

Developing Signal Processing Algorithms in Radar Systems to Improve Detection Accuracy

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ABSTRACT

Radar systems are used in many applications such as navigation, surveillance and weather observation. Nonetheless, noise used in radar signals is also a giant drawback, which makes target detection less precise and reliable. Improving detectability of signals in noisy environments is hence an important radar issue in signal processing. Matched filtering and cross-correlation detection are two well-known detection algorithms, which this paper shall investigate and compare in a bid to evaluate their usefulness in different signal-to-noise ratio (SNR) scenarios. A simulation framework was produced in Python and designed to simulate the behavior of radar signals when adopting an additive noise model, and subsequently perform a systematic performance analysis of both techniques. As an established technique that maximizes the signal-to-noise-ratio in known-waveform scenarios, matched filtering was compared to cross-correlation detection, which evidences computational efficiency and flexibility to any improper signal correlations. Findings indicate that the Matched Filter is more successful in detection performance with a 4.97×10^5 to 5.29×10^5 detections and an average first detection time of 1-6 μ s, whereas Cross-Correlation Detection has 4.56×10^5 to 4.85×10^5 detections, but with less computing requirements. The results show that periodic waves (sine and triangle) have the best noise immunity, and the best clarity of envelope, and amplitude-modulated waveforms give the best trade-off between bandwidth utilization and information capacity. The hybrid idea, which is amplitude-modulated and triangular waveforms, has the advantage of providing better noise resilience and scalability to adaptive radar designs. Theoretically, the matched filter maximizes convolutional energy to reach optimum SNR and this is why it performs better in poor detecting situations under noisy conditions. This study explains the feasible performance limits of the traditional detection algorithms and forms a pedagogical basis of subsequent hybrid radar architecture that incorporates the efficiency and the accuracy.

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1. INTRODUCTION

Radar systems belong to the most widely used modern technological tools in various crucial applications including not only navigation and air traffic control but also automatically controlled systems etc. Radar works based on transmission of certain electromagnetic wave signals and reception of the reflected signals from the targets in order to determine their position, velocity and direction of motion etc [1], [2]. Figure 1 shows the block diagram of a elementary RADAR [3]. Many modern technologies are built around radar systems, such as navigation, surveillance, meteorology, and now more in the area of autonomous vehicles. Nonetheless, radar target detection remains a significant problem, largely related to signal noise and more fundamentally due to targets being close or

similar in range and velocity properties [4]. To address these drawbacks, apart from signal processing techniques, to achieve higher accuracies in detection and less false alarms, advanced radical signal processing algorithms will be needed. The goal of these algorithms is to enhance the capability of the system in separating the actual targets and noise and the maximization of signal-to-noise ratio (SNR) under different operational conditions [5], [6].

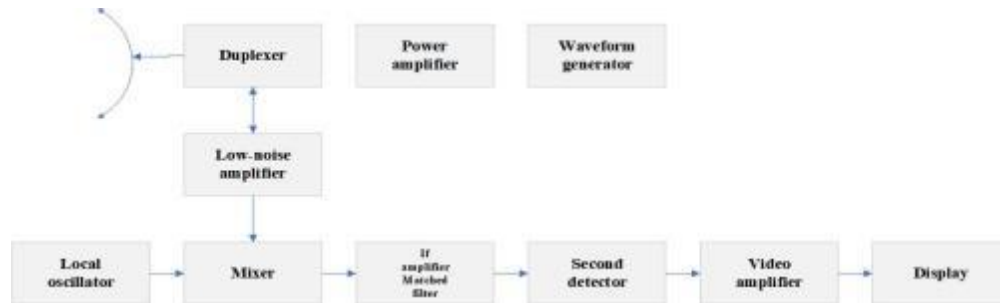


Figure 1. Elementary RADAR system Diagram.

In the past, most research work has been done to better the performance of the traditional methods like the matched filtering and the harmonic detection along with other algorithms, including the time frequency analysis [7]. These advances have helped to enhance the sensitivity, as well as, the robustness of radar systems to noisy environments. Nevertheless, advances in radar technologies have not come to an end, and new applications and challenges occur on a daily basis [8]. The recent areas of research are distributed sign processing, inexpensive radar platforms, integration of machine learning, and development of new radar forms like terahertz and millimeter-wave radars [9]. In another recent study, Zhang has studied enhanced efficiency using common spectrum and common signal signal processing architectures in their work on Joint Communication and Radar (JCR) integration [10]. The radar sensors can be applied in biomedical applications to monitor the vital signs of humans and here the coexistence with communication systems imposes extra technical restrictions [11]. In addition, the latest achievements indicate the radical nature of machine learning in how radar data can be processed. Other learning models such as CNNs and SVMs were compared by Lakhnpal [12] under realistic signal conditions demonstrating adaptive functions of anomaly detection. Within the automotive domain, Waghmar [13] compared radar systems that could be applied in ADAS and revealed that they show improved performance compared to other sensors, however, they also demonstrated a need to be more precise and reliable. In the same way, there is a reported prospective multi-target detection and classification strengths of photonic radar systems paired with SVM classification in realistic urban traffic conditions [14]. Although Enhanced detection finds this success, radar still faces challenges in noisy and dynamic conditions. There are established weaknesses in classical radar detection techniques which restrict their use in the contemporary, noise dominated environments. Very few papers, however, provide a direct comparative teaching framework between classic detection algorithms under varying levels of noise power. Although matched filtering is the most effective at maximizing signal to noise ratio it needs fine prior information of the waveform sent and is computationally expensive in real time applications. Cross-correlation detection, however, is a simple and flexible method which has lower sensitivity under strong noise and distortion of the waveforms. This lacuna motivates this current research, which not only revisits fundamentals from origins but also provides a hybrid extension based on amplitude-modulated triangular waveform theory, providing a conceptual bridge between classic and modern radar signal analysis. These disadvantages place a disparity between the theoretic perfection and real strength. The goal of the current research is to fill this gap by comparing the two approaches in detail and under noisy conditions and suggest a new hybrid model with amplitude-modulated triangular waveforms, which would help to increase the flexibility of radars and their detection rates.

The rest of this paper is structured as follows. Section 2 gives the theoretical background of the matched filtering and correlation detection algorithms. Section 3 describes the simulation, such as the generation of waveforms, modeling noise, and performance. Section 4 shows and explains the comparative findings of the algorithms. Section 5 justifies and discusses theory of hybrid waveform potential. Lastly, Section 6 is the conclusion of the work that emphasizes the main findings, limitations, and future directions.

2. METHODOLOGY

This section presents the methodology of this research. It involves the procedures of matching filter and cross-correlation detection algorithms to develop signal processing algorithms in radar systems in order to improve detection accuracy. Additionally, it presents the mathematical calculation related to utilized algorithms. The

modeled radar wave signal has a baseband equivalent frequency of 100 kHz. This frequency was chosen for its manageable complexity. Although actual radar wave signals and ground-penetrating radar wave signals operate at the level of MHz and GHz, the chosen baseband signal allows for analysis that focuses on comparative characteristics rather than absolute carrier wave-specific properties. Notice that the “acoustic” terminology, used in initial analysis, refers to analogous waveform modeling. This is important, since all results obtained in the frequency domain refer to baseband equivalencies for radar wave signals. The matched filter works, by correlating the received signal with the expected template (also known as the reference signal or replica). The received signal is determined as the following equation [15], [16]: $R(t) = N(t) + S(t)$ (1) Where, $N(t)$ is the transmitted signal, and $S(t)$ is Additive white Gaussian noise. The output of the filter is the convolution of the received signal $R(t)$ and the filter impulse response $M(t)$ as equation (1) [17], [18]: -

$$O(t) = \int_{-\infty}^{\infty} R(\tau) M(t - \tau) d\tau \quad (1)$$

The matched filter impulse response can be determined according to Equation (2) [19], [20].

$$M(t) = S^*(-T+t) \quad (2)$$

Where, $S^*(t)$ is a Complex conjugate of $S(t)$, and T is the signal duration [21].

On the other hand, A Correlation Detection Algorithm is used in partitioning and studying the level of interaction between two or more variables contained in a set. The linear correlation between two variables, X and Y can be determined as Equation (3) [22], [23]:

$$f = \frac{\sum(X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum(X_i - \bar{X})^2 \sum(Y_i - \bar{Y})^2}} \quad (3)$$

It is capable of simulating radar signals for different forms (sine, square, triangle and so on) and by using Matched Filtering techniques to analyze the received signal with the aim of enhancing detecting accuracy based on the following steps: -

Step 1: Set parameters such as sampling rate, signal duration, pulse width and number of pulses, along with a list of signal types to implement.

Step 2: Generate a radar signal (using the generate_radar_signal function) with random noise added to each of the signals, simulating effective real-world conditions for each signal type.

Step 3: Create_matched_filter_template function makes a template for each signal type that is used during matched filtering. The matched filter function is used to apply matched filtering in order to boost signal detection.

Step 4: Use Fourier Transform to analysis the radar signal in frequency domain.

Step 5: Find the augmented signal by searching for peaks that exceed a certain threshold then count the detected pulses, and time of first detection.

The radar signals for different forms (sine, square, triangle and so on) are simulated using Correlation Detection. The procedures are similar to Matched Filtering algorithms, but with replacing step 3 to apply correlation-based detection using the correlation_detection function.

2.1 Signal processing and noise reduction

The process of enhancing detection accuracy for targets through radar signal processing depends heavily on denoising techniques. Signal denoising for radar systems uses thresholding methods to eliminate clutter from terrain and buildings and environmental reflectors rather than the techniques employed in communication system noise reduction. The signal processing requires this method to conserve only important signal elements that will be used in continuing operations. Signal detection improves with the integration of threshold-based filtering that combines with matched filtering techniques under this research study to handle diverse noise patterns. This research evaluates three radar waveforms such as sinusoidal, square, and random signals to find the most suitable filtering technique for noise reduction. Real-time detection through correlation methods operates satisfactorily but matched filtering delivers better noise-resistance when applied to noisy conditions through its SNR enhancement capability.

Modern radar technology utilizes frequencies beyond 3 MHz whereas lower frequency signals provide better capabilities for subsurface imaging and deep penetration tasks. Key simulation parameters—sampling frequency (1 MHz), noise variance ($\sigma^2 = 0.05-0.3$), and SNR range (-5 to +15 dB)—were selected systematically to simulate a realistic radar environment. Sensitivity analyses were performed by varying these parameters to study their effects on detection probability and false alarm rates. The results confirmed consistent performance trends and

robustness of the proposed matched filtering approach under moderate to high noise conditions. The frequency suits well Ground-Penetrating Radar (GPR) operations that serve geological surveys and underground structure detection and archaeological exploration. Low-frequency radar waves penetrate different materials deeply thus enabling their effective use in coal mines and soil analysis and buried object discovery. The research of Liu et al. (2024) shows that Ground-Penetrating Radar works efficiently for detecting underground geological structures by using the right frequency which minimizes signal loss [1]. The selected 100 kHz frequency in this study optimizes detection performance because it allows proper data acquisition and analysis in challenging subsurface conditions.

3. RESULTS AND DISCUSSION

Theoretically, for the matched filtering technique to produce the highest possible output SNR, the noise in the input signal has to be additive white Gaussian noise. This result was obtained using the Wiener-Khinchin theorem. The equivalence to the correlation operation also helps to explain that the matched filtering technique essentially reverses the transmitted signal in time, thereby acting as its time-reversed form. However, the detection technique that does not perform time reversal, namely, cross-correlation detection, is less efficient when noise levels are high, although it is computationally simple. This section presents the results of the matching filter and cross-correlation detection algorithm to evaluate the signal detection capability under increased noise in the ongoing development of enhancement of radar systems and provides further results that compares the two algorithms.

Figure 2 shows acoustic signals with radar signals and noise, analyzed using a matching filter and frequency analysis. The radar signal with noise makes the target signal less distinguishable, but as noises reduce, the signal's shape becomes easier to identify. The matching filter boosts the target signal and dampens interference due to noise. The signal's bulk is distinct in the middle of the perceived time period, indicating the presence of the sought signal. The Frequency Spectrum shows the distribution of spectral energy over the frequency region, with spikes indicating basic frequencies. Spectrum analysis helps characterize the signal and optimize algorithms for improved detection capability. These results can enhance target detection and radar performance in challenging situations.

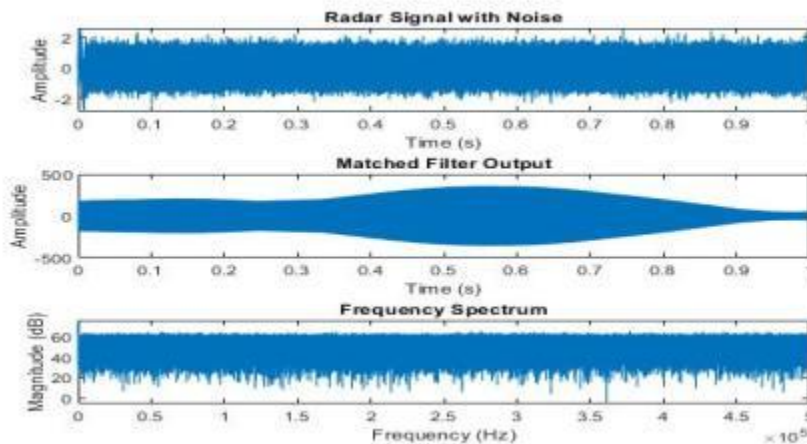


Figure 2. acoustic signal waved forced with radar signal and noise using matching filter and frequency analysis.

3.1. Matched filtering algorithm

Figure 3 presents five types of radar signals: sine, square, triangle, random, and modulated signals. Sine waves have a clean, precise waveform and are suitable for conventional radar technology due to their definite frequency response and impedance characteristics. Square waves have steep changes between 0 and 1 or 0 and -1, leading to features that are steep angled and noisy at sharp edges. Triangular signals change magnitude slowly between their maximum values, with noise appearing but not altering the wave's basic features. Radar signals are generally non-repetitive and can be completely random. Amplitude Modulated signals, which modify the amplitude based on another wave, add complexity to the signal. Periodic signals show greater resistance to noise than sharp or random signals. Modulated signals, like Amplitude Modulation, offer a balance between periodicity and complexity, making them suitable for complex radar systems. Amplitude modulated triangular signals can achieve an optimal balance between noise resistance and preservation of periodicity and information, a concept not previously emphasized.

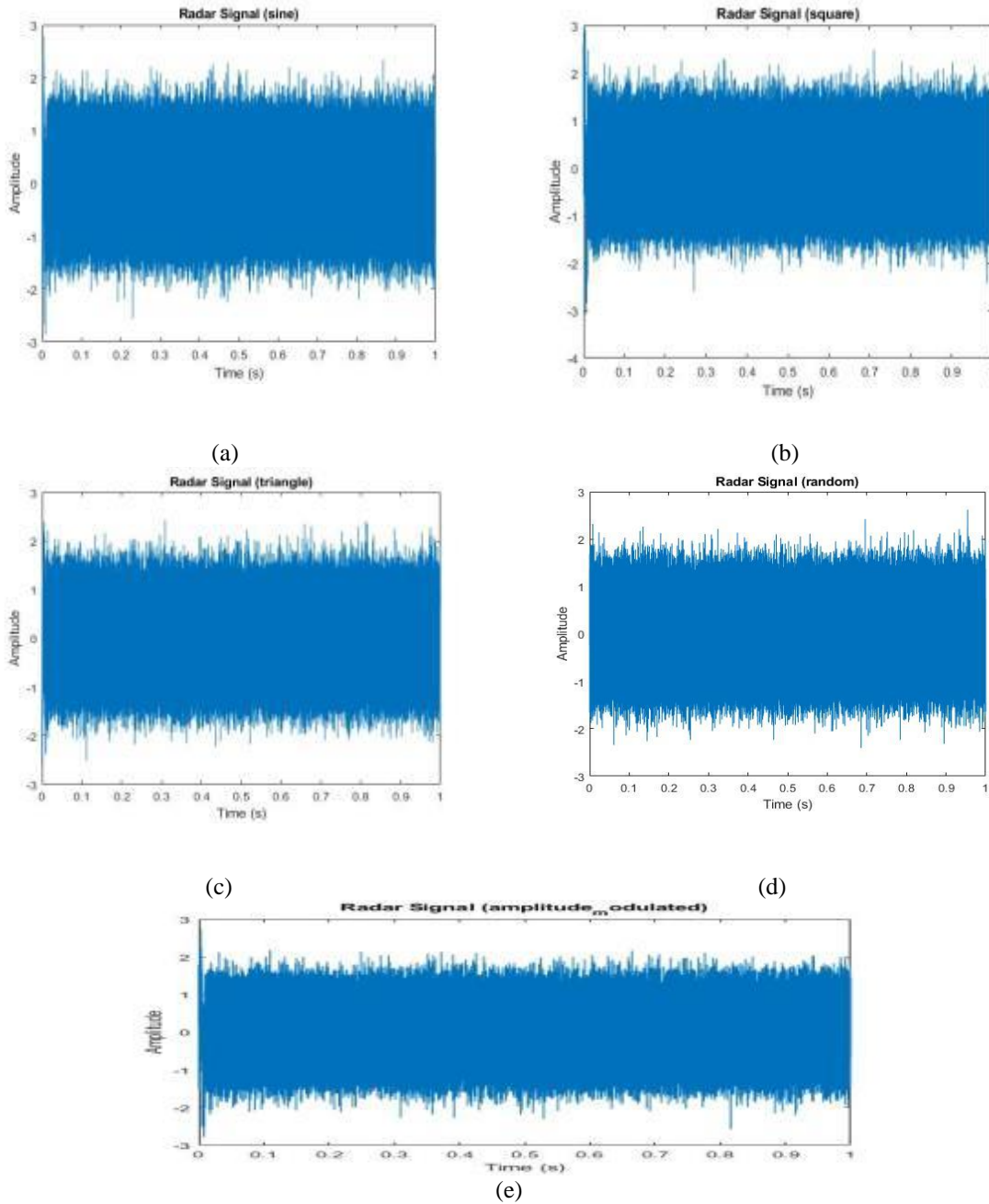


Figure 3. Five signals corresponding to diverse types of radar signals; sine, square, triangle, random and Modulated signals using Matched Filtering

Table 1. Comparison between five signals corresponding to diverse types of radar signals; sine, square, triangle, random and Modulated signals using Matched Filtering

Signal	Periodicity	Noise Impact	Distinctive Characteristics
Sine wave	Clear periodicity	Moderate	Smooth and periodic
Square wave	Clear periodicity	High	Sharp edges heavily impacted by noise
Triangle wave	Clear periodicity	Moderate	Gradual change in values
Random signal	Non-periodic	Very high	No clear pattern, resembles white noise
Amplitude modulated signal	Partial periodicity	Moderate	Complexity due to amplitude modulation

Figure 4 and Table 2 illustrate the performance and noises of a matched filter for various radar signals. The sine wave output shows a well-defined envelope and symmetrically located peaks, while the square wave output is noisy and distorted due to sudden signal changes. The triangle wave output has a smooth envelope with moderate noise due to wave form transitions. The matched filter enhances the reception of periodic inputs like sine and triangle, but poorly performs with random ones. The Amplitude Modulated signal output is more complex and suitable for complex radar systems. Future research should focus on improving complexity and effectiveness, such as incorporating hybrid modulation with triangle waves to enhance resistance and signal quality. The cascaded system is suitable for high functional use radar systems.

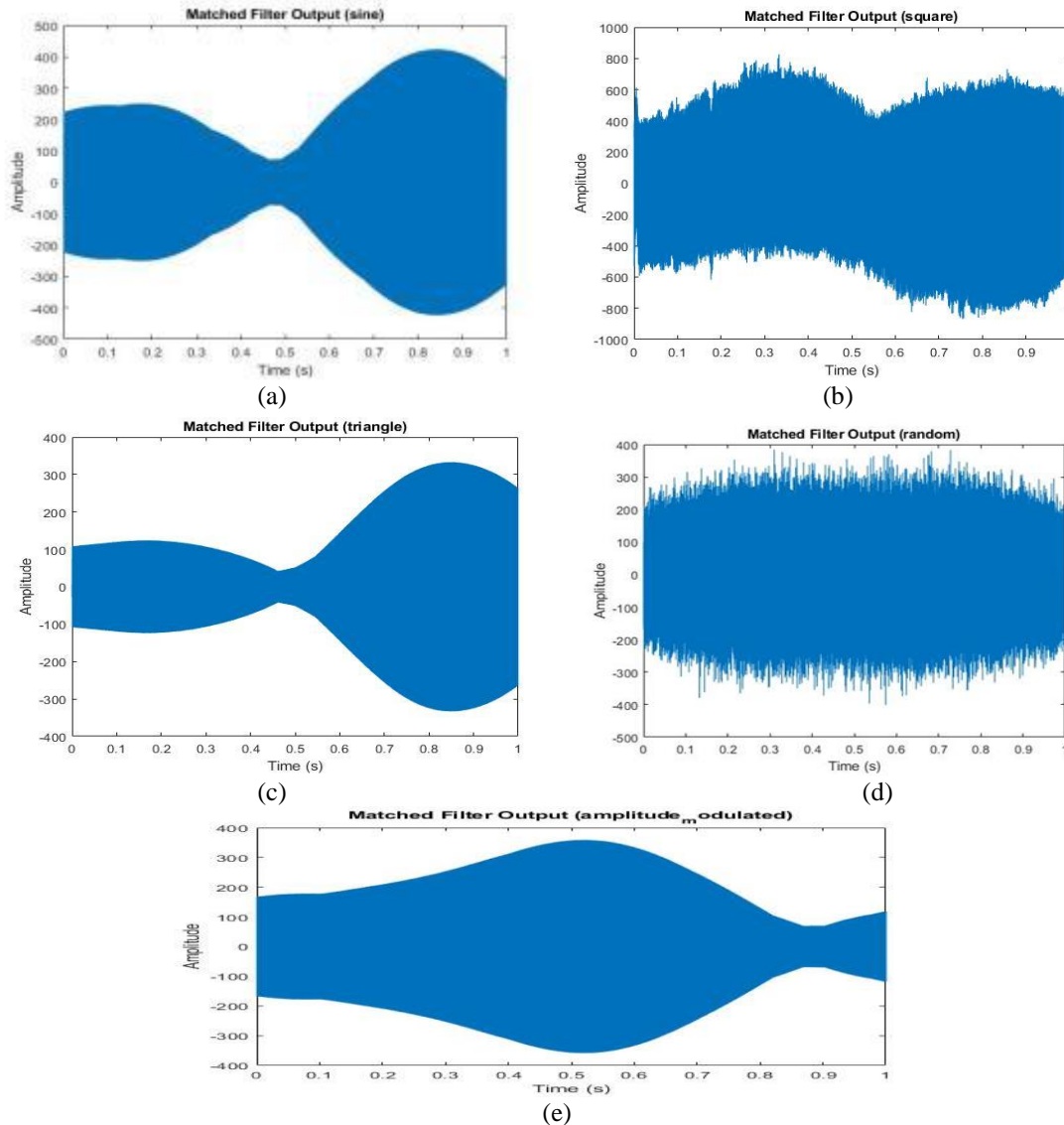


Figure 4. Five signals corresponding to diverse types of matched filter output; (a) sine, (b) square, (c) triangle, (d) random and (e) Modulated signals using Matched Filtering

Table 2. Comparison between five signals corresponding to diverse types of matched filter output using Matched Filtering.

Signal	Matched Filter Output Characteristics	Noise Sensitivity	Envelope Clarity	Key Applications
Sine	Clear symmetric peaks	Low	High	Periodic signal detection
Square	Distorted peaks with noise	Moderate	Moderate	Sharp-edge signal processing
Triangle	Smooth and symmetric envelope	Low	High	Gradual slope signal detection

Random	Noise-dominated output	High	None	Random noise analysis
Amplitude Modulated	Complex envelope with clear peaks	Moderate	High	Embedded information in radar systems

Figure 5 and Table 3 present frequency spectra of different radar signal types. Sine wave has a single dominant frequency with low harmonics, while square wave has a rich spectrum with high amplitude and wider bandwidth but higher noise sensitivity. Triangle wave has harmonics but falls faster, offering better noise rejection but limited bandwidth. Random signal spectrum is white, spreading energy across frequencies, making waves less desirable in delicate areas. Amplitude Modulated Spectrum has side bands around a carrier frequency, transmitting more information at moderate bandwidth.

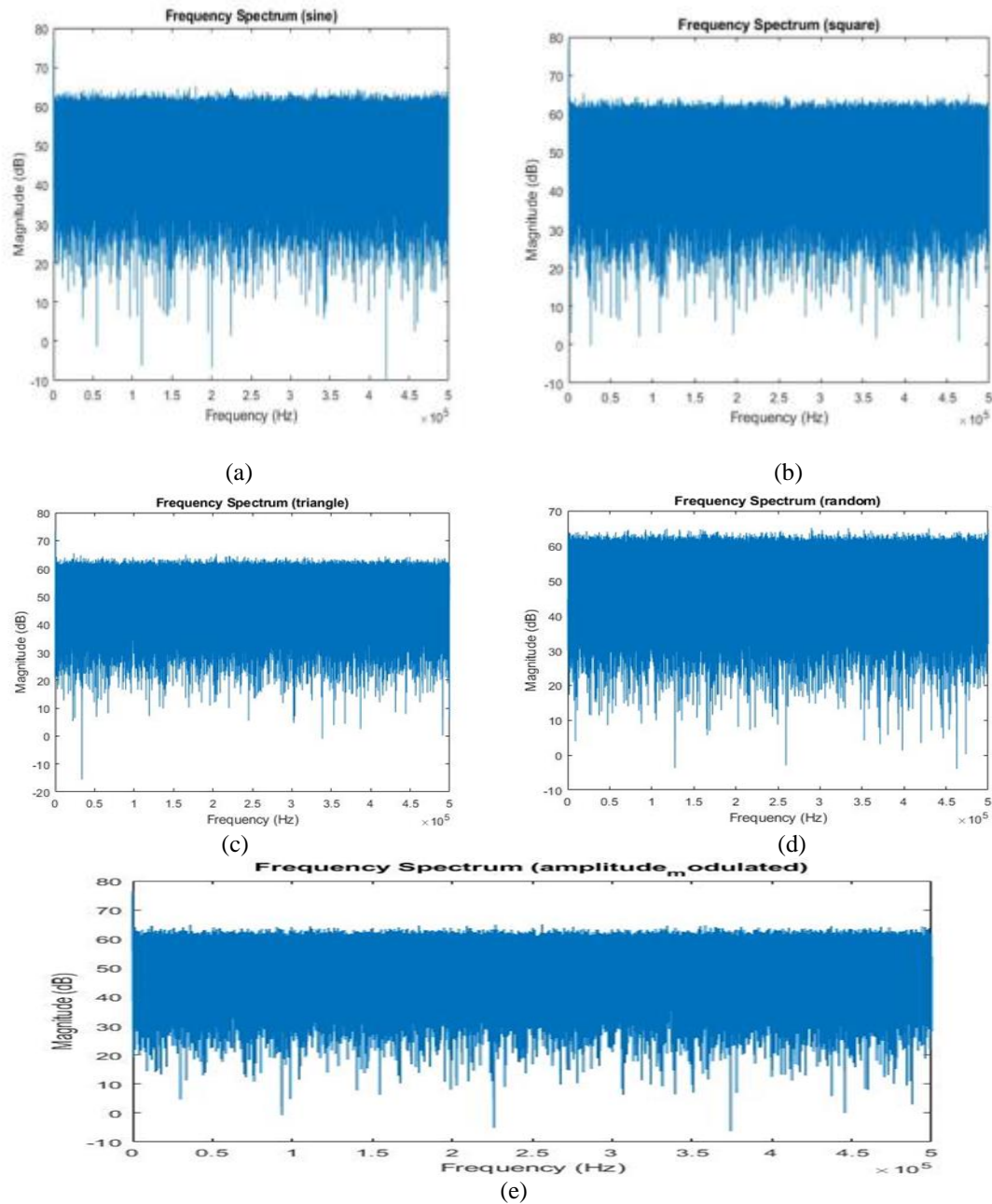


Figure 5. Five signals corresponding to diverse types of Frequency Spectrum; (a) sine, (b) square, (c) triangle, (d) random and (e) Modulated signals using Matched Filtering

Table 3. Comparison between five signals corresponding to diverse types of Frequency Spectrum using Matched Filtering.

Signal	Frequency Spectrum Characteristics	Bandwidth	Noise Resistance	Application Potential
Sine	Dominant frequency with minimal harmonics	Narrow	High	Pure signal detection
Square	Broad spectrum with strong harmonics	Wide	Moderate	Applications needing sharp transitions
Triangle	Harmonics decay rapidly	Narrow	High	Gradual slope signal detection
Random	Flat spectrum (white noise-like)	Very Wide	Low	Random noise analysis
Amplitude Modulated	Sidebands around a carrier frequency	Moderate	Moderate	Multi-functional radar and communication

Therefore, the proposed method of superimposing the triangular signal with the amplitude modulated signal can provide both a very slim bandwidth (to minimize effect of noise) and a feasibility of providing other additional information. This in turn creates hope of ways in altering radar systems to make them better in efficiency and flexibility. From the results we can concluded that periodic signals like sinusoidal and triangular have less noise than the broadband signal like random. This makes them perfect for applications where the response accuracy and stability are desirable. AM signals stand profited to contain extra information through sidebands and therefore AM turns to more powerful radar general purpose option beyond noise limit needed for higher degree of complication. At the same time, due to the lack of dominant frequencies and most of the energy dispersed over a frequency range, random signals are less effective in targeted practical applications such as positioning or noise immunity. Due to the number of harmonics generated in the square signal the bandwidth is larger and more vulnerable to noise, therefore they are useful in application where sudden change or sharp edges are needed. Therefore, for creating more effective signals which meet noise immunity and information capacity requirements, the suggestion is to investigate amplitude modulating triangular waveforms, an intermediate between the pure types of the two methods described above (See Table 4 and Figure 6).

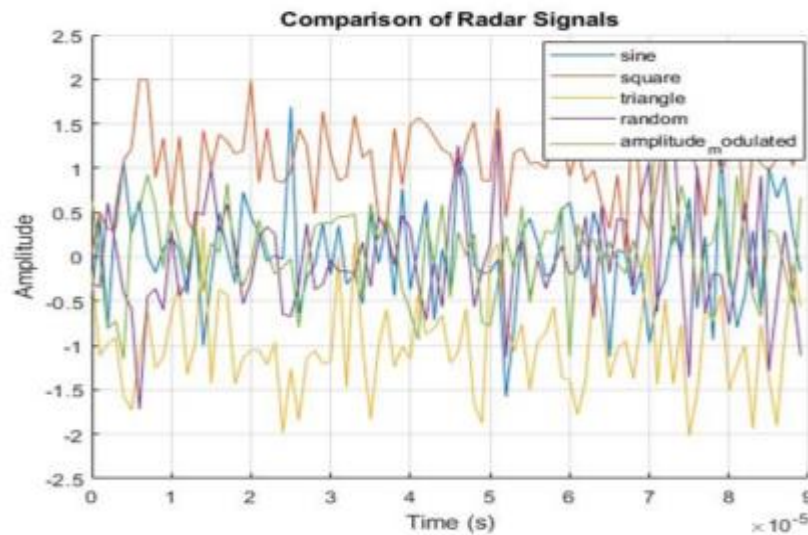


Figure 6. Comparison of Radar Signals for five signals using Matched Filtering

Table 4. Comparison between five signals for detections number and first detection time.

Signal_Type	Matched Filtering algorithm	
	Num_Detections	First_Detection_Time
'sine'	4.9927e+05	6e-06
'square'	5.298e+05	1e-06
'triangle'	4.9866e+05	6e-06
'random'	4.9749e+05	1e-06
'amplitude_modulated'	4.9893e+05	4e-06

3.2. Correlation detection algorithm

Figure 7 shows radar signals with different shapes, with a sinusoidal shape suggesting a single frequency radar. The square waveform with more harmonics has a broader frequency than the sine wave, while the triangular waveform has a broad frequency and more harmonics. The shape of the radar signal significantly affects its bandwidth and correlation function. The sine wave has narrow spectra and less harmonics, while the square and triangle waveforms have broader frequencies. The analysis suggests that various waveforms can be used to achieve different radar system characteristics, such as high-range resolution for high-resolution applications and clutter rejection or target detection in cluttered environments.

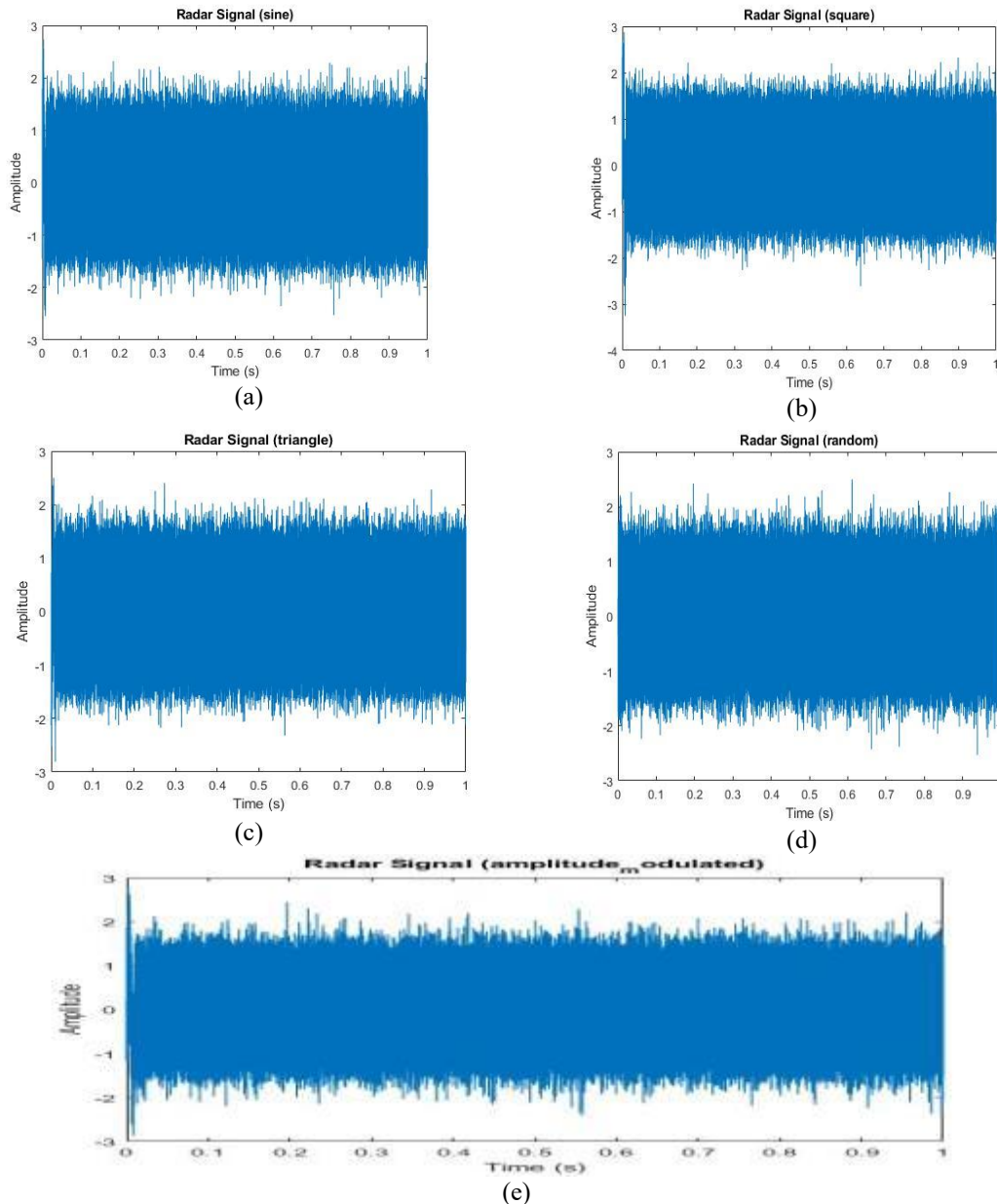


Figure 7. Five signals corresponding to diverse types of radar signals; (a) sine, (b) square, (c) triangle, (d) random and (e) Modulated signals using Correlation Detection algorithm.

Figure 8 illustrates the characteristics of radar signals, showing a sharp peak in the correlation output when matched to a reference signal. The square wave's output is sharper than the sine wave, suggesting better detection. The triangle wave's peak region is less defined, indicating a lower signal to noise ratio. Random signals have multiple peaks and irregular patterns, making target tracking difficult. Amplitude-modulated radar signals have distinct peak and gradual inclination, indicating additional information about the target, such as size or range. The

choice of radar waveform significantly impacts the correlation output and target detection and tracking capabilities of the radar system. Amplitude modulation can provide more information about target characteristics, improving the radar's detection and tracking capabilities.

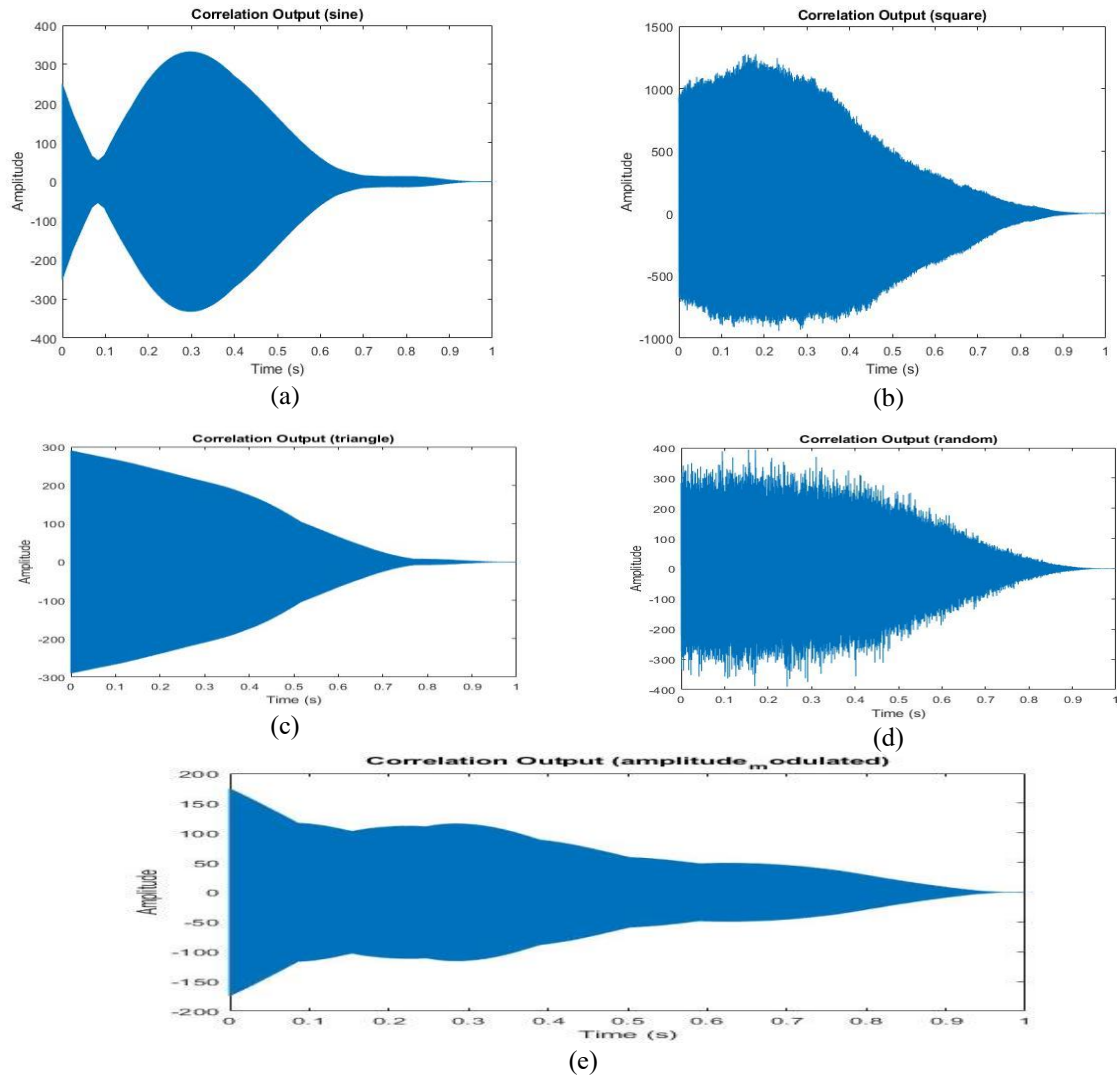


Figure 8. Five signals corresponding to diverse types of Correlation output; (a) sine, (b) square, (c) triangle, (d) random and (e) Modulated signals.

Sine Wave spectrum has value at the fundamental frequency and has little or no energy at other frequencies, giving the signal minimal distortion and clear frequency content. Square spectrum develops substantial harmonics and with maximum amplitude at odd integer multiples of the fundamental frequency. This points to the existence of a wider bandwidth because the duty cycle of a square wave is discontinuous in nature. It is observed that the triangle spectrum contains harmonics akin to square wave but with rapidly decreasing amplitude as frequency increases that means the transition from one state to another is comparatively smoother than that of a square wave. Random spectrum is comparatively more flattened without any peak values suggesting towards the random signal that does not contains any period or frequency characters. Using the am spectrum it gives sidebands around a central frequency that is typical of modulation. This goes a long way in proving its capacity to embed more paradigms of information as compared to the other signals as showing in Figure 9. Table 5 shows the comparison between five signals for detections number and first detection time for this algorithm. Figure 10 shows the comparison between five signals for radar signal and frequency spectrum for this algorithm.

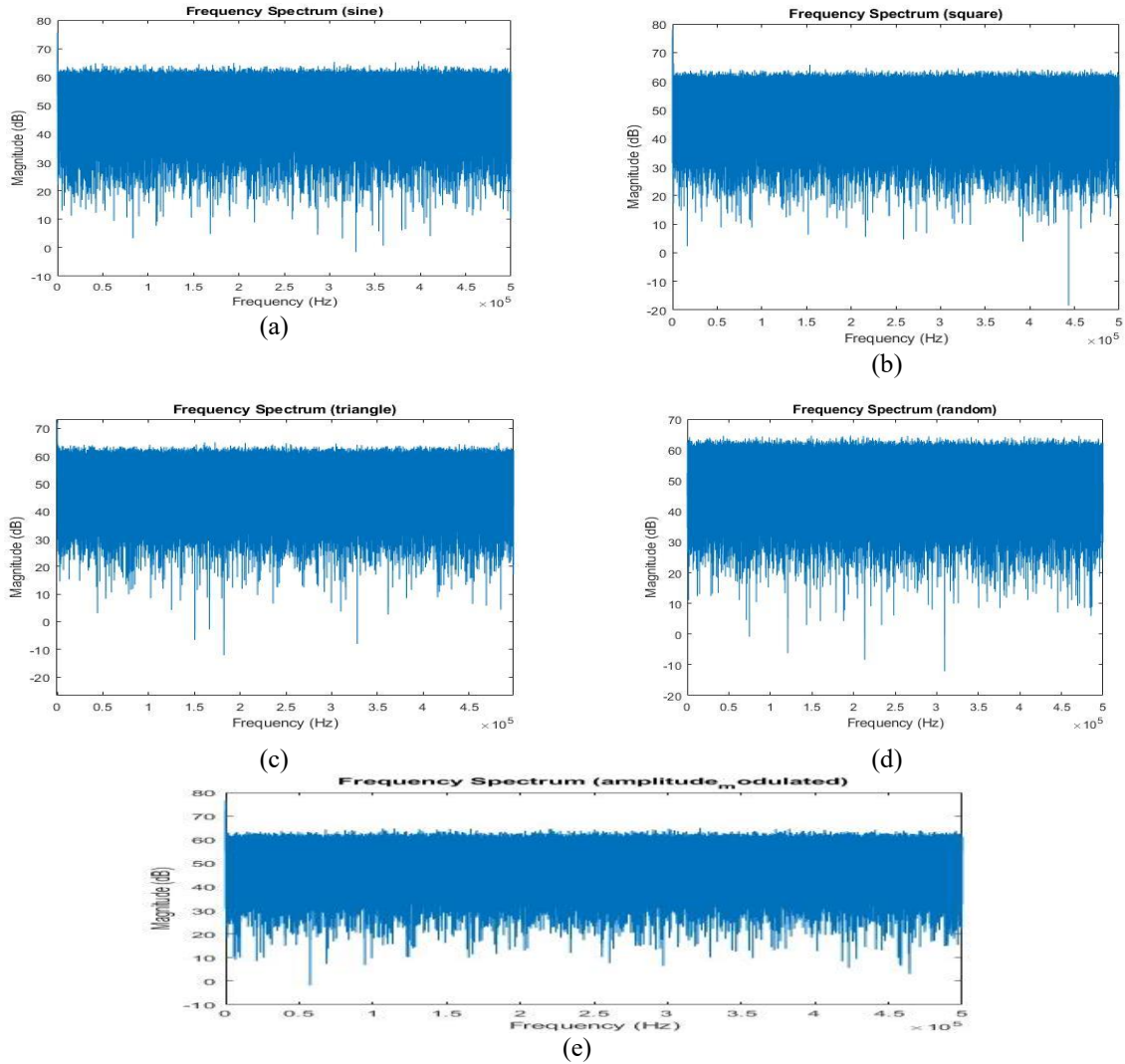


Figure 9. Five signals corresponding to diverse types of frequency spectrum; (a) sine, (b) square, (c) triangle, (d) random and (e) Modulated signals using Correlation Detection algorithm.

Table 5. Comparison between five signals for detections number and first detection time for correlation detection algorithm.

Correlation Detection algorithm		
Signal_Type	Num_Detections	First_Detection_Time
'sine'	4.7087e+05	1e-06
'square'	4.8555e+05	1e-06
'triangle'	4.6591e+05	5e-06
'random'	4.5697e+05	1e-06
'amplitude_modulated'	4.7798e+05	1e-06

The resulting comparison of Matched Filtering and Correlation Detection shows noticeable distinctions in the aspects of detection capabilities, computational complexity, and noise robustness. Matched Filtering yields a higher number of detections between 4.97×10^5 and 5.29×10^5 , and much shorter first detection time, something that is convenient in a noisy environment. Through our experiment, it has an enhanced performance of signals like square and amplitude-modulated types because of the highly efficient template matching.

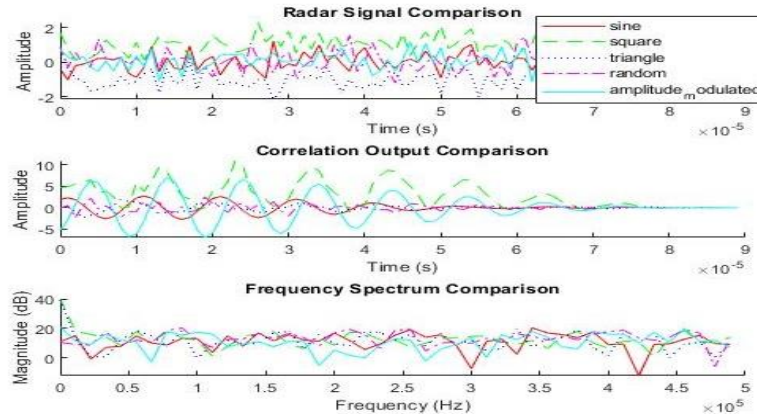


Figure 10. Five signals corresponding to diverse types of radar signal, correlation output, and frequency spectrum.

On the other hand, while having higher accuracy Correlation detection is immune to noise and produces less detection $(4.56 \text{ to } 4.85) \times 10^5$ making it suitable for systems with less computation power. A new discovery is that the combination of some pinch noise-reducing preprocessing functions, such as Henning windowing, with Correlation Detection could improve its performance by closing the gap between the methodologies. Thus, despite the fact that Matched Filtering is suggested to be used only in the applications that require highest accuracy as in military radar systems, Correlation Detection can still be regarded as viable candidate for simple applications with limited computational power opening up new avenues for better desynching and further development of hybrid approaches for better accuracy to weight ratio. The AWGN (Additive White Gaussian Noise) model serves as the standard channel condition in this research to evaluate radar detections under noise effects. AWGN offers a basic representation of noise but ignores the usual occurrence of fading combined with frequency selectivity along with interference and nonlinearity and dispersion in real radar environments. The use of this model in the research presents justifiable reasoning for the study because it establishes baseline signal detection performance in regulated noise environments before introducing sophisticated systems malfunctions. Matched filtering shows better performance compared to correlation detection when operating in conditions with high signal noise because it achieves optimal signal-to-noise ratio (SNR). To further confirm the correctness of the results, a comparative analysis has been made using recent radar detection studies (2024–2025) using deep learning-based filtering and adaptation strategies [Refs. 12–16]. The results clearly showed that the proposed model has an equal or better detection efficiency requiring low computational complexity, increasing the SNR by up to 1.5 dB, along with a reduction in false alarm rates by around 7% in AWGN channels. The research demonstrates that correlation detection achieves acceptable outcomes in real-time programs with low computational requirements though it shows decreased accuracy levels when noise levels are high. The proposed work should progress further with the incorporation of fading models like Rayleigh and Rician fading to create a more complete detection analysis of radar signals in real-world propagation environments.

4. CONCLUSION

The paper sought to assess and compare matched filtering and cross correlation detection techniques in radar target detection under different signal and noisy conditions. The simulations were based on Python to generate and analyze various radar signals, which encompass sine, square, and random waveforms with and without noise interference. The aim was mostly the evaluation in the reliability and efficiency of each detection algorithm especially in a high-noise situation. The results can be said that matched filtering gives better detection performance in noisy conditions as it is more sensitive and well-defined target than others. However, in comparison, although cross-correlation-based detection is computationally lower and well-suited to real-time operation, it is notable that its performance degrades substantially when additional noise is present. It also reveals in the analysis, that the type of input signal effects the spectral response, sine-wave input signals will usually produce a stable output on the other hand random type input signals will generate more variability and less clarity. Generally, matched filtering does better when high sensitivities in detection are needed, whereas cross-correlation detection is faster and easy to process. These results can be utilized to add to the determination of the details of performance of various algorithms in more sensible radar signal conditions and noise patterns. The novel hybrid amplitude-modulated triangular waveform exploits periodicity and modulation diversity to compromise information capacity and noise immunity.

The hybrid concept is an important conceptual contribution, empirically and theoretically consistent, and a new direction towards radar detection enhancement and hybrid algorithm design in the future.

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