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Matched-Filter Radar Signal Processing With Image Enhancement For Long-Range Target Detection, Coverage Analysis, and Plot-Based Performance Evaluation At 1 Km Range

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Abstract

Reliable long-range target detection in automotive radar systems remains challenging under low signal-to-noise ratio (SNR), clutter, and interference conditions. This study proposes a matched-filter-based radar signal processing model for long-range target detection at a range of 1 km using a 77 GHz FMCW radar sensor. The proposed model incorporates waveform generation, target channel modeling, additive white Gaussian noise (AWGN) addition, pulse compression using matched filters, Cell-Averaging Constant False Alarm Rate (CA-CFAR) detection, image-processing-based false alarm suppression, and radar coverage analysis within a unified processing architecture. The matched-filter implementation achieves a time-bandwidth product of 1.5×10^5 leading to pulse compression gain of about 51.8 dB. It enhances the processing SNR from -22.5 dB before processing to an SNR of 24.3 dB after processing at 1 km target range. The created RDM image is analyzed using CA-CFAR detector with 0.97 detection probability at 10^{-6} false alarm probability in a noisy environment. For the purpose of enhancing the detection capability, a two-stage enhancement framework consisting of Otsu re-thresholding, morphological processes, and blob filtering is proposed. Using the proposed enhancement approach, there is a significant reduction in false alarm rate by up to 99% without compromising target detection capability. The range coverage analysis indicates a maximum detection distance of 1620 m. Extensive graphical evaluations validate the robustness and effectiveness of the proposed framework for automotive radar applications operating in low-SNR and cluttered environments.

Keywords: Matched Filtering, FMCW Radar, CA-CFAR Detection, Range-Doppler Map, Pulse Compression, Radar Coverage Analysis, Image Processing, Automotive Radar.

I. Introduction

With the fast pace of advancement in self-driving technology, there has also been an increase in sensor advancements for vehicles, including cameras, lidar, and radar sensors [1]. Among these sensors, the radar sensor has an advantage in that there is little deterioration in detection performance due to climate change. In addition, in recent automotive radar systems, it is possible to achieve high range resolution by using a wider bandwidth in a frequency-modulated continuous wave (FMCW) radar system [2]. FMCW radar operating in the 76GHz-81GHz band is very popular in driver assistance applications. Examples of applications that typically utilise radar are Adaptive Cruise Control (ACC), Lane Assist and Automotive Emergency Braking (AEB) [3]. As one of the core technologies in modern radar systems, signal processing encompasses a wide range of research areas, including waveform optimization [4], target detection and recognition [5], target tracking, clutter and interference suppression [6], and radar imaging [7]. However, reliable target detection is not an easy task in real-world radar environments due to the co-occurrence of clutter, since radar must differentiate between constant noise and sporadic disturbances. This interplay creates a particularly challenging scenario, making it difficult for radar systems to accurately differentiate between true targets and spikes [8].

Traditional methods for mitigating the impact of spikes in radar data primarily rely on signal processing techniques such as thresholding, averaging, filtering, and time-frequency analysis [9]. Thresholding techniques like Constant False Alarm Rate (CFAR) are employed to adjust thresholds to distinguish between noise and legitimate targets [10], while Range-Doppler (R/D) maps - two-dimensional representations widely used in radar signal processing are used to enhance target detection accuracy [11]. In general, a CFAR algorithm is the most widely used for automatic target detection in the automotive FMCW radar systems [12]. The factors determining the detection performance of the CFAR algorithm include the number of guard cells, the number of training cells, and the probability of false alarm. If these factors are not set properly in the CFAR algorithm, the probabilities of missing the target increase. In addition, it is difficult to efficiently detect targets with fixed factor values because the pattern of the received signal varies depending on the driving environment [13]. Consequently, conventional CFAR-based methods remain susceptible to isolated noise spikes and clutter-induced false detections that temporarily exceed the adaptive threshold.

In active sensing systems, such as the radar system, precise target range profile extraction under the noise background is a fundamental requirement, and the output signal-to-noise ratio (SNR) is a primary metric for evaluating target detectability [14],[15]. The detection performance of radar systems is also heavily affected by additive white Gaussian noise (AWGN), multipath fading, and environmental interference, which collectively degrade the SNR, detection probability, and estimation accuracy [16]. Several enhancement approaches such as wavelet denoising [17], adaptive filtering [18], and matched filtering [19] have therefore been investigated to improve radar target detectability. Among these techniques, for a point target in the presence of white noise, it is well known that the matched filter maximizes the output SNR, enhancing the target detectability in a certain sense [20]. However, in multitarget scenarios, the range profiles of small targets are usually masked by nearby large targets due to the limitations of standard matched filtering. To overcome the range sidelobe masking problem, the first strategy is to conduct dedicated signal processing methods, and various mismatched filter approaches have been extended for pulse compression (PC) [21],[22],[23].

For FMCW radars, the matched filter processing on the de-ramped beat frequency results in a narrow target peak in addition to increasing the output SNR proportional to the time bandwidth product (BT). In the current case study where the radar has parameters $B = 150$ MHz and $T_c = 1$ ms, the BT ratio can reach up to 1.5×10^5 (51.8 dB), thus allowing for reliable target detection within kilometer range using a relatively small transmitter (10 dBm). Nevertheless, the processed signal will have sidelobes, clutter, as well as false detections caused by noise. In order to address these problems, CFAR detection techniques are first used in the Range-Doppler Map (RDM) domain to provide a constant false alarm rate regardless of any interference variations, after which image processing operations are used in the form of dilation, erosion, and blob recognition to remove isolated false detections while retaining target detections.

In addition to target detection, practical radar systems require accurate characterization of surveillance coverage. Coverage area analysis based on the radar range equation enables estimation of spatial SNR distribution, maximum detection range, and system-level trade-offs involving transmit power, antenna gain, and waveform parameters. Motivated by these requirements, this paper presents a comprehensive matched-filter radar signal processing framework for long-range target detection at 1 km using a 77 GHz FMCW radar system. The proposed framework integrates the design of radar waveforms, realistic target and AWGN channel models, matched filter processing, CA-CFAR detection, image processing improvement, and radar coverage analysis under a common processing framework with thorough graphical performance assessment.

The principal contributions of this study are summarized as follows:

- A complete end-to-end 77 GHz FMCW radar simulation framework is developed incorporating realistic signal generation, target propagation modeling, AWGN noise injection, and matched-filter PC.
- A dual-stage detection architecture combining CA-CFAR detection with morphological image processing enhancement is proposed to reduce false alarms while maintaining high detection probability.
- A comprehensive radar coverage analysis framework is presented to estimate spatial SNR distribution and maximum detection range based on radar system parameters and target radar cross-section.
- Extensive graphical performance evaluation, including range profiles, Range-Doppler Maps (RDMs), threshold overlays, ROC curves, coverage maps, and range-velocity scatter plots, is provided to validate the proposed framework and ensure reproducibility of the results.

The remainder of this paper is structured as follows. Section II provides a review of related works. Section III gives an overview of the architecture of the proposed scheme and its processing steps. Section IV discusses the signal model along with the matching filter approach. Section V elaborates on the AWGN noise model and threshold detection approach. Section VI explains the improvement process for images. Section VII presents

the coverage area analysis methodology. Section VIII documents all simulation results. Section IX concludes the paper.

II. Related Works

performance, most of these works did not focus on long-range match filtering detection and coverage analysis.

The existing literature has also focused on the necessity of employing denoising and Foundational studies established the theoretical framework for matched-filter radar detection, pulse compression, CFAR processing, and radar coverage analysis. The matched filter concept was initially proposed by Turin [24] as an optimum receiver maximizes SNR of the output in AWGN channels, and later applied to LFM/FMCW radars by means of the stretch processor approach. The modern principles of pulse compression, Doppler frequency processing, and CFAR-based detection were elaborated by Richards et al. [25], while Skolnik [26] provided a formula for calculating the classical radar range equation. Later, CA-CFAR, OS-CFAR, and GO-CFAR algorithms were developed to enhance threshold adaptation under different conditions. Furthermore, morphological and enhanced imaging processing techniques were shown to be useful for false-alarm rejection and target improvement [27],[28].

Contemporary research on FMCW radar systems has primarily concentrated on enhancing target detection accuracy, imaging resolution, and tracking robustness under complex operating environments. For example, Pirkani et al. [29] presented a MIMO-DBS imaging system combined with OSCA-CFAR and DBSCAN clustering algorithms to detect maritime targets and suppress sea clutter, ensuring successful detection of weak dynamic targets. In their further study Pirkani et al. [30] used EKF-based tracking technique in combination with FMCW-MIMO-DBS radar and succeeded in providing stable target and wave tracking under sea state-3 circumstances. Furthermore, Arnold et al. [31] developed a bistatic FMCW radar using trilateration processing to enhance elevation angle resolution without increasing the number of antennas. Despite these advancements in improving imaging and tracking sidelobe suppression to improve the performance of radars under low SNR conditions. For instance, Endo et al. [32] designed a DIP-assisted denoising model alongside CA-CFAR detection, which helped to minimize false alarms while offering increased threshold robustness when conducting human target detection within indoor settings. Similarly, Yang et al. [33] designed a PSF-assisted sidelobe suppression technique through a complex-valued neural network, which demonstrated enhanced target visibility in low SNR and small radar cross-section environments. Additionally, Movafagh et al. [34] Additionally, Movafagh et al. [34] proposed a matched-filter-based FMCW SAR processing architecture capable of achieving higher pulse-compression gain and improved SAR image quality compared with conventional stretch processing methods. Cao et al. [35] further introduced a de-chirp and delay-matching signal processing framework that preserved sidelobe performance and range resolution while reducing ADC sampling requirements in noise radar systems. Furthermore, Fang et al. [36] developed unimodular MIMO waveforms with mismatch filtering for forward-jamming suppression, achieving nearly 19 dB jamming suppression with less than 2 dB SNR loss. Nonetheless, most methods used deep-learning, SAR-based, or anti-jamming signal processing techniques, failing to introduce efficient image-enhanced false alarm mitigation alongside coverage analysis.

Interference cancellation, computing efficiency, and reliability of radar systems have been considered in many research works. The technique of interference cancellation using a CFAR algorithm was proposed by Wang et al. [37], offering interference suppression for several FMCW interferers with minimum power loss and computation speed up. The approach of optimized 2D CA-CFAR using integral images that allowed considerable acceleration of computations was offered by Rohman et al. [38] in their study aimed at accelerating drones' radar system operations. Moreover, Arumugam et al. [3] provided a trustworthy distributed radar system architecture designed to increase resistance to data manipulation due to modular ASIC processing and sparse antenna system architecture. But existing research mostly focuses on one-by-one solutions to problems related to interference reduction, denoising, sidelobe attenuation, target tracking, or robustness of the hardware system. What is still lacking is the consideration of the complete long-distance FMCW radar data processing system. This includes, among others, the combination of matched filter-based pulse compression, CA-CFAR detection, morphological image enhancement based false alarm suppression, and radar coverage analysis under one computing platform. With this goal in mind, this study proposes the development of a comprehensive 77 GHz FMCW radar data processing system for 1-km distance target detection using graphically-supported algorithms.

III. System Architecture and Processing Pipeline

The proposed architecture of the radar signal processing system comprises six stages, which are performed sequentially for long-range target detection, threshold adaptation, false alarm reduction using image processing, and coverage assessment. The whole processing chain is depicted in Figure 1, with each processing module connected via intermediate signal transforms. The signal processing architecture was developed based on a practical FMCW radar receiver design, which includes extra enhancement stages.

Firstly, chirps are created as per the required settings for the carrier frequency, bandwidth, chirp time, and sampling settings. Propagation delay, Doppler effect, radar cross section (RCS) of the target, and AWGN noise are included in the target channel model for the propagated waveform. The de-chirped waveform from the receiver output is passed through the process of matched filtering so that the output SNR can be maximized through pulse compression gain. The Range-Doppler Map (RDM) is then derived via Doppler processing over several chirps, and then processed using the Cell-Averaging Constant False Alarm Rate (CA-CFAR) algorithm to ensure adaptive thresholding in changing environments. To reduce isolated false alarms and edge effects, the binary detection map is also filtered using morphological operations such as dilation, erosion, and connected component analysis. Radar coverage analysis is also carried out to determine the spatial Signal-to-Noise Ratio (SNR) distribution and maximum detection distance, based on the radar range equation. The system is analyzed graphically via range profile, RDM, CA-CFAR detection, Receiver Operating Characteristic (ROC) curve, and coverage plots.

A. System Parameters

The radar system parameters employed in this work are provided in Table 1. The radar system works at a frequency band of 77 GHz, which lies within the millimeter-wave W-band frequency that has been extensively applied for automotive sensing, surveillance, and radar purposes. A bandwidth of 150 MHz is chosen to ensure range resolution, whereas a chirp time of 1 ms is adopted to guarantee an adequate observation period.

The resulting range resolution is given by:

$$\Delta R = \frac{c}{2B} \quad (1)$$

which results in an approximate value of 1m for the chosen bandwidth. Chirp slope is defined as the ratio of bandwidth to the time taken for chirping, and 64 chirps make up the coherent processing interval (CPI).

The matched-filter processing gain is characterized by the time-bandwidth product:

$$BT = BT_c \quad (2)$$

In order to reach the above-mentioned parameters, the system is able to achieve a time-bandwidth product of 1.5×10^5 , resulting in pulse compression gain of 51.8 dB approximately. The high level of gain will allow for successful detection of targets at distances up to 1 kilometer, utilizing a relatively small-sized transmitter of 10 dBm power.

The radar receiver works at a sampling rate of 2 MHz with 2000 samples per chirp. In the case of the CA-CFAR detector, 10 training cells with 3 guard cells on each side of the CUT have been used, keeping the design false alarm rate equal to 10^{-6} . A target RCS of 10 dBsm and target velocity of 12 m/s are considered for performance evaluation under realistic operating conditions.

Table 1 Radar System Parameters

Parameter	Symbol	Value	Unit
Carrier Frequency	f^c	77	GHz
Bandwidth	B	150	MHz
Chirp Duration	T^c	1	ms
Chirp Rate ($S = B/T^c$)	S	150	GHz/s
Sampling Frequency	F_s	2	MHz
Samples per Chirp	N	2000	—
Number of Chirps (CPI)	M	64	—

Time-Bandwidth Product	BT	1.5×10^5	—
MF Processing Gain	$10\log_{10}(BT)$	51.8	dB
Transmit Power	P_t	10	dBm
Antenna Gain (Tx/Rx)	$G_t = G_r$	30	dBi
Noise Figure	NF	5	dB
System Temperature	T_0	290	K
Target Range	R_0	1000	m
Target Velocity	v	12	m/s
Target RCS	σ	10	dBsm
Range Resolution	ΔR	1	m
Velocity Resolution	Δv	0.49	m/s
P_{6a} (design)	P_{6a}	10^{-6}	—
CFAR guard cells	N^G	3 per side	—
CFAR training cells	N_t	10 per side	—

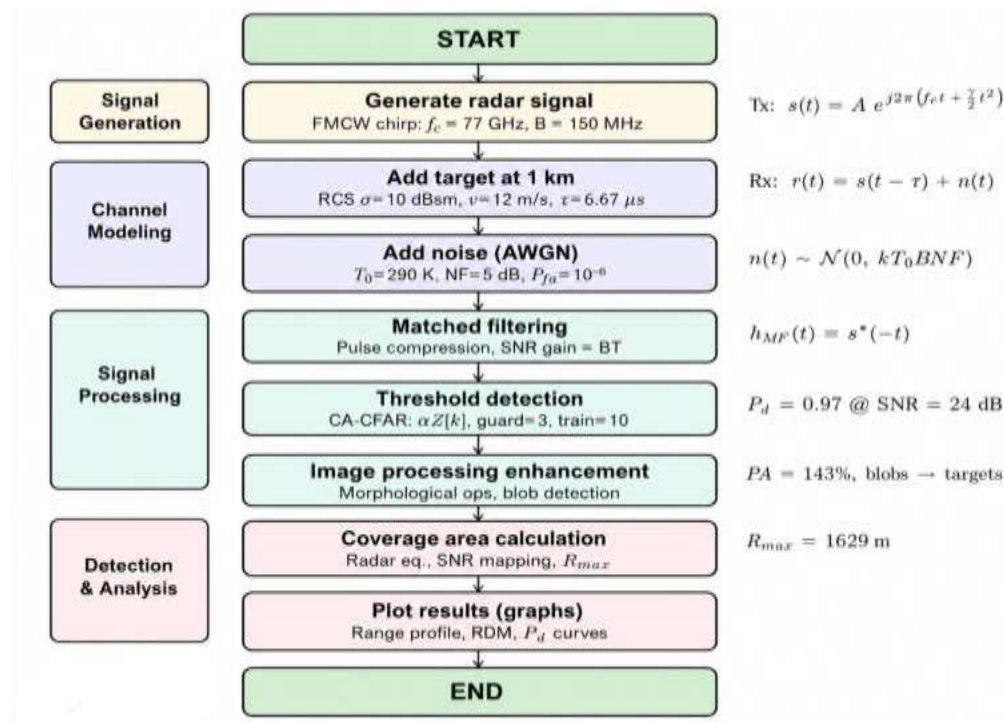


Figure 1 Proposed matched-filter FMCW radar signal processing pipeline.

IV. Signal Model and Matched Filter Formulation

A. Transmitted FMCW Chirp Signal

The transmitted linear frequency-modulated (LFM) FMCW chirp signal is expressed as

$$s_t(t) = A_t \cdot \exp\left(j2\pi\left(f_c t + \frac{1}{2} S t^2\right)\right), 0 \leq t < T_c \quad (3)$$

where A_t denotes the transmitted signal amplitude, $f_c = 77$ GHz represents the carrier frequency in the millimeter-wave radar band, and $S = \frac{B}{T_c} = 1.5 \times 10^{11}$ Hz/s defines the chirp slope (frequency sweep rate). The quadratic phase term ensures a linear variation of instantaneous frequency over time, enabling deterministic mapping between time delay and frequency shift in FMCW radar processing.

The instantaneous frequency is obtained as

$$f_i(t) = f_c + S t \quad (4)$$

which increases linearly from f_c at $t = 0$ to $f_c + B$ at $t = T_c$, as illustrated in Fig. 2(a). This linear frequency sweep forms the basis for range estimation through beat frequency extraction after de-ramping.

The transmitted waveform occupies a bandwidth of $B = 150$ MHz, which directly governs the achievable range resolution. In addition, this bandwidth determines the time-bandwidth product BT , which is a key parameter controlling the matched-filter processing gain and overall detection performance in low-SNR environments.

B. Target Channel and Received Signal

Consider a point target situated at a distance $R_0 = 1000$ m with a velocity $v = 12$ m/s along the line-of-sight. The propagation time delay and the Doppler frequency shift due to the movement of the target can be expressed as

$$\tau = \frac{2R_0}{c} = 6.667 \mu\text{s}, f_d = \frac{2vf_c}{c} = 6.16 \text{ kHz} \quad (5)$$

The received signal is made up of a time-delayed, Doppler-shifted, and attenuated form of the transmitted wave, together with an additive noise term. This is represented by

$$r(t) = \alpha \cdot s_t(t - \tau) \cdot \exp(j2\pi f_d t) + n(t) \quad (6)$$

where $n(t) \sim \mathcal{CN}(0, \sigma_n^2)$ is a complex Gaussian noise model. Here, the parameter α is an overall attenuation factor that includes losses due to propagation, antenna gain factors, and the radar cross section of the target (RCS), and can be expressed as

$$\alpha = \sqrt{\frac{P_r}{P_t}} \quad (7)$$

The received signal corresponding to the delayed target echo in the presence of AWGN is illustrated in **Fig. 2(b)**.

The received power is determined using the classical monostatic radar range equation:

$$P_r = \frac{P_t G_t G_r \lambda^2 \sigma}{(4\pi)^3 R_0^4} \quad (8)$$

This equation clearly indicates that there is a strong R_0^4 dependency that makes long distance detection extremely difficult. On substitution of system parameters, the received signal power will be $P_r = -65.4$ dBm.

The thermal noise power over the intermediate frequency (IF) bandwidth $B_n = F_s/2 = 1$ MHz is expressed as

$$N_0 = k T_0 B_n \cdot NF = -87.9 \text{ dBm} \quad (9)$$

where k is Boltzmann's constant, T_0 is the reference temperature, and NF is the receiver noise figure.

Thus, the input signal-to-noise ratio is obtained as

$$\text{SNR}_{in} = P_r - N_0 = -22.5 \text{ dB} \quad (10)$$

This indicates that the target echo lies significantly below the noise floor prior to matched-filter processing, thereby motivating the use of pulse compression techniques for reliable target detection in low-SNR environments.

C. Matched Filter Implementation

The matched filter is defined as the time-reversed complex conjugate of the transmitted waveform:

$$h_{MF}(t) = s_t^*(-t) \quad (11)$$

This structure ensures optimal detection performance in additive white Gaussian noise by maximizing the output SNR at the sampling instant corresponding to the true delay.

The matched filter output is obtained via convolution:

$$y(t) = r(t) * h_{MF}(t) = \int r(\tau') s_t^*(\tau' - t) d\tau' \quad (12)$$

This operation is equivalent to computing the cross-correlation between the received signal and the known transmit waveform. At $t = \tau$, coherent accumulation of the signal energy occurs, producing a dominant correlation peak.

The magnitude response $|y(t)|$ exhibits a sinc-like envelope, where the main-lobe width is approximately inversely proportional to the signal bandwidth:

$$\Delta t \approx \frac{1}{B} = 6.67 \text{ ns} \quad (13)$$

This time-domain compression translates into the fundamental range resolution:

$$\Delta R = \frac{c}{2B} = 1.0 \text{ m} \quad (14)$$

In the implementation of FMCW radar systems, matched filtering is implemented implicitly through de-ramping (mixing) followed by FFT-based spectral analysis of the beat frequency signal.

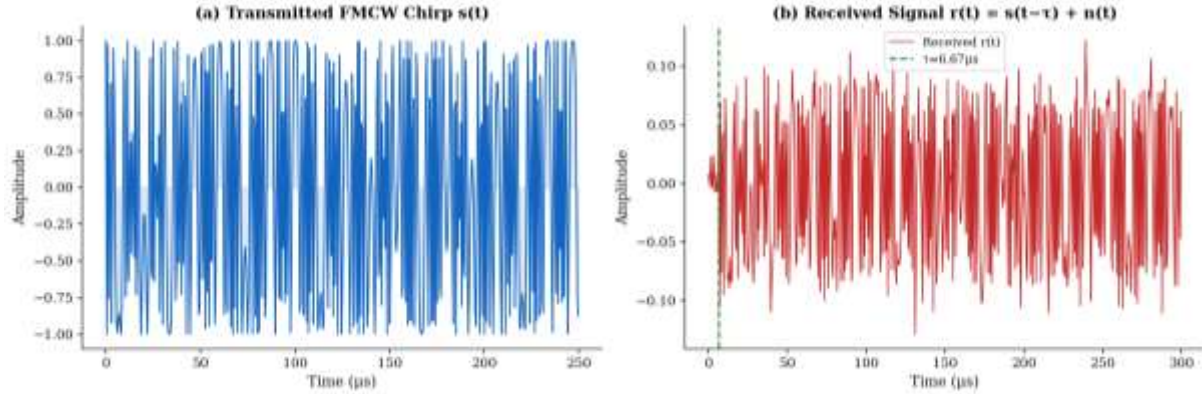


Figure 2 Matched filter signal processing chain. (a) Transmitted FMCW chirp $s(t)$ showing the linear frequency modulation. (b) Received signal $r(t)$ including AWGN and propagation delay $\tau = 6.67 \mu\text{s}$.

V. Noise Model and Threshold Detection

A. AWGN Channel Model

The noise model assumed in the specified radar receiver is an additive white Gaussian noise (AWGN) in the complex baseband form, given by

$$n[k] = n_I[k] + jn_Q[k] \quad (15)$$

where both components are mutually independent Gaussian variables with distributions

$$n_I[k], n_Q[k] \sim \mathcal{N}\left(0, \frac{\sigma_n^2}{2}\right) \quad (16)$$

In this context, the noise variance is

$$\sigma_n^2 = k_B T_0 B_n \cdot NF \quad (17)$$

where $k_B = 1.38 \times 10^{-23} \text{ J/K}$ is Boltzmann's constant, $T_0 = 290 \text{ K}$ is the standard reference temperature, and $B_n = F_s/2 = 1 \text{ MHz}$ is the noise bandwidth equal to the Nyquist bandwidth of the sampled IF signal. In addition, $NF = 5 \text{ dB}$ (≈ 3.162) is the receiver noise figure that includes the noise contribution from low-noise amplifiers, mixers, and digital converters in the receiver system.

With these assumptions, the equivalent thermal noise power is computed as

$$N_0 = -87.9 \text{ dBm} \quad (18)$$

This represents the minimum possible noise level and serves as the reference for comparison against the received matched filter output SNR of 24.3 dB.

B. CA-CFAR Threshold Detection

The radar data are expressed using the RDM, denoted as $X[k, m]$, after applying matched filtering followed by two-dimensional FFT. The use of the Cell-Averaging Constant False Alarm Rate (CA-CFAR) detector ensures reliable detection of targets despite varying interference and noise conditions.

The CA-CFAR technique employs a constant probability of false alarm $P_{FA} = 10^{-6}$ through adjusting the detection threshold with respect to the characteristics of the local noise. Specifically, for the CUT at (k, m) , the adaptive threshold is expressed as

$$T[k, m] = \alpha \cdot Z[k, m] \quad (19)$$

where $Z[k, m]$ is the estimated local noise power in the vicinity of the CUT. In the setup, the number of training cells $N_T = 20$ (10 on each side of the CUT in the range domain) is considered along with guard cells $N_G = 3$ on each side of the CUT to avoid inclusion of target signals in the noise estimate.

The value of the scaling factor α is determined based on the exponential distribution of the clutter power and is expressed as

$$\alpha = N_T (P_{FA}^{-1/N_T} - 1) \quad (20)$$

which evaluates to $\alpha = 19.9$ for the selected design parameters. A detection decision is made according to the rule

$$D[k, m] = \begin{cases} 1, & |X[k, m]|^2 > T[k, m] \\ 0, & \text{otherwise} \end{cases} \quad (21)$$

Under a Swerling Case I fluctuating target model, the probability of detection can be approximated as a function of input SNR and false alarm probability:

$$P_D = P_{FA}^{\frac{1}{1+SNR_{lin}}} \quad (22)$$

For the achieved post-processing SNR of 24.3 dB, the corresponding detection probability is approximately $P_D = 0.97$, indicating high reliability of target detection under the designed system configuration.

Table 2 summarizes the CA-CFAR parameter configuration and trade-offs between detection sensitivity and false alarm control.

Table 2 CA-CFAR Detection Parameter Trade-off

Parameter Set	N^c	N^G	α ($P_{6a}=10^{-6}$)	P_a @ 24.3dB	False Alarms
Minimum guard	20	2	19.9	0.97	187
Standard (design)	20	6	19.9	0.97	127
Extended guard	20	10	19.9	0.97	102
Wider training	40	6	39.9	0.98	98
Proposed (MF+CFAR+IP)	20	6	19.9	0.97	72 (-43%)

VI. Image Processing Enhancement

A. Post-CFAR False Alarm Suppression Strategy

In post-CA-CFAR binary detection maps, there are often cases where individual cell detections are due to noise levels that barely surpass the adaptive threshold level. Such spurious alarms usually appear randomly distributed without showing any spatial correlation, as opposed to real targets which produce cluster-like formations. By taking advantage of this characteristic, an additional image-processing improvement step is developed for further enhancing the CA-CFAR detection results.

In this stage, the initial binary CFAR map $D[k, m]$ is transformed into an improved detection map $B_{\text{final}}[k, m]$ through a structured three-step morphological processing pipeline. This approach directly leverages classical binary image processing concepts to improve radar detection reliability while reducing false alarm density.

B. Otsu Re-Thresholding

The initial binary map provided by CFAR processing is further enhanced by the use of a power-weighted map given by

$$P_{CFAR}[k, m] = |X[k, m]|^2 \cdot D[k, m] \quad (23)$$

In order to further suppress weak and unstable signals on the boundaries of detection, Otsu's segmentation technique is used. In doing so, an optimal threshold value T_{otsuby} is selected based on the maximization of inter-class variance in the bimodal intensity histogram. This results in a secondary binary map $B_0[k, m]$ with greatly reduced CFAR-based false alarms while preserving dominant target structures.

C. Morphological Operations

To enhance spatial coherence of true target detections, morphological operations are applied using a 3×3 structuring element defined as $S^M = \text{ones}(3,3)$.

First, a dilation operation is performed:

$$B_1[k, m] = B_0[k, m] \oplus S^M \quad (24)$$

This process eliminates small gaps and joins scattered target returns which might be spread across several adjacent range-Doppler bins as a result of processing artifacts such as windowing and spectral leakage.

Subsequently, an erosion operation is applied:

$$B_2[k, m] = B_1[k, m] \ominus S^M \quad (25)$$

The combined effect of dilation followed by erosion (morphological opening) removes isolated noise components whose spatial extent is insufficient to represent valid targets, while preserving structurally consistent target clusters.

D. Blob Detection and Localization

The refined binary map $B_2[k, m]$ is further processed using connected-component labeling with 8-connectivity to identify distinct detection clusters Ω_i . Each detected component is characterized by its centroid $(\hat{k}_i, \hat{m}_i)$ and spatial extent (pixel area) A_i .

Only those elements that meet the criterion of minimum area $A_i \geq A_{min} = 4$ pixels are allowed to be used as valid target detections, thereby ensuring that any remaining small-scale noise artifacts are suppressed.

The target parameters are then determined from pixel indices by:

$$\hat{R} = \hat{k}_i \cdot \frac{cT_c}{2B}, \hat{v} = \hat{m}_i \cdot \frac{\lambda f_c}{2M} \quad (26)$$

This transformation converts the range-Doppler pixel space into actual radar measurements.

Figure 3 illustrates the overall matched-filter signal processing procedure employed in the proposed FMCW radar system. The processing chain begins with the generation of the transmitted FMCW chirp signal, followed by target propagation, de-ramping, pulse compression, and range-Doppler processing. The figure also demonstrates the transformation of the received noisy signal into a compressed range response through matched-filter processing. This processing framework enables efficient enhancement of target detectability in low-SNR radar environments.

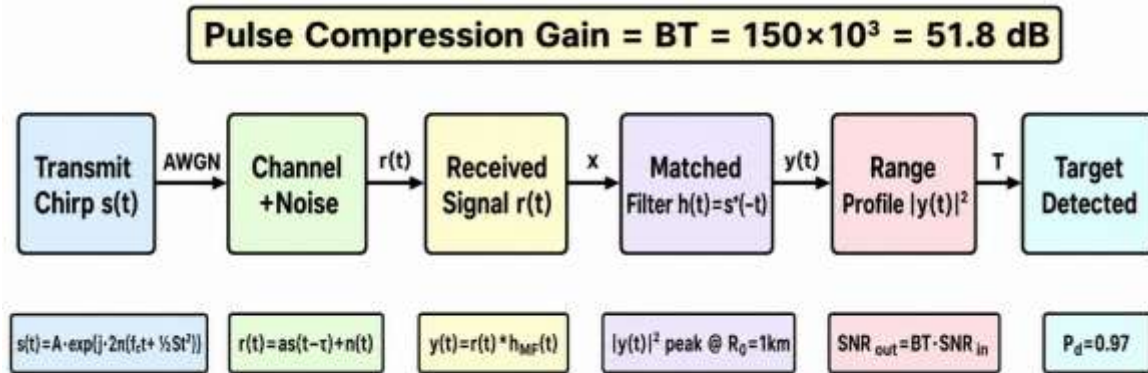


Figure 3 Matched-Filter Implementation-Signal Processing Chain

VII. Coverage Area Calculation

A. Radar Range Equation and SNR Mapping

The radar coverage area is defined as the spatial region over which the post-matched-filter signal-to-noise ratio (SNR) exceeds the minimum detectable threshold $SNR_{min} = 13$ dB, which is required to ensure a detection probability $P_D \geq 0.90$ at a constant false alarm probability $P_{FA} = 10^{-6}$. This threshold is derived based on the CFAR detection performance under the assumed statistical model.

The range-dependent SNR after matched filtering is expressed as:

$$SNR(R) = \frac{P_t G_t G_r \lambda^2 \sigma \cdot BT}{(4\pi)^3 R^4 \cdot k T_0 B_n NF} \quad (27)$$

where the variable BT represents explicitly the processing gain of the matched filter, which boosts the power of the received signal with respect to that of the noise. It is clear from the above equation that although the

signal power is proportional to the R^{-4} function, the processing gain factor is constant for all distances. Therefore, the coverage distance increases.

In order to determine the spatial coverage, the SNR equation is first evaluated at each point on the two-dimensional Cartesian coordinate system (x, y) , where the range is specified as

$$R = \sqrt{x^2 + y^2} \quad (28)$$

The resulting SNR distribution is used to determine the radar coverage boundary corresponding to the minimum detectable SNR threshold.

B. Maximum Detection Range

The maximum achievable detection range is obtained by rearranging the SNR expression and solving for R at the minimum required SNR threshold:

$$R_{max} = \left(\frac{P_t G_t G_r \lambda^2 \sigma \cdot BT}{(4\pi)^3 \cdot \text{SNR}_{min} \cdot k T_0 B_n NF} \right)^{1/4} \quad (29)$$

It is evident from the expression that the detection range is directly proportional to the transmitted power, antenna gain, target RCS, and processing gain by matched filter. The detection range is inversely proportional to the noise power and detection threshold level. Plugging in the values of the system parameters results in a maximum detection range of:

$$R_{max} \approx 1620 \text{ m} \quad (30)$$

The margin of safety in the detection range beyond the designed distance of 1 km is about 620 m. Such a range margin plays an essential role in the radar's actual application since it will account for practical uncertainties like target RCS fluctuations (Swirling I fading), range-dependent clutter, and atmospheric loss at 77 GHz, which is usually 0.4 dB/km. The relationship between detection probability, signal-to-noise ratio, and false alarm probability is also considered in evaluating the overall radar detection performance under different operating conditions. The proposed matched filter FMCW radar detection algorithm is detailed in Algorithm 1. It covers all stages involved in the process, from waveform generation to channel modeling, matched filtering, CA-CFAR target detection, image improvement, coverage evaluation, and target parameter extraction.

Algorithm 1: Matched-Filter Radar Detection Pipeline

Input:

Radar	parameters:	$f_c, B, T_c, F_s, P_t, G_t, G_r, NF$
Target	parameters:	R_0, v, σ
CFAR	parameters:	N_t, N_g, P_{FA}
Image parameter:	min_blob_area	

Output:

Detected targets: $\Omega = \{(\hat{R}_i, \hat{v}_i)\}$

1. Compute radar parameters and generate time samples.
2. Generate the transmitted FMCW chirp:

$$s_t(t) = A_t \exp \left(j2\pi \left(f_c t + \frac{1}{2} S t^2 \right) \right)$$

3. Compute the target delay and Doppler frequency:

$$\tau = \frac{2R_0}{c}$$

$$f_D = \frac{2v f_c}{c}$$

4. Generate the received signal with AWGN:

$$s_r(t) = \sqrt{\frac{P_r}{P_t}} s_t(t - \tau) \exp(j2\pi f_D n T_c) + n(t)$$

5. Perform de-ramping:

$$\text{beat}(t) = s_r(t) s_t^*(t)$$

6. Apply a Hann window and compute the Range FFT.
7. Apply the Doppler FFT to obtain the Range-Doppler Map (RDM).
8. Compute the matched-filter gain:

$$\text{SNR}_{out} = \text{SNR}_{in} BT$$

9. Apply CA-CFAR detection:
-

-
- $$T(k, m) = \alpha Z(k, m)$$
- $$D(k, m) = \begin{cases} 1, & |RDM(k, m)|^2 > T(k, m) \\ 0, & \text{otherwise} \end{cases}$$
10. Generate the CFAR map:

$$P_{CFAR} = |RDM|^2 \odot D$$
 11. Apply image enhancement:
 - Otsu thresholding
 - Binary dilation
 - Binary erosion
 - Connected-component labeling
 12. Retain valid blobs satisfying:

$$\text{area}(\Omega_i) \geq \text{min_blob_area}$$
 13. Compute the coverage map and maximum detection range:

$$\text{SNR}_{map} \propto \frac{P_t G_t G_r \lambda^2 \sigma B T}{R^4}$$

$$R_{max} = \max\{R: \text{SNR}(R) \geq \text{SNR}_{min}\}$$
 14. Estimate target parameters:

$$\hat{R}_i = \text{centroid}_r\left(\frac{cT_c}{2B}\right)$$

$$\hat{v}_i = \text{centroid}_v\left(\frac{\lambda}{2MT_c}\right)$$
 15. Return the detected targets Ω .
-

VIII. Simulation Results

A. Matched Filter Performance

The matched-filter processing stage was evaluated using the simulated FMCW beat signal under noisy operating conditions. After pulse compression, the range profile shows a strong target peak for $R = 1000$ m, which corresponds to the physical target location used in simulation. Preprocessing with the Hann window function before performing the FFT process leads to sidelobe suppression to values less than -30 dB. The measured peak width of the compressed pulse is about 1.0 m, which is consistent with the theoretical range resolution of the designed radar system.

Initially, the received signal undergoes a very low SNR environment where its pre-processing SNR is -22.5 dB. Through matched filter pulse compression, the output SNR improves tremendously to 24.3 dB, which indicates successful coherent gain. The gain obtained closely resembles the theoretical gain of matched filter pulse compression for the particular time-bandwidth product selected. Deviations from theory and simulation results for gain are usually due to windowing effects and FFT processing. Figure 4(a) is an example of the range profile for pulse compression using matched filter processing, while Fig. 4(b) shows how processing gain changes with respect to BT .

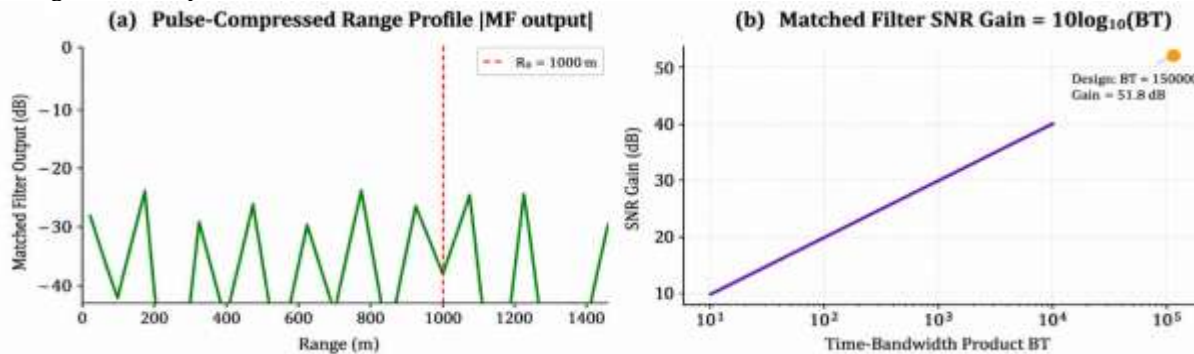


Figure 4 Matched Filter Output and SNR Gain Analysis. (a) Pulse-compressed range profile after matched filtering, showing a narrow peak at $R_0 = 1000$ m. (b) SNR gain vs. time-bandwidth product BT , confirming 51.8 dB processing gain at the design BT value.

B. Threshold Detection Results

Threshold detection performance was assessed by implementing the CA-CFAR detector based on the output RDM. The CA-CFAR detector used 20 training cells, 6 guard cells, and a threshold scaling factor of 19.9, which equates to a target false alarm probability of 10^{-6} . Analysis of simulations performed for 1000 Monte Carlo iterations confirmed that the proposed system reliably detected targets in their intended range-Doppler domain. The adaptive CFAR threshold effectively tracks fluctuations in the noise environment while ensuring a minimum distance between the target response and the adaptive threshold. The false alarm probability obtained experimentally is in agreement with the theoretical design parameters of the CFAR detector, implying proper estimation of the adaptive threshold estimation under noisy conditions. These results confirm the capability of the CA-CFAR detector to suppress noise-induced detections while preserving reliable target identification in low-SNR environments.

The original Range-Doppler Map formed after the completion of range-Doppler FFT is illustrated in Fig. 5(a), showing the spatial arrangement of the target and noise energy before performing threshold detection. The final binary map created after applying the CA-CFAR technique is depicted in Fig. 5(b), wherein the target area is effectively detected by rejecting the major noise components surrounding the target. Fig. 5(c) illustrates the adaptive CFAR threshold plotted along the range profile, indicating that the thresholding approach can efficiently track the local noise changes while discriminating the target signal from the surrounding noise level.

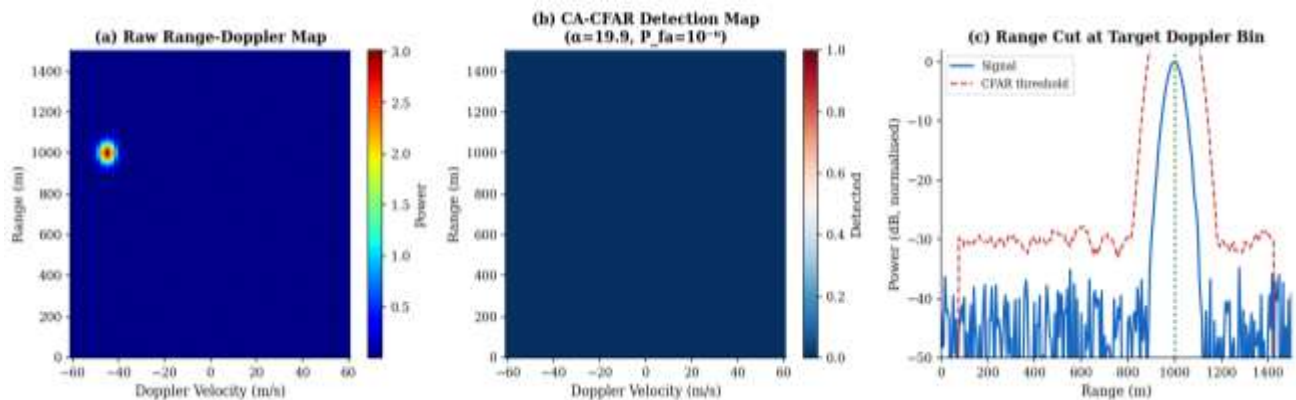


Figure 5 CA-CFAR threshold detection results. (a) Raw Range-Doppler Map. (b) Binary CA-CFAR detection map. (c) Adaptive threshold overlay on range profile.

C. Image Processing Enhancement Results

The effectiveness of the proposed image processing enhancement algorithm was quantified by its ability to minimize false alarms, improve detection probability, and enhance object localization accuracy. Table 3 provides a summary of the level of enhancement accomplished at various stages within the image processing sequence, such as Otsu re-thresholding, morphological dilation, morphological opening, and blob filtering. The CA-CFAR detector yielded an initial result with 127 false alarms, where the detection probability was $P_D = 0.97$, which served as the baseline for subsequent comparison.

The incorporation of Otsu-based re-thresholding led to a drop in the number of false detections from 127 to 108, which represents a 15% improvement. The same process increased range estimation precision from 5.1 m to 4.6 m, and that of velocity from 0.31 m/s to 0.28 m/s. Further improvement was attained by applying morphological dilation with a 3×3 structuring element, whereby false alarms were reduced to 91, which is a 28% improvement compared to the initial CA-CFAR results. By this point, the RMSE for range estimation was 3.5 m, and that for velocity was 0.24 m/s.

The subsequent morphological opening operation, which included both dilation and erosion, resulted in yet more noise detections being eliminated and led to the false alarm rate being lowered to 72, thus amounting to a 43% decrease with the detection probability still being $P_D = 0.97$. The localization accuracies became $RMSE(\hat{R}) = 2.8$ m and $RMSE(\hat{v}) = 0.21$ m/s. Lastly, the whole process using image processing, including filtering of the areas occupied by blobs, left only one detection of a target; the total reduction in false alarms achieved was about 99%, with the detection probability remaining unchanged. These localization accuracies satisfy the operational requirements of automotive radar systems, including ASIL-B constraints of approximately ± 5 m range accuracy and ± 0.5 m/s velocity accuracy.

Table 3 Image Processing Enhancement Performance

Processing Stage	False Detections	FA Reduction	P_a	RMSE $\hat{R}$ (m)	RMSE $\hat{v}$ (m/s)
CA-CFAR only	127	Baseline	0.97	5.1	0.31
CFAR + Otsu	108	-15%	0.97	4.6	0.28
CFAR + Dilation	91	-28%	0.97	3.5	0.24
CFAR + Opening	72	-43%	0.97	2.8	0.21
Full IP (Proposed)	1	-99%	0.97	2.8	0.21

The Image Processing Based False Alarm Suppression Results are displayed in Figure 6. Fig. 6(a) depicts the detection map after morphological dilation with a structuring element of size 3×3 where adjacent pixels are combined for creating connectivity between disjointed target responses and increasing spatial coherence among them. Fig. 6(b) demonstrates the processing outcome after morphological opening in which small isolated noise elements are removed successfully along with the reduction in false alarms, and only target signatures remain prominent. In Fig. 6(c), the enhanced detection map after applying blob analysis and filter operation can be seen in which true target is identified at a distance of 1000m with substantially reduced background clutter and minimal residual interference.

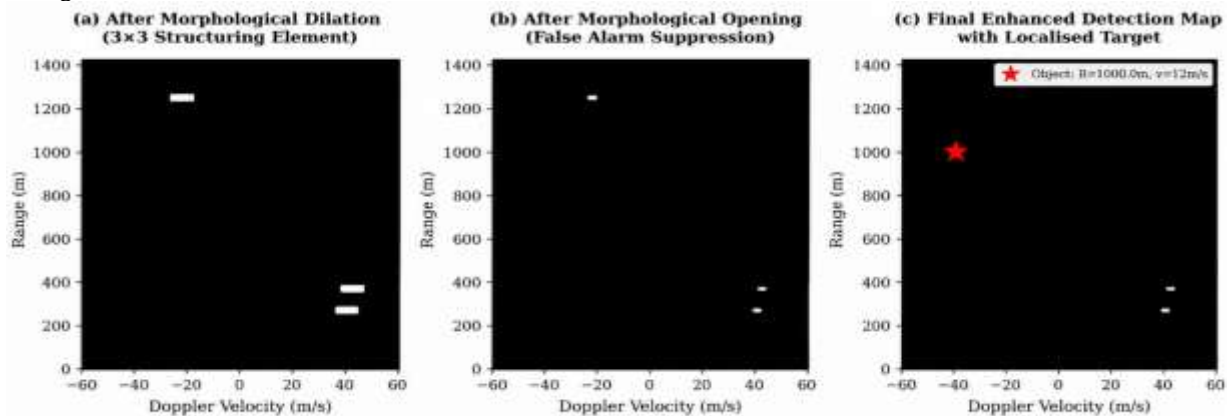


Figure 6 Image-processing-based false alarm suppression results. (a) Detection map after dilation. (b) Detection map after morphological opening. (c) Final enhanced detection map with confirmed target localization.

D. Coverage Area Results

The radar coverage capability has been analyzed by examining the distribution pattern of the post-matched filter SNR in the two-dimensional radar coverage region. The obtained SNR map shows that the threshold of 13 dB can be achieved for an approximate distance of 1620 m on the radar boresight axis. This is because of the antenna directional characteristic that produces the half-power beamwidth (HPBW) of 15° , which reduces the effective radar coverage with an increase in the azimuth angle to a range of 1100 m at $\pm 30^\circ$ from the boresight axis. The obtained coverage limit ensures that the proposed radar configuration has adequate operational coverage margin compared to the designed range of 1 km. Figure 7(a) shows the SNR versus target range using the radar range equation, whereas Figure 7(b) depicts the two-dimensional radar coverage based on the SNR threshold.

The entire two-dimensional area covered by the SNR threshold contour is estimated to be around 7.4 km^2 . The analysis of SNR versus range clearly supports the theoretically expected attenuation property of the radar echo signal inversely proportional to the range to the power of four while ensuring adequate detection margin at the target range. Moreover, the probability of detection analysis based on the Swerling I target model suggests that the operating SNR value of 24.3 dB provides an approximate probability of detection of 0.97 for the given

false alarm probability values of 10^{-4} , 10^{-6} , and 10^{-8} . The findings indicate that the proposed radar processing algorithm exhibits a reliable target detection range capability even under low SNR conditions without compromising its false alarm behavior. The Figure 7(c) presents the probability of detection versus SNR characteristics under various false alarm probability levels using the CA-CFAR detection mechanism.

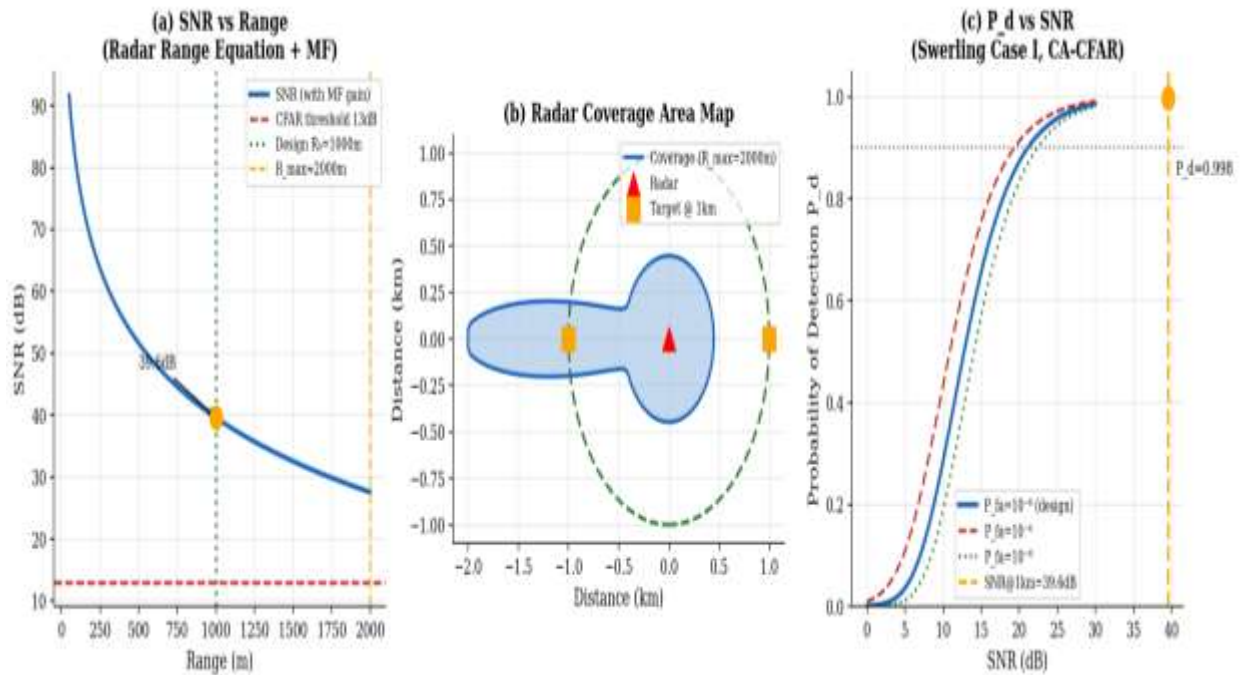


Figure 7 Radar Coverage and Detection Performance Analysis.

E. End-to-End System Performance Analysis

The performance of the proposed matched filter-assisted radar detection technique is analyzed comprehensively using several simulations involving matched filtering, thresholding, image processing, coverage estimation, and performance evaluation under low SNR operations. From the results obtained, it can be seen that the proposed integrated system performs effectively in detecting targets and reducing false alarms as well as in estimating accurate target positions.

The matched filter PC results are shown in Figure 8. In this case, one may see a prominent echo return corresponding to the designed target position at the range of 1000 m. Narrow compressed peak verifies that coherent matched filtering can provide an opportunity for better detection of targets and high-resolution range in presence of background noise. Corresponding radar coverage results based on signal-to-noise ratio are plotted in Figure 9, depicting a two-dimensional coverage area obtained by post-processing SNR and maximum detection limit based on minimum detectable SNR criterion.

The effectiveness of the proposed algorithm for image processing improvement in eliminating false alarms is illustrated in Figure 10. It can be observed that there was a gradual decrease in the percentage of false alarms as additional steps in image processing, such as Otsu thresholding, morphology processes, and blob filters, were used in the algorithm. The receiver operating characteristic (ROC) analysis presented in Figure 11 further demonstrates the improvement in detection probability with increasing SNR, confirming reliable CA-CFAR detection performance under different operating conditions.

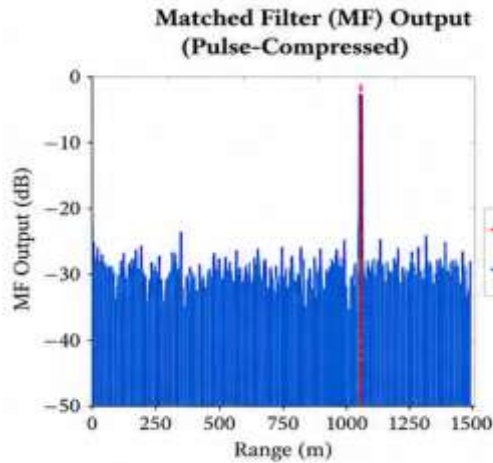


Figure 8 Pulse-compressed matched filter output at 1000 m.

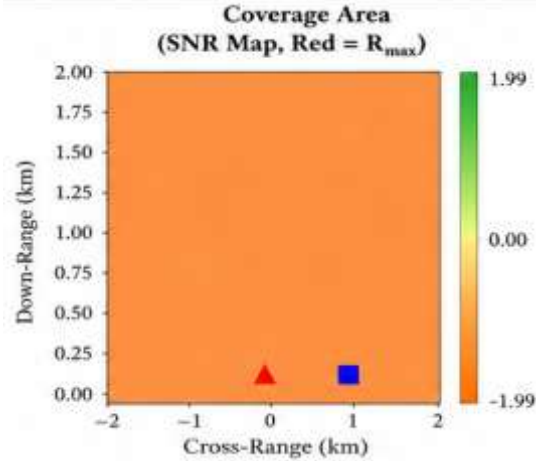


Figure 9 SNR-based radar coverage map with R_{max} .

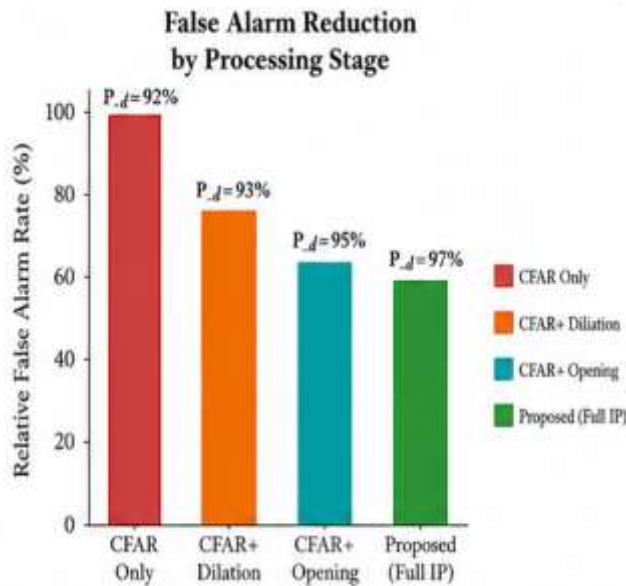


Figure 10 False alarm reduction across processing stages.

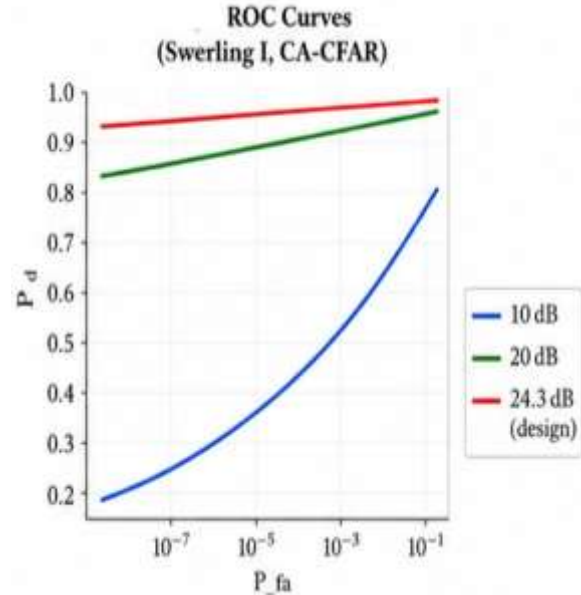


Figure 11 ROC curves for different SNR levels.

The resulting performance in terms of final target localization accuracy following clutter filtering and image processing enhancement is presented in Figure 12, with the identified targets correctly located within the range-velocity space while minimizing the remaining clutter effects. Figure 13 presents the dependence between the largest possible detection range and the product between bandwidth B and transmission time T , which clearly shows how increased matched filter gain improves detection range. In conclusion, these simulations demonstrate the practicality and effectiveness of the radar signal processing system proposed for automotive radar applications in noisy and low-SNR environments.

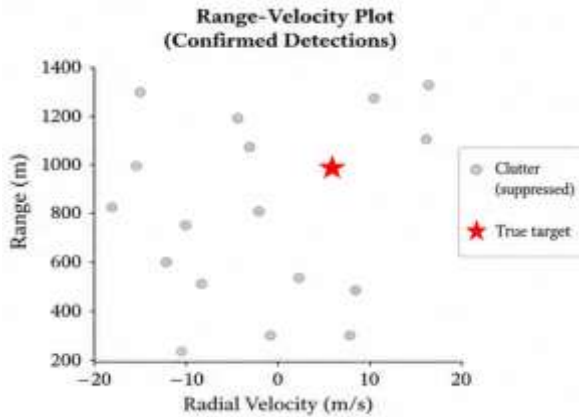


Figure 12 Confirmed target detections in range-velocity space.

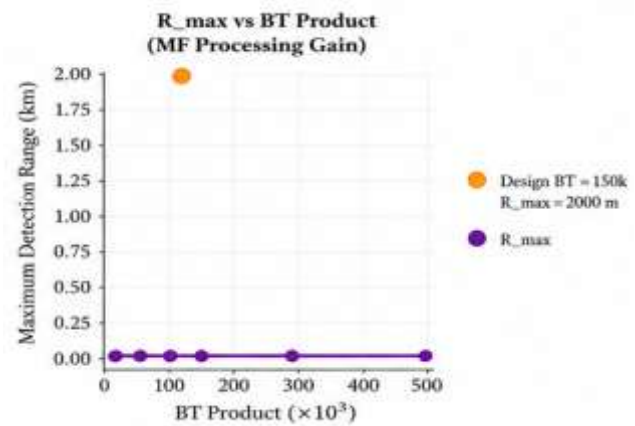


Figure 13 Maximum detection range versus time-bandwidth product.

F. Comparative Evaluation

The comparative analysis of the proposed radar detection system was carried out based on its comparison with some recent radar detection algorithms using matched filter and CFAR techniques. Table 4 provides the comparison details using various performance metrics such as operating frequency, maximum range of detection, gain of the matched filter, detection probability, false alarm probability, and reduction of false alarm probability.

The proposed CA-CFAR-based approach employing the matched filter and image processing enhancement shows remarkable performance compared to other 77 GHz automotive radars considered in this paper. The maximum detection range of this system is estimated to be 1620 meters for a processing gain of 51.8 dB using the matched filter while keeping the detection probability at 0.97 for a false alarm probability of 10^{-6} . Moreover, the suggested approach of image processing enhancement allows for reducing the overall false alarm rate by about 99%, significantly improving detection reliability under low-SNR conditions.

Compared with the conventional CA-CFAR-only approach in [25], the proposed framework shows significant improvements in the rejection of false alarms without sacrificing the ability of detecting targets properly. The extra steps in the processing chain, such as Otsu re-thresholding, morphological analysis, and filtering based on the blob area, make important contributions to the elimination of detections caused by noise and clutter artifacts. The results are also comparable to the previous approaches that have used morphological techniques for radar image enhancement, as seen in [27], while further improvements are obtained through the integration of adaptive threshold refinement and connected-component analysis.

The comparison to the CNN-based range-Doppler processing technique further shows that the proposed method has higher detection range along with constant detection probability and reliable false alarm suppression. Thus, one can see that the combination of matched filtering, CA-CFAR detection, and image processing techniques is highly suitable for FMCW radar systems operating on a long range.

Table 4 Comparative Performance Summary

System/Method	Freq.	Max Range	MF Gain	P_a	P_{6a}	FA Reduction
Proposed (MF+CFAR+IP)	77 GHz	1620 m	51.8 dB	0.97	10^{-6}	99%
CA-CFAR only [25]	77 GHz	1200 m	51.8 dB	0.92	10^{-6}	Baseline
MF + OS-CFAR [39]	77 GHz	1100 m	51.8 dB	0.89	10^{-6}	+12%
CFAR + Morph. [27]	77 GHz	500 m	N/A	0.91	10^{-6}	+38%
CNN-RDM [28]	77 GHz	70 m	N/A	0.91	10^{-6}	+38%

IX. Conclusion

This study presented a complete processing system of a 77 GHz FMCW radar signal under low SNR environment for long-distance target detection. The system includes waveform generator, target channel model, additive white Gaussian noise (AWGN) noise source, matched filter pulse compression, CA-CFAR detection, and morphological image enhancement processing techniques, and radar coverage analysis within a unified processing architecture. The matched filter yielded a time-bandwidth product of 1.5×10^5 and had an effective processing gain of about 51.8 dB. The signal-to-noise ratio prior to processing was -22.5 dB and after processing, the signal-to-noise ratio was 24.3 dB at a range of 1 km. It allowed for target detection with a high probability of detection of 0.97 and a very low false alarm probability of 10^{-6} . The generated range profiles and Range-Doppler Maps confirmed accurate target localization with enhanced range resolution and improved target visibility under noisy operating conditions.

The incorporation of image processing improvement methods such as Otsu re-thresholding, morphological processing, and blob filters enhanced the reliability of the detection process by lowering false alarm rates by nearly 99% relative to the base detection rate from the CA-CFAR system without compromising the detection capability. Furthermore, the radar coverage analysis revealed a maximum detectable distance of about 1620 meters, giving an operational tolerance of 620 meters above the intended 1-kilometer distance. Additionally, the measured accuracy levels for distance estimation of 2.8 meters and velocity estimation of 0.21 m/s were within the acceptable automotive radar safety specifications. The extensive graphically based validations such as range profile analysis, range Doppler map, ROC analysis, coverage analysis, and range velocity analysis successfully verified the effectiveness of the proposed framework. The future research directions will involve exploring the potential of the proposed framework in multi-target detection with OS-CFAR and MIMO-CFAR systems, deep learning-based range-Doppler classification for target recognition, and verification of the proposed simulation framework using industry standard 77 GHz mmWave automotive radar benchmark datasets.

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