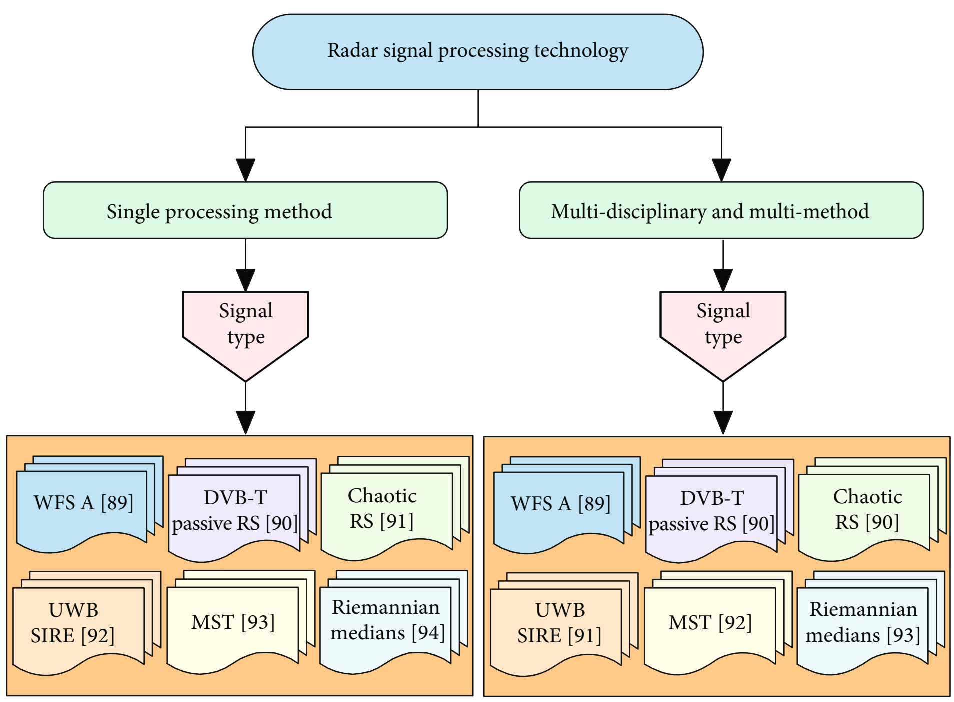


FIGURE 11: RS processing types of single and the combination of multidisciplinary and multimethod.

TABLE 3: RS performance improvement aspect through processing.

Processing methods	Performance improvement aspect	Details
Model-based frequency algorithms [166]	Resolution enhancement	Fourier transformation
Coherent processing [167]	Integrate target energy	Linear transformations
Coprime sampling [168]	Power spectrum density	Ambiguity function of matched filter
Coherent fusion scheme [169]	Range resolution with low sidelobes	Estimate the phase difference

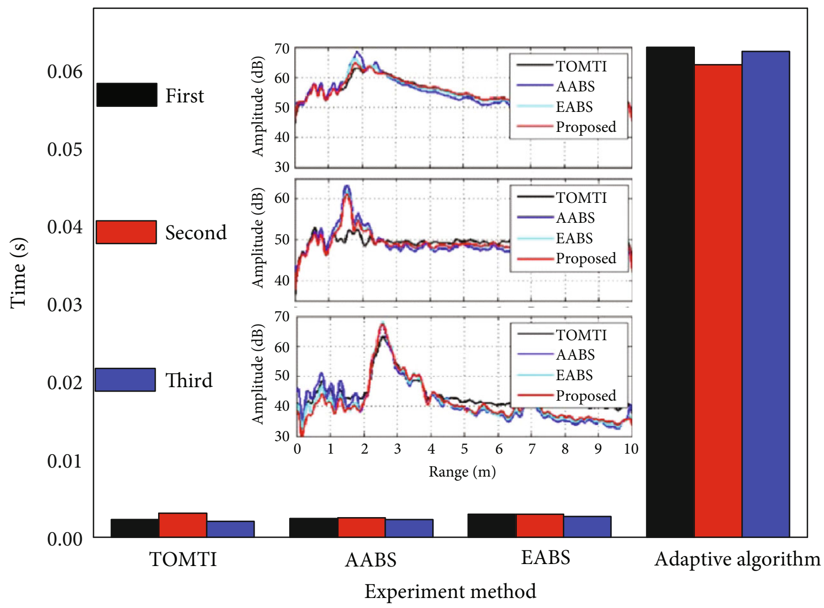


Figure 12: Consumed comparison time of processing 200 pulses in the 3 experiments (the data were obtained from Ref. [101]).

of the RS are studied by Griffiths [99] which can reduce the noise floor in addition to the suppression of strong interference lines such especially at Doppler frequencies -21 Hz and -9 Hz. Raju and Reddy [100] proposed a nonparametric and hyperparameter-free iterative adaptive approach to estimate the power spectral density for getting the accurate amplitude and frequency of the simulated data with less computational time.

Adaptive computing time is related to the structure of the algorithm. Sometimes, in order to get the desired results, it is worth sacrificing some computing time. In order to search the optimum tap-length of the RS combined with target motions, Hu et al. [101] developed an adaptive algorithm under a tap-length gradient control scheme and selected the parameter, which is checked by the experiments on human target with different motions behind wall. Among the approaches of two-order moving target indication (TOMTI), accumulative average background subtraction (AABS), moving average background subtraction (MABS), exponential average background subtraction (EABS), and the proposed adaptive algorithm methods, the comparison of the consumed time and amplitude of processing 200 pulses in the 3 experiments is listed in Figure 12. Proposed adaptive algorithm method needs more computing time (<0.6 s; this time consumption is completely acceptable.) to search optimum tap-length but it is still acceptable for real-time implementation. Compared with the conventional background subtraction methods, the proposed adaptive algorithm magically solved the tailings problem with overcoming the target information loss in the two-order moving target indication method, which can retain more motion details with a good adaptive ability to indicate different motions.

Liu et al. [102] designed the multichannel adaptive filters to achieve effective clutter suppression and target signal preservation. Robust adaptive signal processing methods for heterogeneous radar clutter scenarios were measured by Rangaswamy et al. [103] with the self-adaptive method [104]. The adaptive method can be used in many aspects of radar signal processing including radar waveform optimization [105], signal synthesis adaptive antenna design [106], and 2-D signal adaptive processing QR and IQR algorithm optimization [107, 108].

4.2. Pulse Compression Management. The process of generating narrow time pulses by compression filter processing is called pulse compression. The condition of pulse compression is that the transmitting pulse signal has a large time-bandwidth product and a compression network to eliminate the phase dispersion of the input echo signal. Pulse compression signals include linear frequency modulation signal, nonlinear frequency modulation signal and phase-coded signal, and so on. Time-domain processing and frequency-domain processing are two common processing methods. Pulse compression management (PCM) is one of the most necessary and effective means to improve signal performance [109].

Some radar signals employ very narrow pulses which make little jitter inaccuracy large enough to destroy the signal correlation property and then degrade clutter suppression performance. Zhu et al. [110] proposed the PCM method to remove the clutter through impulse plus exponential mean background subtraction algorithm which can improve through-wall human indication performance during the experiments. Levanon and Mozeson [111] created a complementary set between the frequency and pulse of the sequences of N pulses is sequenced to reduce the sidelobe level around the main autocorrelation lobe. The conclusion was obtained that a coherent pulse train can provide an alternative to single-frequency signals with good immunity against mutual interference or jamming. Levanon et al. [112] obtained the frequency weighting to get desired weighting law with reducing the desired sidelobe which can be stretched based on the single-size frequency step. Zhang

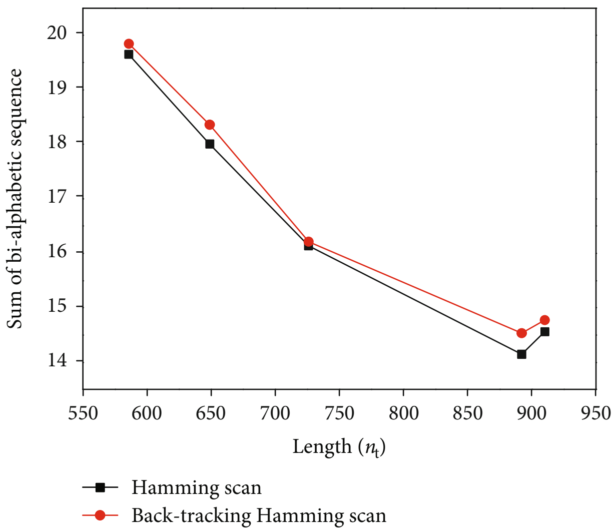


Figure 13: Comparison of Hamming scan and backtracking Hamming scan (the data were obtained from Ref. [114]).

et al. [113] established a monopulse theory radar model to receive signals returned from extended objects and the targets can be localized by a maximum likelihood estimator to detect and localize multiple unresolved extended targets. Based on the desideratum of the merit factor, bialphabetic pulse compression radar signal algorithm was designed by the research team of Pasha et al. [114] to solve the pulse compression problem by Hamming scan optimization. The results showed that the backtracking algorithm for bialphabetic sequence can improve the merit factor values compared with the Hamming scan as displayed in Figure 13. The changes in the two modes are roughly the same, but the backtracking Hamming scan value is higher than Hamming scan with the max value of 19.8 and the min value of 14.

The optimization is not only limited to the improvement of algorithm but also embodied in the design and upgrade of digital signal processor. Real-time parallel implementation of pulse Doppler radar signal processing chain was designed by Klilou et al. [115] to improve the parallel system efficiency about 90% by experiment verification. The interprocessor communication can be reduced by the proposed optimization with eliminating the Doppler filtering and the postprocessing. The parallel machine executes 94% of communication with the pulse compression. The pulsed high-efficiency power amplifier can improve the spectral purity with the increasements of the power amplifier and peak-to-average ratio with 78% and 90%, respectively [116].

4.3. Digital Filtering. Filtering is an effective technique to eliminate clutter and enhance RS performance which is an important measure to suppress and prevent interference by filtering the frequency of a specific band in the signal. Radar interferogram filtering for geophysical applications was developed by Goldstein and Werner [117] to improve both measurement accuracy and phase. Compared with 64% of the unfiltered segment, it achieves 92% unwrapping the test interferogram segment. The digital filtering function of the Potin et al. [118] is to remove clutter with the established clutter geometrical model of a frequency analysis. The R_c (the first criterion is the percentage measurement of the clutter power) comparisons of the adapted filter and the filter coefficients depend the filter order $N_w = 5$, 10, and 15 are listed in Figure 14 which illustrated that R_c decreases with the increase of filter order. The adapted filter has significant advantages with the $R_c = 96\%$. Adapted filtering has stronger adaptability and better filtering performance with research object of uncertain system or information process. It is widely used in many fields, such as system identification, echo cancellation, adaptive spectrum enhancement, adaptive channel equalization, speech linear prediction, adaptive antenna array, and so on. Moreover, the implementation of adapted filter is simple with low computational cost with high false alarm detection probability.

How the pulses are attenuated and distorted and the frequency-dependent properties were analyzed by Shaari et al. [119] through the ground-penetrating radar. The pulse shape and amplitude relationship between the different moisture contents and of propagation distances were obtained which expanded the research depth and scope of filtering. Based on uniform filter banks, the spectrum and variance estimation of atmospheric radar signal were studied by Reddy and Reddy [120] to find wind speed at an altitude of 18 kilometers which made the SNR improvement of about 6 dB at low SNR regions. The effect of single filtering application is obvious, and the performance of filtering function combined with other methods is improved, such as the optimization of wavelet in radar signal Brown noise [121], deinterlacing, and pseudorandom filtering recognition [122].

4.4. Doppler Method. The phenomenon when the source and the observer have relative motion and the frequency of the wave received by the observer is different from the frequency of the source is called Doppler effect. Pulse Doppler radar can search at the same time of tracking and can change or increase the working state of radar which makes radar have the ability to deal with various jamming and recognize targets beyond visual range. Radar can work at different pulse repetition frequencies and has the ability of adaptive waveform. It can select low, medium, or high pulse repetition frequencies waveforms according to different tactical states and can obtain the best performance of various working states [123]. Using Doppler beam sharpening technology to obtain high resolution, high-resolution map mapping and high-resolution local magnification mapping can be provided in air-to-ground applications [124, 125] and dense formation targets can be distinguished by judging the state of air-to-air enemy. Within the framework of the Kirchhoff approximation, different mD responses for various air targets were experimental tested by Meshkov and Karaev [126] using collecting the radar signal with the digital television broadcast signals. The shift and width of the Doppler spectrum of a microwave signal were derived which can stand for the reflected from a rough water surface in the case of a small incidence angle. Doppler spectrum of a microwave radar signal with a fundamental modulation period of 0.83 ms reflected from a water surface with the 24 fan blades and

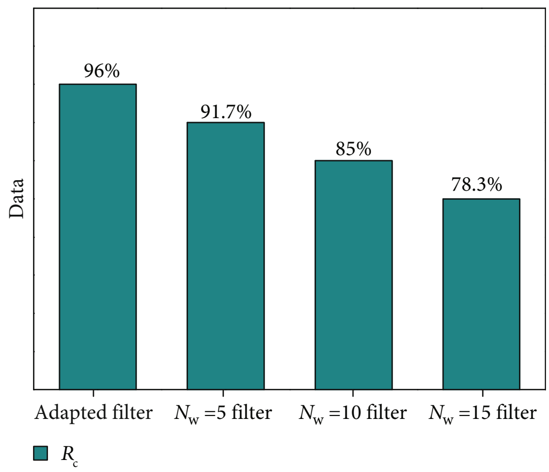


FIGURE 14: Comparison of the first criterion is the percentage measurement of the clutter power R_c (the data were obtained from Ref. [118]).

the specify nominal operation 55%~60% of the max value, resulting in an expected fan speed of approximately 3000 r/min [127].

5. Future Research Trends and Challenges Based on the Multidisciplinary

The progress and development of radar technology cannot be separated from the promotion of multidisciplinary basic research, such as optics [128, 129], measuring means [130–132], imaging [133], experimental observation [134], algorithm improvement [135], and model optimization [136]. Multidisciplinary radar design and optimization [137, 138] not only considers the coupling design between disciplines but also is more appropriate to the essence of the problem, so that the radar signal can be high quality and fidelity. Most multidisciplinary optimizations [139] consider the multiobjective mechanism to balance the interdisciplinary influence and explore the overall optimal solution, which can effectively avoid the waste of manpower, physics, financial resources, and time caused by repeated design [140]. Some radar multidisciplinary optimization can adopt collaborative design and concurrent design, which can shorten the cycle as much as possible.

5.1. Future Research Trends

5.1.1. Deeply Expand the Basic Content. With the scientific progress in microwave, computer, semiconductor, large-scale integrated circuit, and other fields, radar technology is developing continuously and its connotation and research content are constantly expanding [141]. Radar function has gradually evolved from a single function to a multitask and multifunction radar system. Radar engineering theory is not confined to Shannon theorem whose working frequency, bandwidth, and resolution are improving with the multifunctional architecture [142]. The implementation and analysis of the path planning and wavelength are also applied [143, 144].

5.1.2. Diversification of Signal Processing Technology. In addition to conventional processing methods such as correlated/uncorrelated processing, signal processing technology includes space-time adaptive (STAP), multiple-input multiple-output (MIMO), synthetic aperture (SAR/I-SAR/CSAR), synthetic pulse and aperture (SIAR), and adaptive/cognitive radar signal processing technology based on artificial intelligence [145].

5.1.3. Classification of Detection Techniques. The corresponding detection means are also varied for differentiated waveforms of radar signals [146]. Multiple technology methods of wavelet-based transform, clutter detection, algorithmic improvement, time-frequency, and phase-coded are applied to detect the radar signal, which can reduce signal divergence and attenuation dramatically [147, 148]. The work done can effectively help promote the stability of radar signal which is essential to image resolution of coherent imaging, data transmission, and radar receive.

5.2. Research Challenges

5.2. Research Challenges. Significant changes have taken place in the targets observed by radar, and the electromagnetic environment of radar work has deteriorated seriously, which has a tremendous impact on the development of radar.

5.2.1. New Challenges in the Used Environment. Ground radars are difficult to detect and early warn from a long distance because of the observation dead angle, strong ground clutter background, and much higher flight speed than ground vehicles. The harsh electromagnetic environment of strong electronic jamming in the future, as well as the discovery, recognition, and confirmation of high-speed, invisible targets (cruise missiles) and camouflage, concealment and deception CCD targets in the background of severe ground and sea clutter, makes it difficult for the original centralized launching mechanical scanning radar to meet these new requirements [149].

5.2.2. Active Phased Array Radar Technical Requirement. Active phased array radar needs a large number of T/R components whose performance, weight, size, and cost of T/R components are important considerations for the whole AESA system. The phase shifter, attenuator, amplifier, preamplifier driver stage, switch, and control circuit are all integrated in a single circuit with only about 4~5mm^2 chip of the multifunctional core which is limited by chip development technology.

5.2.3. Heat Dissipation of Radar System. Radar system is a complex and multifunctional integrated system. Data processing is carried out at all times. This way of work will generate a lot of heat. The problem of heat dissipation of multifunctional radar system needs to be solved urgently. Some heat dissipation techniques can be tried and applied, such as heat pipe heat dissipation [150, 151] and establishment and development of heat management system [152, 153].

6. Conclusion

With the increasing energy shortage [154–158], pollutant generation [159–163], and the rapid development of large-scale integrated circuits, the application of radar has gradually changed from military to civilian [164, 165]. It has been found that the development of radar [166–170] in the field of industrial products is unprecedented in our daily life, covering transportation, search and tracking, navigation, and so on. Direct or indirect acquisition of high-quality and stable radar signals is the main research focus of researchers [171–173]. Radar signal, as a special signal, has opened up new research fields and methods for meteorology, exploration, flight, and autopilot and even opened up new horizons [174–176]. In this review, the design and classification of the radar signal are introduced by this paper primarily to reflect signal's differences and advantages according to radar signal respective characteristics. And then the multidisciplinary processing technology of the radar signal is classified and compared in details referring to adaptive radar signal process, pulse signal management, digital filtering signal mode, Doppler method, and high frequency. It can be concluded that radar signals will become more common and stable in future applications.

(1) The transmission process of radar signal is summarized including the transmission steps of radar signal and the factors affecting radar signal transmission and radar information screening

(2) The design method of radar signal and the corresponding signal characteristics are compared in terms of performance improvement. Radar signal classification method and related influencing factors are also contrasted and narrated. Different radar signal forms have different applications and effects

(3) Radar signal processing technology is described in detail including multidisciplinary technology synthesis. Adaptive radar signal process, pulse compression management, digital filtering, and Doppler method are very effective technical means, which have its own unique advantages

(4) The current trends of radar signal research, the technical progress achieved, and the existing limitations are listed. The future research trends and challenges of technologies of the radar signals are proposed

Nomenclature

RS: Radar signal
NUBF: Nonuniform beam filling
UWB: Ultra-wideband
MIMO: Multiple-input multiple-output
ACF SLL: Autocorrelation function sidelobe level
AF: Ambiguity function
BCL: Barker code length
t': Main lobe centered at time
FEB: Finite energy and bandwidth
L: Number of sequences
RSP: Radar signal processor
DFC: Discrete frequency-coded
ASP: Autocorrelation sidelobe peaks
CP: Cross-correlation peaks
JPL: Jet Propulsion Laboratory
FMCW: Frequency-modulated continuous-wave
IRFs: Impulse response functions
MMI: Maximizing mutual information
PMS: A phase-modulated surface
LDA: Linear discriminant analysis
SVM: Support vector machine
f_{m}: Range frequency
TOMTI: Two-order moving target indication
AABS: Accumulative average background subtraction
MABS: Moving average background subtraction
EABS: Exponential average background subtraction
PCM: Pulse compression management
R_{c}: The first criterion is the percentage measurement of the clutter power
N_{w}: The filter coefficients depend only on the filter order
SNR: Signal to noise ratio.

Conflicts of Interest

The authors declare that they have no conflict of interests regarding the publication of this paper.

Acknowledgments

This work is supported by the National Natural Science Foundation of China under the research grant of 61471370.

References

[1] F. Michler, B. Scheiner, F. Lurz, R. Weigel, and A. Koelpin, "(Micro) metering with microwaves: a low-cost, low-power, high-precision radar system," *IEEE Microwave Magazine*, vol. 20, no. 1, pp. 91–97, 2019.

[2] T. G. Farr, P. A. Rosen, E. Caro et al., "The shuttle radar topography mission," *Reviews of Geophysics*, vol. 45, no. 2, p. 361, 2007.

[3] B. Rabus, M. Eineder, A. Roth, and R. Bamler, "The shuttle radar topography mission—a new class of digital elevation models acquired by spaceborne radar," *ISPRS Journal of Photogrammetry and Remote Sensing*, vol. 57, no. 4, pp. 241–262, 2003.

[4] R. J. Doviak, D. S. Zrnic, and R. M. Schotland, "Doppler radar and weather observations," *Applied Optics*, vol. 33, no. 21, article 4531, 1994.

[5] J. L. Davis and A. P. Annan, "Ground-penetrating radar for high-resolution mapping of soil and rock stratigraphy," *Geophysical Prospecting*, vol. 37, no. 5, pp. 531–551, 2010.

[6] J. Cai, Y. Zhang, R. J. Doviak, Y. Shrestha, and P. W. Chan, "Diagnosis and classification of typhoon-associated low-altitude turbulence using HKO-TDWR radar observations and machine learning," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 57, no. 6, pp. 3633–3648, 2019.

[7] W. Shao, A. Bouzerdoum, S. L. Phung, L. Su, B. Indraratna, and C. Rujikiatkamjorn, "Automatic classification of

ground-penetrating-radar signals for railway-ballast assessment," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 49, no. 10, pp. 3961–3972, 2011.

[8] D. Massonnet and K. L. Feigl, "Radar interferometry and its application to changes in the Earth's surface," *Reviews of Geophysics*, vol. 36, no. 4, pp. 441–500, 1998.

[9] L. Piazzo, M. C. Raguso, R. Seu, and M. Mastrogiuseppe, "Signal enhancement for planetary radar sounders," *Electronics Letters*, vol. 55, no. 3, pp. 153–155, 2019.

[10] B. A. Cooper, M. G. Raphael, and D. E. Mack, "Radar-based monitoring of marbled murrelets," *Condor*, vol. 103, no. 2, pp. 219–229, 2001.

[11] U. Majumder, M. Minardi, E. Blasch et al., "Radar signals dismount data production," in *Proceedings Volume 6237, Algorithms for Synthetic Aperture Radar Imagery XIII*, Orlando (Kissimmee), FL, USA, May 2006.

[12] N. Pohl, M. Gerding, B. Will, T. Musch, J. Hausner, and B. Schiek, "High precision radar distance measurements in overmoded circular waveguides," *IEEE Transactions on Microwave Theory and Techniques*, vol. 55, no. 6, pp. 1374–1381, 2007.

[13] C. Haldoupis, G. C. Hussey, A. Bourdillon, and J. Delloue, "Azimuth-time-intensity striations of quasiperiodic radar echoes from the midlatitude E region ionosphere," *Geophysical Research Letters*, vol. 28, no. 10, pp. 1933–1936, 2001.

[14] E. M. Bracalente, C. L. Britt, and W. R. Jones, "Airborne Doppler radar detection of low-altitude wind shear," *Journal of Aircraft*, vol. 27, no. 2, pp. 151–157, 2015.

[15] P. Hyson, "Wind finding data from radar tracking of high altitude sensors," *Quarterly Journal of the Royal Meteorological Society*, vol. 94, no. 402, pp. 592–597, 2010.

[16] S. Jazayeri, N. Kazemi, and S. Kruse, "Sparse blind deconvolution of ground penetrating radar data," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 99, pp. 1–10, 2019.

[17] M. R. Bell, "Information theory and radar waveform design," *IEEE Transactions on Information Theory*, vol. 39, no. 5, pp. 1578–1597, 2002.

[18] S. Skaria, A. al-Hourani, M. Lech, and R. J. Evans, "Hand-gesture recognition using two-antenna Doppler radar with deep convolutional neural networks," *IEEE Sensors Journal*, vol. 19, no. 8, pp. 3041–3048, 2019.

[19] D. Massonnet, M. Rossi, C. Carmona et al., "The displacement field of the Landers earthquake mapped by radar interferometry," *Nature*, vol. 364, no. 6433, pp. 138–142, 1993.

[20] S. Mohd Basir, I. Pasya, T. Yaakob, N. E. Abd Rashid, and T. Kobayashi, "Improvement of Doppler measurement using multiple-input multiple-output (MIMO) concept in radar-based automotive sensor detecting pedestrians," *Sensor Review*, vol. 38, no. 2, pp. 239–247, 2018.

[21] H. Z. Zhao, F. U. Qiang, and J. X. Zhou, "The analysis of acceleration resolution and application for the radar signal," *Acta Electronica Sinica*, vol. 31, no. 6, pp. 958–961, 2003.

[22] W. Kofman, R. Orosei, and E. Pettinelli, "Radar signal propagation and detection through ice," *Space Science Reviews*, vol. 153, no. 1-4, pp. 249–271, 2010.

[23] E. P. Magee and T. J. Kane, "Bistatic coherent laser radar signal-to-noise ratio," *Applied Optics*, vol. 41, no. 9, pp. 1768–1779, 2002.

[24] G. P. Tsoflias, J. P. van Gestel, P. L. Stoffa, D. D. Blankenship, and M. Sen, "Vertical fracture detection by exploiting the polarization properties of ground-penetrating radar signals," *Geophysics*, vol. 69, no. 3, pp. 803–810, 2004.

[25] K. Y. Guo, X. Q. Sheng, R. H. Shen, and C.-J. Jing, "Influence of migratory scattering phenomenon on micro-motion characteristics contained in radar signals," *IET Radar Sonar & Navigation*, vol. 7, no. 5, pp. 579–589, 2013.

[26] G. Alberti, G. Schirinzi, G. Franceschetti, and V. Pascazio, "Time-domain convolution of one-bit coded radar signals," *IEE Proceedings F-Radar and Signal Processing*, vol. 138, no. 5, pp. 438–444, 2002.

[27] M. Gosset and I. Zawadzki, "Effect of nonuniform beam filling on the propagation of the radar signal at X-band frequencies. Part I: changes in thek(Z) relationship," *Journal of Atmospheric and Oceanic Technology*, vol. 18, no. 7, pp. 1113–1126, 2001.

[28] M. Gosset, "Effect of nonuniform beam filling on the propagation of radar signals at X-band frequencies. Part II: examination of differential phase shift," *Journal of Atmospheric and Oceanic Technology*, vol. 21, no. 2, pp. 358–367, 2004.

[29] E. Nielsen, C. F. D. Pozo, and P. J. S. Williams, "VHF coherent radar signals from the E region ionosphere and the relationship to electron drift velocity and ion acoustic velocity," *Journal of Geophysical Research Space Physics*, vol. 107, no. A1, pp. SIA 4-1–SIA 4-9, 2002.

[30] C. Grima, D. D. Blankenship, and D. M. Schroeder, "Radar signal propagation through the ionosphere of Europa," *Planetary and Space Science*, vol. 117, pp. 421–428, 2015.

[31] J. R. Espley, W. M. Farrell, D. A. Brain et al., "Absorption of MARSIS radar signals: solar energetic particles and the daytime ionosphere," *Geophysical Research Letters*, vol. 34, no. 9, pp. 139–158, 2007.

[32] E. Rignot, K. Echelmeyer, and W. Krabill, "Penetration depth of interferometric synthetic-aperture radar signals in snow and ice," *Geophysical Research Letters*, vol. 28, no. 18, pp. 3501–3504, 2001.

[33] S. Close, T. Hamlin, M. Oppenheim, L. Cox, and P. Colestock, "Dependence of radar signal strength on frequency and aspect angle of nonspecular meteor trails," *Journal of Geophysical Research Space Physics*, vol. 113, no. A6, article A06203, 2008.

[34] A. Muqaibel and A. Safaai-Jazi, "Characterization of wall dispersive and attenuative effects on UWB radar signals," *Journal of the Franklin Institute*, vol. 345, no. 6, pp. 640–658, 2008.

[35] V. K. Anandan, G. Ramachandra Reddy, and P. B. Rao, "Spectral analysis of atmospheric radar signal using higher order spectral estimation technique," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 39, no. 9, pp. 1890–1895, 2002.

[36] D. J. Daniels, "Resolution of ultra-wideband radar signals," *IEE Proceedings-Radar, Sonar and Navigation*, vol. 146, no. 4, pp. 189–194, 2002.

[37] S. Y. Matrosov, "Prospects for the measurement of ice cloud particle shape and orientation with elliptically polarized radar signals," *Radio Science*, vol. 26, no. 4, pp. 847–856, 2016.

[38] Z. Wang, F. Tigrek, O. Krasnov, F. van der Zwan, P. van Genderen, and A. Yarovoy, "Interleaved OFDM radar signals for simultaneous polarimetric measurements," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 48, no. 3, pp. 2085–2099, 2012.

[39] J. Davy, "Data modeling and simulation applied to radar signal recognition," *Provincial Medical & Surgical Journal*, vol. 26, no. 25, pp. 165–173, 2005.

[40] C. H. Hsieh, Y. F. Chiu, Y. H. Shen, T. S. Chu, and Y. H. Huang, "A UWB radar signal processing platform for real-time human respiratory feature extraction based on four-segment linear waveform model," *IEEE Transactions on Biomedical Circuits and Systems*, vol. 10, no. 1, pp. 219–230, 2016.

[41] M. P. Kolba, P. A. Torrione, W. R. Scott, and L. M. Collins, "Information-based sensor management for landmine detection using electromagnetic induction, ground-penetrating radar, and seismic sensors," *Journal of the Acoustical Society of America*, vol. 123, no. 5, article 3042, 2008.

[42] M. D. Alekhin, L. N. Anishchenko, A. V. Zhuravlev et al., "Estimation of information value of diagnostic data obtained by bioradiolocation pneumography in non-contact screening of sleep apnea syndrome," *Biomedical Engineering*, vol. 47, no. 2, pp. 96–99, 2013.

[43] K. B. Cooper, R. J. Dengler, N. Llombart, B. Thomas, G. Chattopadhyay, and P. H. Siegel, "THz imaging radar for standoff personnel screening," *IEEE Transactions on Terahertz Science and Technology*, vol. 1, no. 1, pp. 169–182, 2011.

[44] J. Blackledge, "Radar screening of aerospace vehicles using plasma clouds," *ISAST Transactions on Electronics and Signal Processing*, vol. 1, no. 1, pp. 61–71, 2007.

[45] T. Bierwagen, K. Eyferth, and H. Helbing, "Radar screen information access: an explaratory investigation," *Control Engineering Practice*, vol. 4, no. 8, pp. 1177–1182, 1996.

[46] L. Spafford, "Optimum radar signal processing in clutter," *IEEE Transactions on Information Theory*, vol. 14, no. 5, pp. 734–743, 1968.

[47] H. Okamoto, "Information content of the 95-GHz cloud radar signals: theoretical assessment of effects of nonsphericity and error evaluation of the discrete dipole approximation," *Journal of Geophysical Research Atmospheres*, vol. 107, no. D22, pp. AAC 4-1–AAC 4-16, 2002.

[48] R. Price, "Correction to 'optimum detection of radar signals in noise, with application to scatter-multipath communication I'," *IRE Transactions on Information Theory*, vol. 3, no. 4, pp. 256–256, 2003.

[49] H. Kai, "A new OFDM phase-coded stepped-frequency radar signal and its characteristic," *Journal of Electronics and Information Technology*, vol. 33, no. 3, pp. 677–683, 2011.

[50] S. P. Singh and K. S. Rao, "Discrete frequency-coded radar signal design," *IET Signal Processing*, vol. 3, no. 1, pp. 7–16, 2009.

[51] M. A. Sebt, A. Sheikhi, and M. M. Nayebi, "Orthogonal frequency-division multiplexing radar signal design with optimised ambiguity function and low peak-to-average power ratio," *IET Radar Sonar & Navigation*, vol. 3, no. 2, pp. 122–132, 2009.

[52] N. J. Mohamed, "Nonsinusoidal radar signal design for stealth targets," *IEEE Transactions on Electromagnetic Compatibility*, vol. 37, no. 2, pp. 268–277, 1995.

[53] W. Schempp, "Analog radar signal design and digital signal processing-a Heisenberg nilpotent Lie group approach," *Lecture Notes in Physics*, vol. 250, pp. 1–27, 1986.

[54] T. J. Nohara, "Design of a space-based radar signal processor," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 34, no. 2, pp. 366–377, 1998.

[55] Y. Song, J. Hu, J. Zhu, T. Jin, and Z. Zhou, "Waveform design method under dual constraints for radar imaging," *IET Radar, Sonar and Navigation*, vol. 12, no. 5, pp. 575–584, 2018.

[56] C. Haldoupis, G. J. Sofko, J. A. Koehler, and D. W. Danskin, "A new look at type 4 echoes of radar aurora," *Journal of Geophysical Research Space Physics*, vol. 96, no. A7, pp. 11353–11362, 1991.

[57] Z. Shen, L. Tian, Y. Zhang, and G. Ni, "SNR analysis of a new type of airborne three-dimensional gazing gating imaging laser radar system," in *Proceedings Volume 7382, International Symposium on Photoelectronic Detection and Imaging 2009*, p. 122, Beijing, China, August 2009.

[58] Q. Yang, Y. Zhang, and X. Gu, "Design of ultralow sidelobe chaotic radar signal by modulating group delay method," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 51, no. 4, pp. 3023–3035, 2015.

[59] M. Miyakawa, "Tomographic measurement of temperature change in phantoms of the human body by chirp radar-type microwave computed tomography," *Medical & Biological Engineering & Computing*, vol. 31, Supplement 1, pp. S31–S36, 1993.

[60] J. F. Rivest, "Granulometries and pattern spectra for radar signals," *Signal Processing*, vol. 86, no. 5, pp. 1094–1103, 2006.

[61] A. G. Kolodziej Hobson, V. Lakshmanan, T. M. Smith, and M. Richman, "An automated technique to categorize storm type from radar and near-storm environment data," *Atmospheric Research*, vol. 111, no. 1, pp. 104–113, 2012.

[62] J. Li, P. Stoica, L. Xu, and W. Roberts, "On parameter identifiability of MIMO radar," *IEEE Signal Processing Letters*, vol. 14, no. 12, pp. 968–971, 2007.

[63] B. Chambers, A. Tennant, and A. Melnikov, "Detection of a radar signal reflected from a phase-modulated surface," *IEE Proceedings-Radar, Sonar and Navigation*, vol. 153, no. 4, pp. 316–324, 2006.

[64] N. J. Mohamed, "Target signature using nonsinusoidal radar signals," *IEEE Transactions on Electromagnetic Compatibility*, vol. 35, no. 4, pp. 457–465, 2002.

[65] K.-T. Kim and H.-R. Jeong, "Identification of multiaspect radar signals based on the feature space trajectory concept," *IEEE Transactions on Antennas and Propagation*, vol. 53, no. 11, pp. 3811–3821, 2006.

[66] R. Calderbank, S. D. Howard, and B. Moran, "Waveform diversity in radar signal processing," *IEEE Signal Processing Magazine*, vol. 26, no. 1, pp. 32–41, 2009.

[67] J. A. Anderson, M. T. Gately, P. A. Penz, and D. R. Collins, "Radar signal categorization using a neural network," *Proceedings of the IEEE*, vol. 78, no. 10, pp. 1646–1657, 1991.

[68] W. J. Zhang, F. H. Fan, and Y. Tan, "Application of cluster method to radar signal sorting," *Radar Science and Technology*, vol. 4, pp. 219–223, 2004.

[69] S. Q. Wang, D. F. Zhang, D. Y. Bi, and X. J. Yong, "Multiparameter radar signal sorting method based on fast support vector clustering and similitude entropy," *Journal of Electronics & Information Technology*, vol. 33, no. 11, pp. 2735–2741, 2011.

[70] H. J. Cho and M. T. Tseng, "A support vector machine approach to CMOS-based radar signal processing for vehicle classification and speed estimation," *Mathematical and Computer Modelling*, vol. 58, no. 1-2, pp. 438–448, 2013.

[71] A. Gadde, M. G. Amin, Y. D. Zhang, and F. Ahmad, "Fall detection and classifications based on time-scale radar signal characteristics," in *Proceedings Volume 9077, Radar Sensor Technology XVIII*, pp. 103–111, Baltimore, MD, USA, May 2014.

[72] S. J. Roome, "Classification of radar signals in modulation domain," *Electronics Letters*, vol. 28, no. 8, p. 704, 1992.

[73] T. McConaghy, H. Leung, E. Bosse, and V. Varadan, "Classification of audio radar signals using radial basis function neural networks," *IEEE Transactions on Instrumentation & Measurement*, vol. 52, no. 6, pp. 1771–1779, 2003.

[74] D. Zeng, X. Zeng, H. Cheng, and B. Tang, "Automatic modulation classification of radar signals using the Rihaczek distribution and Hough transform," *IET Radar Sonar & Navigation*, vol. 6, no. 5, pp. 322–331, 2012.

[75] F. Gini, M. Montanari, and L. Verrazzani, "Maximum likelihood, ESPRIT, and periodogram frequency estimation of radar signals in K-distributed clutter," *Signal Processing*, vol. 80, no. 6, pp. 1115–1126, 2000.

[76] J. P. Kauppi, K. Martikainen, and U. Ruotsalainen, "Hierarchical classification of dynamically varying radar pulse repetition interval modulation patterns," *Neural Networks*, vol. 23, no. 10, pp. 1226–1237, 2010.

[77] J. Han, M.-H. He, Y.-Q. Zhu, and J. Wang, "Sorting radar signal based on the resemblance coefficient of bispectrum two dimensions characteristic," *Chinese Journal of Radio Science*, vol. 24, no. 5, pp. 286–294, 2009.

[78] G. E. Smith, K. Woodbridge, and C. J. Baker, "Radar micro-Doppler signature classification using dynamic time warping," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 46, no. 3, pp. 1078–1096, 2010.

[79] D. Amiri, M. Keshavarzi, and K. Amiri, "A simple method for pulse repetition interval estimation and tracking radar pulse trains with complex pulse repetition interval modulations," *Advanced Science Letters*, vol. 19, no. 8, pp. 2262–2265, 2013.

[80] S. Zhai and T. Jiang, "Target detection and classification by measuring and processing bistatic UWB radar signal," *Measurement*, vol. 47, no. 1, pp. 547–557, 2014.

[81] F. Gini, A. Farina, and M. Greco, "Selected list of references on radar signal processing," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 37, no. 1, pp. 329–359, 2001.

[82] T. J. Nohara, P. Weber, and A. Premji, "Space-based radar signal processing baselines for air, land and sea applications," *Electronics & Communication Engineering Journal*, vol. 12, no. 5, pp. 229–239, 2000.

[83] B. J. Li, R. Hummel, P. Stoica, and E. G. Zelnio, "Radar signal processing and its applications," *Multidimensional Systems & Signal Processing*, vol. 14, no. 1, pp. 241–263, 2009.

[84] S. Malagodi, L. Orlando, S. Piro, and F. Rosso, "Location of archaeological structures using GPR method: three-dimensional data acquisition and radar signal processing," *Archaeological Prospection*, vol. 3, no. 1, pp. 13–23, 2010.

[85] S. M. Torres, C. D. Curtis, and J. R. Cruz, "Pseudowhitening of weather radar signals to improve spectral moment and polarimetric variable estimates at low signal-to-noise ratios," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 42, no. 5, pp. 941–949, 2004.

[86] M. Soumekh, "Wavefront-based synthetic aperture radar signal processing," *Frequenz*, vol. 55, no. 3-4, pp. 99–113, 2001.

[87] J. E. Palmer, H. A. Harms, S. J. Searle, and L. M. Davis, "DVB-T passive radar signal processing," *IEEE Transactions on Signal Processing*, vol. 61, no. 8, pp. 2116–2126, 2013.

[88] H. Leung and T. Lo, "Chaotic radar signal processing over the sea," *IEEE Journal of Oceanic Engineering*, vol. 18, no. 3, pp. 287–295, 1993.

[89] S. J. Park, J. Ross, D. Shires, D. Richie, B. Henz, and L. Nguyen, "Hybrid core acceleration of UWB SIRE radar signal processing," *IEEE Transactions on Parallel and Distributed Systems*, vol. 22, no. 1, pp. 46–57, 2011.

[90] T. S. Reddy and G. R. Reddy, "MST radar signal processing using cepstral thresholding," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 48, no. 6, pp. 2704–2710, 2010.

[91] M. Arnaudon, F. Barbaresco, and L. Yang, "Riemannian medians and means with applications to radar signal processing," *IEEE Journal of Selected Topics in Signal Processing*, vol. 7, no. 4, pp. 595–604, 2013.

[92] D. R. Martinez, T. J. Moeller, and K. Teitelbaum, "Application of reconfigurable computing to a high performance front-end radar signal processor," *Journal of VLSI Signal Processing Systems for Signal Image and Video Technology*, vol. 28, no. 1/2, pp. 63–83, 2001.

[93] T. Wang, J. M. Keller, P. D. Gader, and O. Sjahputera, "Frequency subband processing and feature analysis of forward-looking ground-penetrating radar signals for land-mine detection," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 45, no. 3, pp. 718–729, 2007.

[94] W. Kleinhempel, W. Stammler, and D. Bergmann, "Radar signal processing for vehicle speed measurements," *Signal Processing*, pp. 1825–1828, 1992.

[95] G. T. Capraro, A. Farina, H. Griffiths, and M. C. Wicks, "Knowledge-based radar signal and data processing: a tutorial review," *IEEE Signal Processing Magazine*, vol. 23, no. 1, pp. 18–29, 2006.

[96] L. E. Brennan and L. S. Reed, "Theory of adaptive radar," *IEEE Transactions on Aerospace and Electronic Systems*, vol. -AES-9, no. 2, pp. 237–252, 2007.

[97] A. Sheikhi, M. M. Nayebi, and M. R. Aref, "Adaptive detection algorithm for radar signals in autoregressive interference," *IEE Proceedings-Radar, Sonar and Navigation*, vol. 145, no. 5, pp. 309–314, 1998.

[98] T. K. Bhattacharya, G. Jones, and S. Haykin, "Information in the time-frequency plane and its applications to adaptive radar signal processing," in *Proceedings Volume 2027, Advanced Signal Processing Algorithms, Architectures, and Implementations IV*, pp. 256–268, San Diego, CA, USA, November 1993.

[99] L. Griffiths, "Time-domain adaptive beamforming of HF backscatter radar signals," *IEEE Transactions on Antennas and Propagation*, vol. 24, no. 5, pp. 707–720, 2003.

[100] C. Raju and T. S. Reddy, "MST radar signal processing using iterative adaptive approach," *Geoscience Letters*, vol. 5, no. 1, 2018.

[101] J. Hu, G. Zhu, T. Jin, and Z. Zhou, "Adaptive through-wall indication of human target with different motions," *IEEE Geoscience and Remote Sensing Letters*, vol. 11, no. 5, pp. 911–915, 2014.

[102] S. Liu, Y. Ma, and Y. Huang, "Sea clutter cancellation for passive radar sensor exploiting multi-channel adaptive filters," *IEEE Sensors Journal*, vol. 19, no. 3, pp. 982–995, 2019.

[103] M. Rangaswamy, F. C. Lin, and K. R. Gerlach, "Robust adaptive signal processing methods for heterogeneous radar clutter scenarios," *Signal Processing*, vol. 84, no. 9, pp. 1653–1665, 2004.

[104] W. Roberts, *Adaptive Radar Signal Processing*, vol. 52, Dissertations and Theses-Gradworks, 2010.

[105] C. Shi, S. Salous, F. Wang, and J. Zhou, "Low probability of intercept-based adaptive radar waveform optimization in signal-dependent clutter for joint radar and cellular communication systems," *EURASIP Journal on Advances in Signal Processing*, vol. 2016, no. 1, 2016.

[106] S. K. Pramanik and G. Panda, "Design of signal synthesis adaptive antenna for estimation of angle of arrival in radar signal processing," *IETE Journal of Research*, vol. 38, no. 6, pp. 311–319, 1992.

[107] S. Dib, M. Barkat, J. M. Nicolas, and M. Grimes, "Two-dimensional signal adaptive processing for airborne radar," *Communications in Computer and Information Science*, vol. 189, pp. 244–257, 2011.

[108] P. Bollini, L. Chisci, A. Farina, M. Giannelli, L. Timmoneri, and G. Zappa, "QR versus IQR algorithms for adaptive signal processing: performance evaluation for radar applications," *IEE Proceedings-Radar, Sonar and Navigation*, vol. 143, no. 5, pp. 328–340, 1996.

[109] F. V. D. Lijn, F. Roth, and M. Verhaegen, "Estimating the impulse response of buried objects from ground-penetrating radar signals," in *Proceedings Volume 5089, Detection and Remediation Technologies for Mines and Minelike Targets VIII*, pp. 387–394, Orlando, FL, USA, September 2003.

[110] G. Zhu, J. Hu, T. Jin, and Z. Zhou, "Effect and compensation of timing jitter in through-wall human indication via impulse through-wall radar," *Radio Engineering*, vol. 23, no. 1, pp. 20–29, 2014.

[111] N. Levanon and E. Mozeson, "Multicarrier radar signal - pulse train and CW," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 38, no. 2, pp. 707–720, 2002.

[112] N. Levanon, "Stepped-frequency pulse-train radar signal," *IEE Proceedings Radar, Sonar and Navigation*, vol. 149, no. 6, pp. 297–309, 2002.

[113] X. Zhang, P. Willett, and Y. Barshalom, "Detection and localization of multiple unresolved extended targets via monopulse radar signal processing," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 45, no. 2, pp. 455–472, 2005.

[114] I. A. Pasha, P. S. Moharir, and N. S. Rao, "Bi-alphabetic pulse compression radar signal design," *Sadhana*, vol. 25, no. 5, pp. 481–488, 2000.

[115] A. Klilou, S. Belkouch, P. Elleaume, P. Le Gall, F. Bourzeix, and M. M'Rabet Hassani, "Real-time parallel implementation of pulse-Doppler radar signal processing chain on a massively parallel machine based on multi-core DSP and serial rapid IO interconnect," *EURASIP Journal on Advances in Signal Processing*, vol. 2014, no. 1, 2014.

[116] M. Roberg, M. Rodriguez, D. Maksimovic, and Z. Popovic, "Efficient and linear amplification of spectrally confined pulsed AM radar signals," *IEEE Microwave and Wireless Components Letters*, vol. 22, no. 6, pp. 279–281, 2012.

[117] R. M. Goldstein and C. L. Werner, "Radar interferogram filtering for geophysical applications," *Geophysical Research Letters*, vol. 25, no. 21, pp. 4035–4038, 1998.

[118] D. Potin, E. Duflos, and P. Vanheeghe, "Landmines ground-penetrating radar signal enhancement by digital filtering," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 44, no. 9, pp. 2393–2406, 2006.

[119] A. Shaari, S. G. Millard, and J. H. Bungey, "Modelling the propagation of a radar signal through concrete as a low-pass filter," *NDT & E International*, vol. 37, no. 3, pp. 237–242, 2004.

[120] T. S. Reddy and G. R. Reddy, "Spectral analysis of atmospheric radar signal using filter banks – polyphase approach," *Digital Signal Processing*, vol. 20, no. 4, pp. 1061–1071, 2010.

[121] A. S. Grispino, G. O. Petracca, and A. E. Dominguez, "Comparative analysis of wavelet and EMD in the filtering of radar signal affected by brown noise," *IEEE Latin America Transactions*, vol. 11, no. 1, pp. 81–85, 2013.

[122] A. W. Ata'a and S. N. Abdullah, "Deinterleaving of radar signals and PRF identification algorithms," *IET Radar, Sonar & Navigation*, vol. 1, no. 5, pp. 340–347, 2007.

[123] J. Klostermeyer, "Maximum entropy estimation of Doppler shift and spectral width of VHF radar signals," *Radio Science*, vol. 24, no. 1, pp. 47–63, 2016.

[124] W. D. Wirth, "Energy saving by coherent sequential detection of radar signals with unknown Doppler shift," *IEE Proceedings-Radar, Sonar and Navigation*, vol. 142, no. 3, pp. 145–152, 2002.

[125] D. A. Warde and S. M. Torres, "The autocorrelation spectral density for Doppler-weather-radar signal analysis," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 52, no. 1, pp. 508–518, 2013.

[126] E. M. Meshkov and V. Y. Karaev, "Determination of the parameters of sea-surface roughness using the Doppler spectrum of a microwave radar signal reflected from a water surface," *Radiophysics and Quantum Electronics*, vol. 47, no. 3, pp. 205–217, 2004.

[127] J. L. Garry and G. E. Smith, "Experimental observations of micro-Doppler signatures with passive radar," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 55, no. 2, pp. 1045–1052, 2019.

[128] M. Aiello, R. Vezzoli, and M. Gianinetto, "Object-based image analysis approach for vessel detection on optical and radar images," *Journal of Applied Remote Sensing*, vol. 13, no. 1, article 14502, 2019.

[129] B. C. Zhou, D. H. Wang, B. Y. Li, Y. J. Zhao, J. J. Ma, and K. X. Li, "Effect of the circular microstructure on absorbing properties of carbonyl iron rubber radar absorbing patch," *International Journal of Modern Physics B*, vol. 33, article 1940049, 2019.

[130] Y. S. Bondarenko, D. A. Marshalov, Y. D. Medvedev et al., "Physical parameters of the asteroid 2017 VR12 from radar and photometric observations," *Astronomy Letters*, vol. 45, no. 2, pp. 104–107, 2019.

[131] X. Xiong, Z. Deng, W. Qi, H. Ou, and Z. Cui, "A novel high-precision range estimation method based on phase of wide-band radar echo," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 57, no. 6, pp. 3392–3403, 2019.

[132] J. Zuk, S. Bocquet, and L. Rosenberg, "New saddle-point technique for non-coherent radar detection with application to correlated targets in uncorrelated clutter speckle," *IEEE Transactions on Signal Processing*, vol. 67, no. 8, pp. 2221–2233, 2019.

[133] W. Feng, J. M. Friedt, G. Cherniak, and M. Sato, "Passive radar imaging by filling gaps between ISDB digital TV channels," *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, vol. 12, no. 7, pp. 2055–2068, 2019.

[134] C. Clemente and J. J. Soraghan, "GNSS-based passive bistatic radar for micro-doppler analysis of helicopter rotor blades," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 504, no. 1, pp. 491–500, 2014.

[135] X. J. Zhang, W. Jia, X. M. Guan, G. Q. Xu, J. Chen, and Y. B. Zhu, "Optimized deployment of a radar network based on an improved firefly algorithm," *Frontiers of Information Technology & Electronic Engineering*, vol. 20, no. 3, article 1365, pp. 425–437, 2019.

[136] E. L. Merle, D. Hauser, and C. Tison, "Directional wave spectra at the regional scale with the KuROS airborne radar: comparisons with models," *Ocean Dynamics*, vol. 69, no. 6, pp. 679–699, 2019.

[137] C. Shi, F. Wang, S. Salous, and J. Zhou, "Low probability of intercept-based radar waveform design for spectral coexistence of distributed multiple-radar and wireless communication systems in clutter," *Entropy*, vol. 20, no. 3, p. 197, 2018.

[138] S. Y. Nusenu, S. Huaizong, P. Ye, W. Xuehan, and A. Basit, "Dual-function radar-communication system design via sidelobe manipulation based on FDA butler matrix," *IEEE Antennas and Wireless Propagation Letters*, vol. 18, no. 3, pp. 452–456, 2019.

[139] S. P. Rajan and C. Vivek, "Analysis and design of microstrip patch antenna for radar communication," *Journal of Electrical Engineering and Technology*, vol. 14, no. 2, pp. 923–929, 2019.

[140] E. Giusti, D. Cataldo, A. Bacci, S. Tomei, and M. Martorella, "ISAR image resolution enhancement: compressive sensing versus state-of-the-art super-resolution techniques," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 54, no. 4, pp. 1983–1997, 2018.

[141] J. V. B. Severino, A. Zimmer, T. Brandmeier, and R. Z. Freire, "Pedestrian recognition using micro Doppler effects of radar signals based on machine learning and multi-objective optimization," *Expert Systems with Applications*, vol. 136, pp. 304–315, 2019.

[142] Y. Song, J. Hu, Y. Dai, T. Jin, and Z. Zhou, "Estimation and mitigation of time-variant RFI in low-frequency ultra-wideband radar," *IEEE Geoscience and Remote Sensing Letters*, vol. 15, no. 3, pp. 409–413, 2018.

[143] S. H. A. Woo, J. J. Shin, and J. Kim, "Implementation and analysis of pattern propagation factor-based radar model for path planning," *Journal of Intelligent and Robotic Systems*, vol. 96, no. 3-4, pp. 517–528, 2019.

[144] R. Zhang and S. Cao, "Real-time human motion behavior detection via CNN using mmwave radar," *IEEE Sensors Letters*, vol. 3, no. 2, pp. 1–4, 2019.

[145] J. L. Chau, "Unexpected spectral characteristics of VHF radar signals from 150-km region over Jicamarca," *Geophysical Research Letters*, vol. 31, no. 23, pp. 357–370, 2004.

[146] M. Bolhasani, E. Mehrshahi, and S. A. Ghorashi, "Waveform covariance matrix design for robust signal-dependent interference suppression in colocated MIMO radars," *Signal Processing*, vol. 152, pp. 311–319, 2018.

[147] M. Anagnostou, E. Nikolopoulos, J. Kalogiros et al., "Advancing precipitation estimation and streamflow simulations in complex terrain with X-band dual-polarization radar observations," *Remote Sensing*, vol. 10, no. 8, pp. 1258–1282, 2018.

[148] B. Gao and J. D. Mathews, "Phase and pattern calibration of the Jicamarca Radio observatory radar using satellites," *Monthly Notices of the Royal Astronomical Society*, vol. 446, no. 4, pp. 3416–3426, 2018.

[149] S. Jazayeri, N. Kazemi, and S. Kruse, "Sparse blind deconvolution of ground penetrating radar data," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 57, no. 6, pp. 3703–3712, 2019.

[150] E. Jiaqiang, X. Zhao, Y. Deng, and H. Zhu, "Pressure distribution and flow characteristics of closed oscillating heat pipe during the starting process at different vacuum degrees," *Applied Thermal Engineering*, vol. 93, pp. 166–173, 2016.

[151] E. Jiaqiang, X. Zhao, H. Liu, J. Chen, W. Zuo, and Q. Peng, "Field synergy analysis for enhancing heat transfer capability of a novel narrow-tube closed oscillating heat pipe," *Applied Energy*, vol. 175, pp. 218–228, 2016.

[152] X. Zhao, J. E, G. Wu et al., "A review of studies using graphenes in energy conversion, energy storage and heat transfer development," *Energy Conversion and Management*, vol. 184, pp. 581–599, 2019.

[153] X. Zhao, J. E, Z. Zhang et al., "A review on heat enhancement in thermal energy conversion and management using field synergy principle," *Applied Energy*, vol. 257, article 113995, 2020.

[154] J. Chen, J. E, S. Kang et al., "Modeling and characterization of the mass transfer and thermal mechanics of the power lithium manganate battery under charging process," *Energy*, vol. 187, p. 115924, 2019.

[155] Q. Peng, Y. Wu, J. E, W. Yang, H. Xu, and Z. Li, "Combustion characteristics and thermal performance of premixed hydrogen-air in a two-rearward-step micro tube," *Applied Energy*, vol. 242, pp. 424–438, 2019.

[156] K. Wei, Y. Yang, H. Zuo, and D. Zhong, "A review on ice detection technology and ice elimination technology for wind turbine," *Wind Energy*, pp. 1–25, 2020.

[157] H. Zuo, G. Liu, J. E et al., "Catastrophic analysis on the stability of a large dish solar thermal power generation system with wind-induced vibration," *Solar Energy*, vol. 183, pp. 40–49, 2019.

[158] H. X. Zou, L. C. Zhao, Q. H. Gao et al., "Mechanical modulations for enhancing energy harvesting: principles, methods and applications," *Applied Energy*, vol. 255, article 113871, 2019.

[159] C. F. Zhou, H. X. Zou, K. X. Wei, and J. G. Liu, "Enhanced performance of piezoelectric wind energy harvester by a curved plate," *Smart Materials and Structures*, vol. 28, no. 12, article 125022, 2019.

[160] E. Jiaqiang, X. Zhao, G. Liu et al., "Effects analysis on optimal microwave energy consumption in the heating process of composite regeneration for the diesel particulate filter," *Applied Energy*, vol. 254, article 113736, 2019.

[161] E. Jiaqiang, M. Zhao, Q. Zuo et al., "Effects analysis on diesel soot continuous regeneration performance of a rotary microwave-assisted regeneration diesel particulate filter," *Fuel*, vol. 260, article 116353, 2020.

[162] Q. Zuo, Y. Xie, J. E et al., "Effect of different exhaust parameters on NO conversion efficiency enhancement of a dual-carrier catalytic converter in the gasoline engine," *Energy*, vol. 190, article 116521, 2020.

[163] Q. Zuo, Y. Xie, Q. Guan et al., "Effect of critical dual-carrier structure parameters on performance enhancement of a dual-carrier catalytic converter and the gasoline engine system," *Energy Conversion and Management*, vol. 204, article 112325, 2020.

[164] C. Peng, Z. Cao, Z. Chen, and X. Wang, "Off-grid DOA estimation using sparse Bayesian learning in MIMO radar with unknown mutual coupling," *IEEE Transactions on Signal Processing*, vol. 67, no. 1, pp. 208–220, 2019.

[165] P. Huang, X. G. Xia, G. Liao, Z. Yang, and Y. Zhang, "Long-time coherent integration algorithm for radar maneuvering weak target with acceleration rate," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 57, no. 6, pp. 3528–3542, 2019.

[166] A. Stelzer and M. Pichler, "Resolution enhancement with model-based frequency estimation algorithms in radar signal processing," *Subsurface Sensing Technologies and Applications*, vol. 4, no. 3, pp. 241–261, 2003.

[167] D. E. Iverson, "Coherent processing of ultra-wideband radar signals," *IEE Proceedings-Radar, Sonar and Navigation*, vol. 141, no. 3, p. 171, 1994.

[168] Q. Wu and Q. Liang, "Coprime sampling for nonstationary signal in radar signal processing," *EURASIP Journal on Wireless Communications and Networking*, vol. 2013, no. 1, 11 pages, 2013.

[169] J. Tian, J. Sun, G. Wang, Y. Wang, and W. Tan, "Multiband radar signal coherent fusion processing with IAA and apFFT," *IEEE Signal Processing Letters*, vol. 20, no. 5, pp. 463–466, 2013.

[170] S. P. Singh and K. S. Rao, "Polyphase radar signal design using modified simulated annealing algorithm," *IETE Journal of Research*, vol. 53, no. 2, pp. 173–182, 2007.

[171] J. R. Klauder, "The design of radar signals having both high range resolution and high velocity resolution," *Bell Labs Technical Journal*, vol. 39, no. 4, pp. 809–820, 2013.

[172] S. Sen and A. Nehorai, "Adaptive design of OFDM radar signal with improved wideband ambiguity function," *IEEE Transactions on Signal Processing*, vol. 58, no. 2, pp. 928–933, 2010.

[173] E. Ragaini and R. F. Woodman, "Demodulation of complex baseband radar signals for the analysis of multiple narrow spectral lines," *Radio Science*, vol. 32, no. 2, pp. 783–789, 2016.

[174] F. Millioz and M. Davies, "Sparse detection in the chirplet transform: application to FMCW radar signals," *IEEE Transactions on Signal Processing*, vol. 60, no. 6, pp. 2800–2813, 2012.

[175] R. R. Musin, M. N. Shneider, A. M. Zheltikov, and R. B. Miles, "Guiding radar signals by arrays of laser-induced filaments: finite-difference analysis," *Applied Optics*, vol. 46, no. 23, pp. 5593–5597, 2007.

[176] L. Jackson, S. Kay, and N. Vankayalapati, "Iterative method for nonlinear FM synthesis of radar signals," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 46, no. 2, pp. 910–917, 2010.

Journal of Engineering
The Scientific World Journal
International Journal of Rotating Machinery
Journal of Sensors
Advances in Multimedia
Advances in Civil Engineering
Journal of Control Science and Engineering
Journal of Robotics
Hindawi
Submit your manuscripts at
www.hindawi.com
Journal of Electrical and Computer Engineering
Advances in OptoElectronics
VLSI Design
International Journal of Navigation and Observation
Modelling & Simulation in Engineering
International Journal of Aerospace Engineering
International Journal of Chemical Engineering
International Journal of Antennas and Propagation
Active and Passive Electronic Components
Shock and Vibration
Advances in Acoustics and Vibration