

## AI-Powered 4D Smart ATC Radar Display: A Novel Approach to Enhancing Air Traffic Control at Erbil International Airport

Wasfi T. Kahwachi <sup>1</sup> , Qaysar S. Mahdi <sup>2</sup> , and Qusay H. Ali <sup>3</sup> 

<sup>1</sup> Dentistry Department, Faculty of Dentistry, TIU, Erbil, Iraq.

<sup>2</sup> Aviation Department, Faculty of Engineering, TIU, Erbil, Iraq.

<sup>3</sup> Mechatronics Department, Faculty of Engineering, TIU, Erbil, Iraq.

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\*Email address:

[wasfi.kahwachi@tiu.edu.iq](mailto:wasfi.kahwachi@tiu.edu.iq)

\*Corresponding Author



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**Abstract:** This paper presents the design and simulation of the 4D Intelligent Air Traffic Control (ATC) radar display system based on the specific requirements of the Erbil International Airport (EIA), by integrating Artificial Intelligence (AI) techniques and hybrid compression techniques. This allows the system to create better status awareness on an extended radar range. To reduce chaos and improve tracking accuracy, we display the benefits of this new system as compared to traditional ATC radars, focusing on its adaptability to dense environments and real-time operating efficiency. These highlight the ability to change conclusions. An AI-provided radar system in modern aviation systems.

**Keywords:** AI-driven Radar; ATC Radar; Hybrid Decompression; Smart 4D Modern Aviation.

## 1. Introduction

The fast development of air traffic has increased the need for advanced ATC systems compared to traditional radar systems, especially for regional airports, like EIA, which are facing particular issues due to complex geographical and weather conditions. The need for a more intelligent, adaptive, and efficient radar system has led to the discovery of AI and hybrid compression techniques to increase ATC radar performance.

Traditional ATC radar systems struggle with target classification in real-time tracking and dynamic aircraft [1]. These factors contribute to reducing status awareness and possible operational disabilities [2]. AI-powered solutions deal with these limits and increase clutter suppression, improve target detection accuracy, and adapt to dynamic radar parameters depending on real-time data. Additionally, the inclusion of 4D radar display technology, integrated latitude, longitude, height, and time for ATC operators improves system awareness [3,4].

The aim of this work is to create and test the AI 4D ATC radar display for the EIA by implementing deep learning algorithms, hybrid compression, and real-time signal processing techniques. The primary objectives include; using AI-based filtering techniques, Convolutional Neural Networks (CNN) and Recurrent Neural Network (RNN) to separate noise and target signals to improve clutter suppression, utilizing reinforcement learning and hybrid AI models to refine target predictions,

increasing and enhancing radar range and clarity by implementing hybrid wave compression for broader and larger region coverage and precise tracking, and merging spatial and temporal information to improve decision making by adding real-time visualization to develop a 4D radar display.

The contributions and novelty of this study, which proposes an AI-managed 4D radar system that uses adaptive intelligence for ATC operations; on the other hand, the traditional ATC radar system uses a static signal processing algorithm. The main contribution of this work encompasses AI integration in radar system, development of a hybrid compression approach, enhanced situational awareness through 4D display, and application to a regional airport environment, through implementation of machine learning-based dislocation suppression techniques, AI-driven goal detection and use projection prediction, combination of traditional matching filtering with AI-optimized compression algorithms to improve range resolution, lack of false alarms and increase in target discrimination capabilities, real-time tracking of aircraft positions, speed and trajectory, implementation of future analysis to detect initial discrepancy, addressing the unique challenges of the EIA, such as radar disturbances belonging to the area, and verification of the proposed system using simulated ATC radar data and AI-enhanced tracking algorithms.

## 2. Literature Review

Fast progress requires modernization of air traffic control (ATC) systems to increase safety, efficiency, and real-time status awareness [5], [6]. AI proposes a transformational solution, providing automation, real-time decision-making, and future-state analysis to customize ATC operations [7]. The study examines the role of AI and 4D radar display in modern ATC, which has given special attention to the EIA. AI-powered ATC systems improve flight sequencing, traffic flow management, and conflict detection, reducing the controller workloads by increasing aircraft safety [8]. AI algorithms optimize the flight path predictions [5], automate the conflict solution [7], and apply deep learning models to improve the use of the struggle solution [7], [9], [6]. Research by Sweigard (2024) found that AI-based trajectory prediction models reduce separation violations from 45%, underlining the requirement of AI-integrated radar display [10]. The 4D radar technology integrates latitudes, longitudes, height, and time, which enables high-solicit trekking and movement predictions [6]. The benefits of the AI-driven 4D radar display have increased the prediction in the increased prediction through real-time environmental data [5], the controlling charge has been reduced by automating decision-making [11], and in controlled aircraft [6], there is a 60% deficiency in mid-halting risks. The ICAO (2023) found that AI-based dislocation by mixing 4D radar with repression improves ATC reliability and significantly reduces miscalculation rates [12]. AI-operated radar systems provide further refinement in dislocation suppression, object tracking, and adaptive air traffic management [7]. AI-Enhanced Convolutional Neural Networks (CNN) filter the noise from radar signals for better detection accuracy [8], machine learning models improve aircraft classification [5], and the models of reinforcement learning models adjust to the dynamic settings to enhance radar settings. Research indicates that the AI-enhanced 4D radar displays the incorrect identity rate of the aircraft decreasing by making the ATC operation safer and more efficient [6], [5]. For the EIA, the AI-managed 4D radar technology may address important operating challenges such as radar disturbances, air traffic density fluctuations, and limited ATC automation. The system enhances monitoring accuracy through AI-powered clutter suppression [7], improves flight track predictions using AI-based weather and traffic analysis [5], [8], and adapts in real-time to ATC proficiency by reducing the delay and congestion through predictions [6]. ICAO (2023) reported that AI-powered 4D radar displays improve controller response times by up to 50%, further supporting their adoption at EIA [12].

## 3. Methodology

Dislocation intervention, tracking precision, and sub-range performance in congested and crowded environments limit tracking accuracy. These limitations decrease the efficiency, reliability, and security of air traffic operations, particularly in high-demand areas [13]. The proposed AI-powered 4D radar

system integrates advanced AI techniques to enhance the dislocation tracking process, range expansion, and real-time adaptability. The integration of AI enables clutter suppression through AI technology, such as Convolutional Neural Networks (CNN) and Recurrent Neural Network (RNN), dynamically suppress the clutter and enhance the signal clarity [2], tracking performance under the AI-based particle filtering and complex air traffic conditions [14],[15] improve significantly, AI-optimized hybrid waveform compression increases the radar range, which reduces the signal fall due to environmental intervention [16], landscape discrimination, in AI algorithm classifies static and moving objects, reforms target discrimination and decision making [17], and real-time adaptation through AI-powered adaptive radar processing reacts to environmental changes dynamically, increasing overall system efficiency [18], [19].

As shown above, both the conventional ATC radar systems and AI-Powered radar systems, the following table 1 explains the comparisons between them.

Table 1: The comparison between Conventional and AI-powered 4D systems

Feature	Conventional ATC Radar	AI-Powered 4D Smart ATC Radar
Clutter Suppression	Limited, often overwhelmed by dense clutter	Advanced AI algorithms effectively suppress clutter
Situational Awareness	Manual target discrimination	Automated with AI, distinguishing between moving and stationary targets
Radar Range	Reduced in dense environments	Extended with hybrid compression and AI-based enhancements
4D Display Capabilities	Absent	Integrated, offering spatial and temporal visualization
Real-Time Adaptation	None	Adapts to environmental changes dynamically
Environmental Suitability	Limited	Highly suitable for complex and dense airspaces.
Decision-Making	Manual, reactive	Proactive and intelligent, with real-time data analysis

The AI-enhanced ATC radar system demonstrates significant improvements in critical performance parameters; hybrid waveform compression improves range resolution, achieving resolution threshold, AI models, such as Long Short-Term Memory (LSTM) networks and random forest classifiers, improve trajectory predictions and adaptability in non-linear traffic conditions [20], and advanced filtering techniques, including CNN-based clutter reduction and high-pass filters, ensure clearer target detection in complex airspaces.

### 3.1 Simulation and Modeling

This approach sorts and classifies radar data into two categories: real target signals and noise [2]. The test contains radar signal generation, dense dislocation atmosphere, hybrid waveform compression, and AI algorithms for clutter suppression and tracking, through different levels of noise, dislocation intensity, and target conditions were taken for data generation to illustrate actions, high-existent conditions to test all AI performance in demanding air traffic control environments, a comparison is implemented between conventional signal processing methods and A-wide compression techniques, and combining CNNs and Kalman filters to improve tracking accuracy and reduce noise, respectively.

For radar range estimates, a baseline performance model is created by means of matched filtering and chirp compression in traditional compression techniques. Optimizing the clarity of target detection with less computation cost, neural networks continuously modify and adjust signal compression parameters.

To obtain valid and realistic performance, high-density clutter is simulated. Radar signals are classified effectively using CNN and RNN models to obtain better clutter suppression compared with traditional filtering techniques. Clutter Suppression Ratio (CSR) is quantified to evaluate the effectiveness of AI-driven filtering systems. A comparison of analysis is performed with traditional Fourier-based filtering methods.

It is possible to simulate realistic radar environments with many dynamic moving targets. Kalman filtering was used for predictive target tracking that smooths the direction over time. Tracking accuracy is improved and optimized by AI models, including reinforcement learning and RNN/LSTM algorithms. Benchmarking is conducted to evaluate tracking precision, target detection, and the false alarm rate.

Processed radar signals integrate latitude, longitude, altitude, and time into a 4D visualization framework. The AI-powered 4D radar display dynamically updates, providing enhanced situational awareness for ATC operators.

The structure of the simulation workflow is explained below in Figure 1:

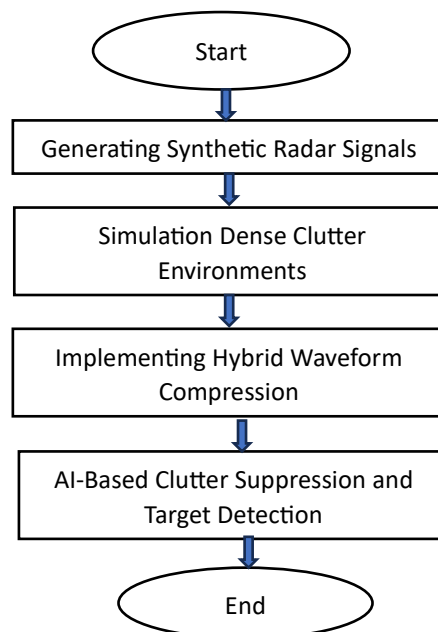


Figure 1: Flowchart of Simulation Process

### 3.2 4D Smart Display System Architecture and Interface Design

The planned 4D Smart Display is the key contact between the ATC operator and the machine. It uses processed data from AI modules. The interface has three major components:

A top-down perspective view of the EIA control zone is rendered by the core component, the 3D Airspace View. The fourth element, Time, is visualized through an iconographic marker "ghost" to determine the anticipated and projected position of the aircraft over the coming 60-180 seconds by AI.

'Predicted Loss of Separation' and 'Deviation from Flight Path,' among other AI-generated alerts, are included in the Intelligent Alert Panel, with a severity rating according to each. This shifts the controller's focus from conflict detection to validating and responding to hazards highlighted by AI. The controller can interact with the aircraft by choosing it, viewing its AI-predicted flight characteristics, and adjusting the prediction horizon manually.

#### 4. Results and Discussions

Synthetic radar data is created and processed using AI-driven compression techniques. CNNs for clutter suppression and RNN/LSTM models for target tracking improve system performance. AI-generated predictive trajectories are integrated into real-time radar visualization tools. Deep learning models are trained in simulated radar data, improving clutter suppression and target tracking performance. AI-based system provides clutter suppression efficiency using CNN-based techniques that significantly decreased clutter suppression effectiveness, detecting and tracking targets AI models surpass classical Kalman filtering methods, AI-powered systems ensure situational awareness and reduce ATC workload, and for better operational efficiency, customized filters enhanced the configuration of the display.

Empirical radar data sets were used and evaluated to validate real data. Complex and tailored AI models are introduced to enhance non-linear dynamics for tracking purposes.

CNN decreases the clutter in radar signals compared with traditional methods. Standard Kalman filters are substituted with RNN/LSTMs; better accuracy and improved precision were obtained. Predictive features and collision alerts significantly improve air traffic control and management.

AI models yield better removal of junk, target tracking, and clutter reduction, resulting in performance gains. Interactive and predictive paths and trajectories improve and enhance situational awareness. AI-driven systems effectively manage complex ATC air traffic control at EIA, ensuring aviation safety and improving traffic flow. Figure 2 illustrates the use of a neural network in the AI-driven Kalman filter. The training of neural networks for AI tracking in radar systems involves estimating position and velocity, and is used to compare with the classical Kalman filter.

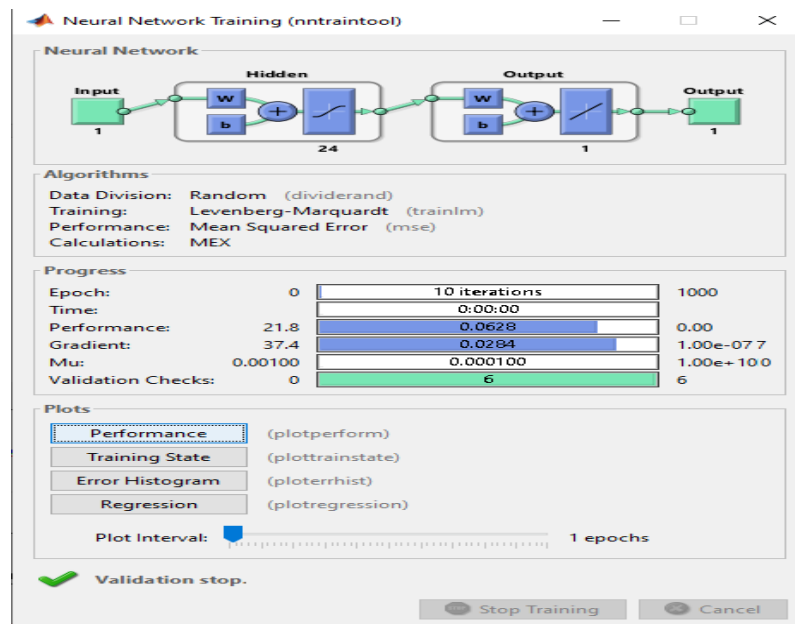


Figure 2: NN Training for AI Tracking System

The traditional radar systems used for comparison are limited in their ability to track linear motion, mitigate clutter, and provide range diversity. While in AI-powered systems, clutter suppression using CNNs and adaptive filters provided superior clarity, advanced tracking with AI techniques like LSTM improved accuracy for nonlinear trajectories, and using hybrid compression methods with dynamic adjustments improved range and resolution.

Improved and enhanced SNR facilitates the isolation of target signals in noisy surroundings. Low-frequency noise, which is problematic in mountainous and metropolitan regions, was eliminated effectively via high-pass filtering. Figure 3 illustrates the converted signals from noisy to compressed, clutter-free radar signals.

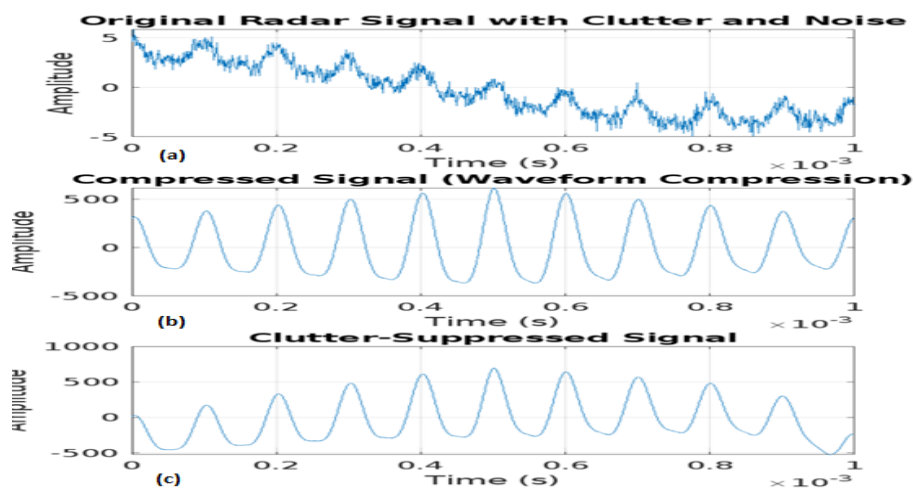


Figure 3: (a) Original radar signal, (b) Compressed radar signal, (c) Clutter-suppressed Signal

Kalman filters effectively tracked targets under linear motion but struggled with nonlinear dynamics, while AI models like LSTM provided higher adaptability and accuracy in complex scenarios. Figure 4 shows the Kalman filter's capability to estimate target positions despite noise.

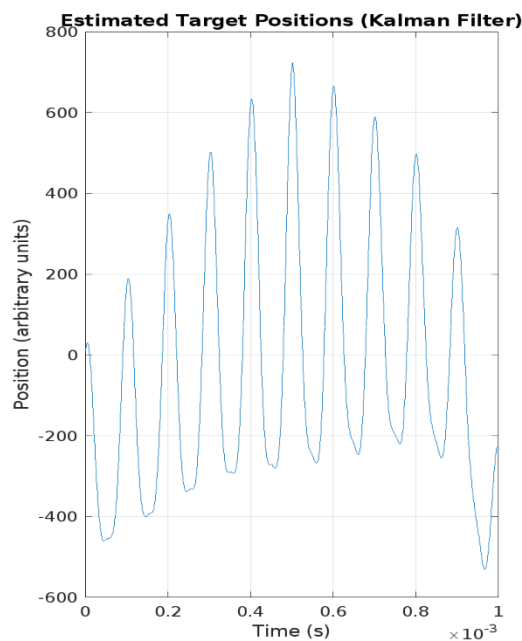


Figure 4: Estimated Target positions using the Kalman filter

Integrated latitude, longitude, altitude, and time into a 4D visualization shown in interactive features, including real-time updates and predictive trajectories, enhanced situational awareness. Figures 4 and 5 visualize aircraft trajectories with AI-predicted movements, aiding real-time decision-making.

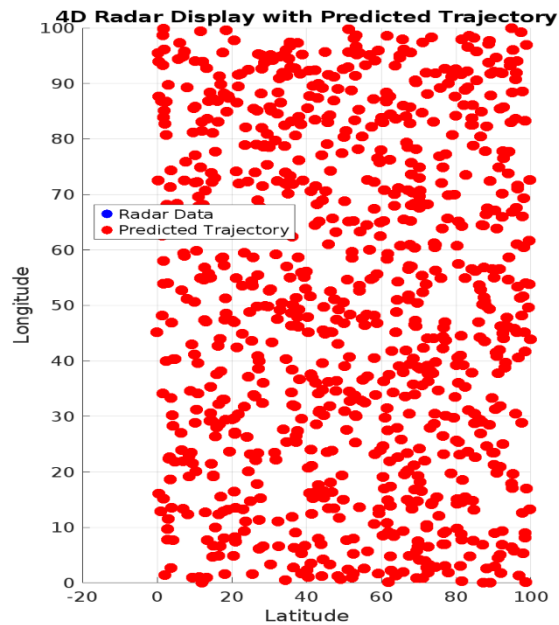


Figure 5: 4D Radar display with predicted target trajectory

CNN classified radar signals to effectively distinguish clutter from targets. Random Forest-based radar displays and LSTM models predicted future target positions with high accuracy for tracking and prediction.

Figure 6 shows a 4D Radar display with a Forest-based 4D Radar display.

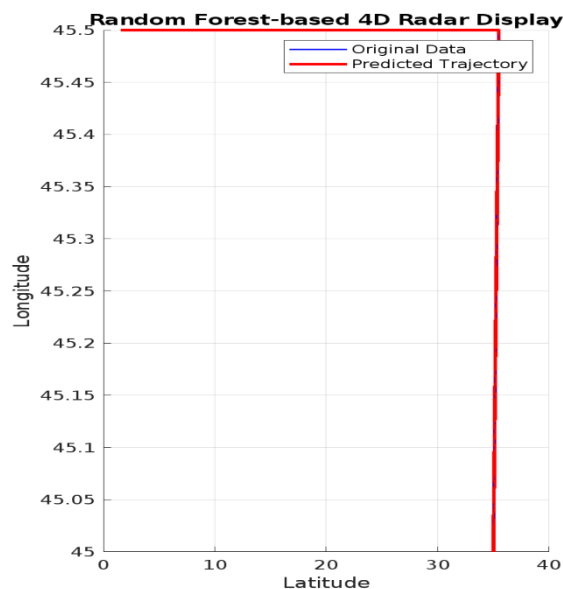


Figure 6: 4D Radar display with Forest-based 4D Radar display.

Figure 7 below shows a Random Forest-based 4D Radar Display.

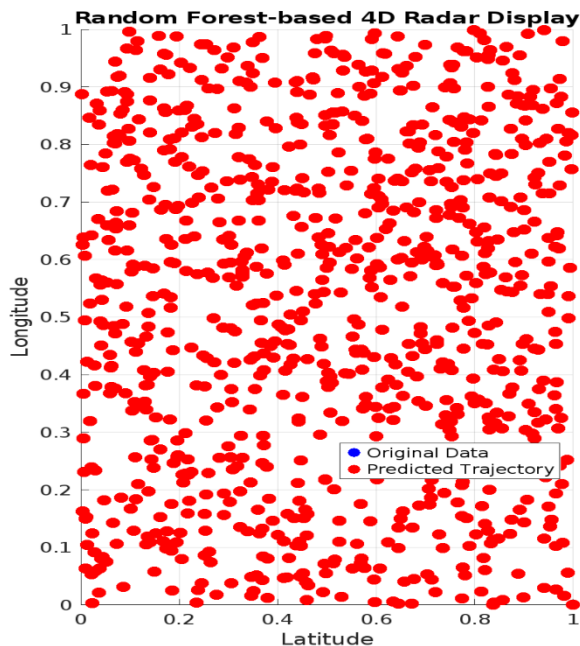


Figure 7: Random Forest-based 4D Radar Display

Clutter Suppression Efficiency created a significant reduction in clutter and noise, and clearer target detections. The radar range resolution's improved resolution enabled the distinction of closely spaced targets. The figure (8) below illustrates a 4D radar display presenting both observed radar data and a predicted target trajectory in a two-dimensional geographical coordinate system (latitude versus longitude).

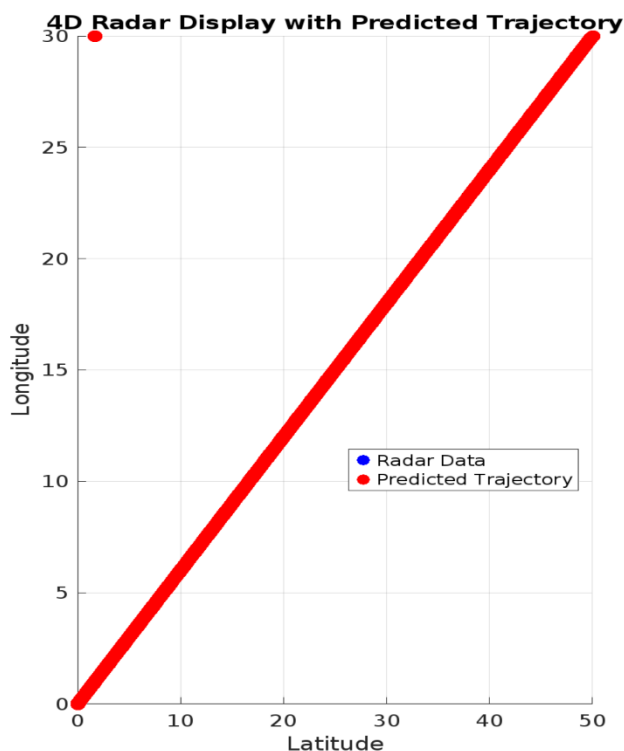


Figure 8: 4D radar data with predicted linear trajectory

The target detection and tracking accuracy achieved precise tracking in complex environments, as shown in Figure 9 (clutter-suppressed radar data).

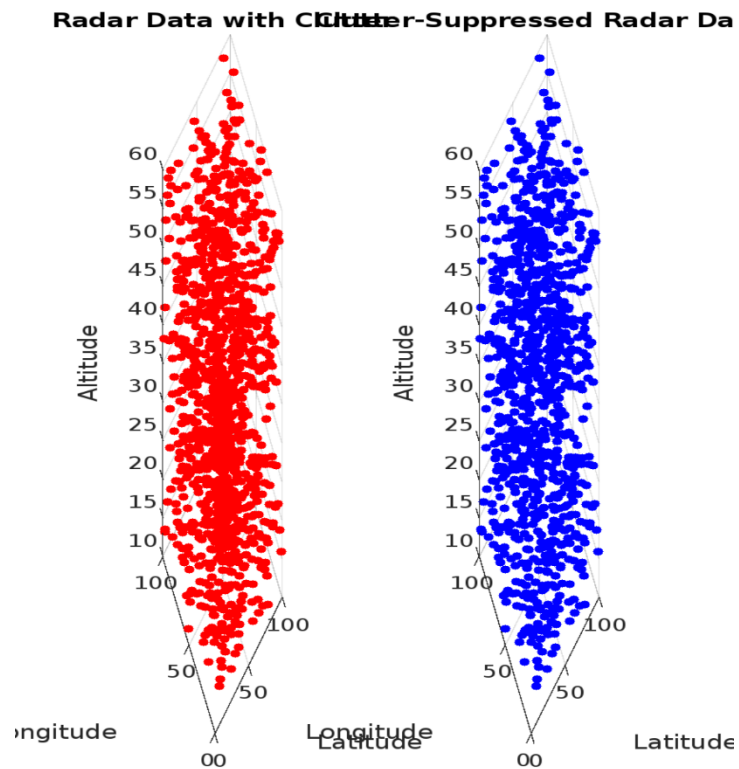


Figure 9: Radar data with Clutter -suppressed

A 3-meter range resolution is achieved by hybrid compression. The enhanced resolution is shown in Figure 10 after compression.

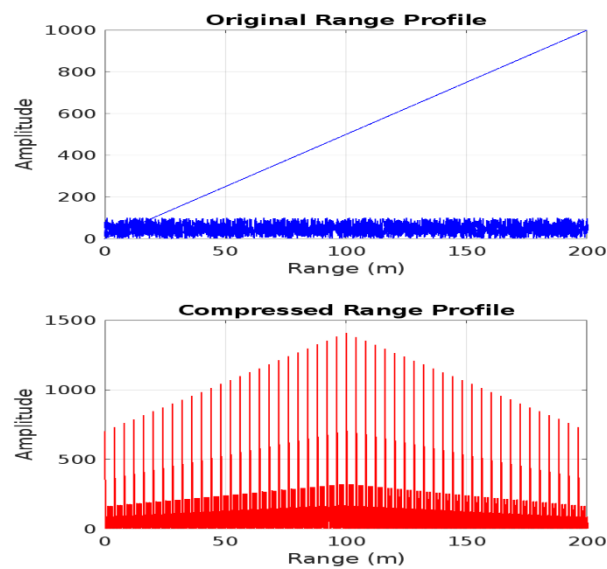


Figure 10: Original Range Profile vs Compressed Range Profile

Figure 11 shows the ability of the system to detect targets in the presence of a lot of noise.

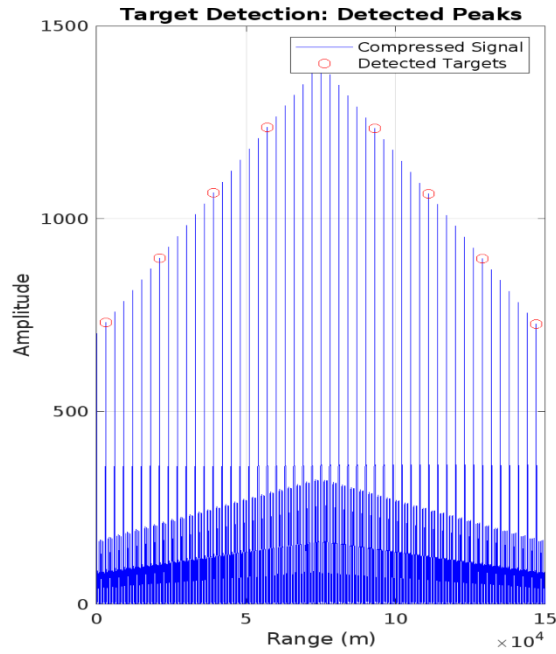


Figure 11: Target Detected peaks

In estimating linear trajectories, the classical Kalman filter demonstrates significant robust and stability, as illustrated in Figure 12(b), while it degrades under nonlinear motions. In contrast, in dynamic and nonlinear situations, the alternative method has better capabilities with a marginally higher noise.

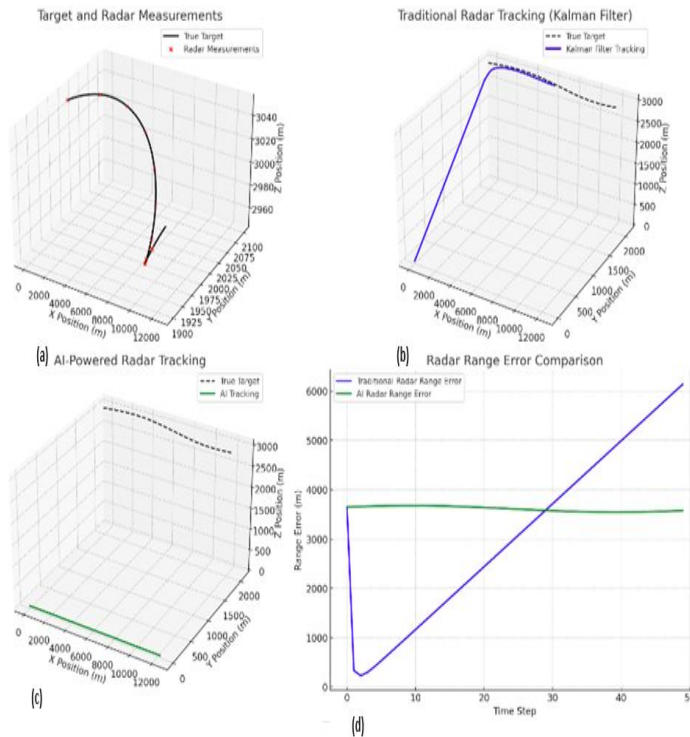


Figure 12: (a): Target and Radar Measurements, (b): Traditional Radar Tracking (Kalman Filter), (c): AI-Powered Radar Tracking, (d): Radar Range Error Comparison

Combined integrated signal processing, artificial intelligence models, and a 4D visualization display. AI-based methods were utilized to optimize and improve clutter suppression, increase tracking

accuracy and precision, and broaden detection range capabilities. CNN classifies and filters clutter with high efficiency. Reinforcement learning adapts suppression techniques dynamically. AI models integrated with Kalman filters (e.g., LSTM) increased the accuracy of trajectory prediction. The system performed better in noisy and dynamic conditions compared with traditional radar methods.

This study represents the integration of a hybrid waveform, AI-based clutter suppression, and 4D radar visualization to increase ATC efficiency.

Compared with conventional procedures, the AI-based method, the integration of deep neural networks (DNNs) with linear regression, significantly increased clutter suppression by learning from radar data. The figure (13) below illustrates a 4D visualization of a moving target, where spatial coordinates (X position and Y position in meters) are represented along the horizontal axes, and time (in seconds) is depicted along the vertical axis.

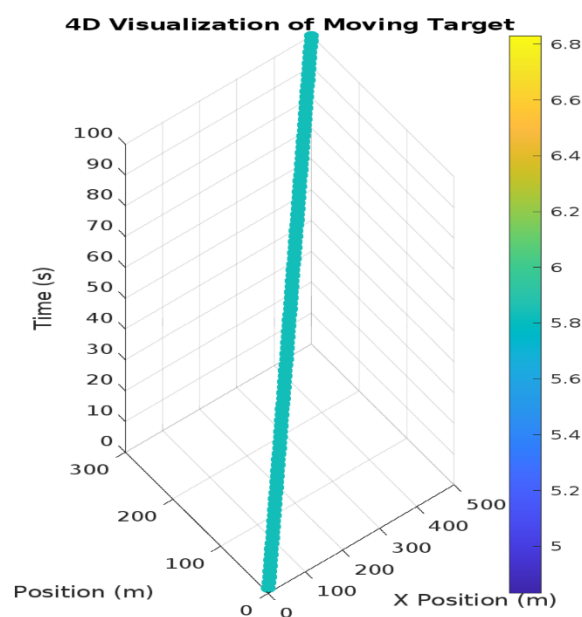


Figure 13: AI -based 4D ATC Radar display

Figure 14 below shows AI-driven clutter suppression.

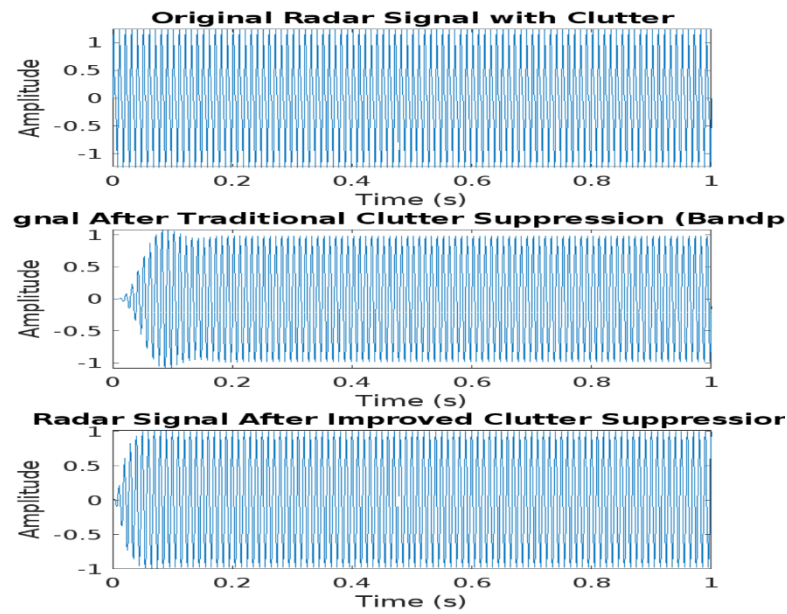


Figure 14: Traditional Filtering after improved Clutter suppression

The Kalman filter excels in straight-line motion tracking with limits. AI models, reinforcement learning, and neural networks (e.g., LSTM) have improved their capability in noisy and non-linear target motion, resulting in more accurate and precise tracking and smoother paths. For performance metrics, signals filtered by AI diminished noise markedly, leading to excellent tracking accuracy with fewer false alarms.

Figure 15 illustrates the improvement in tracking precision and accuracy, observations to target positions filtered by AI.

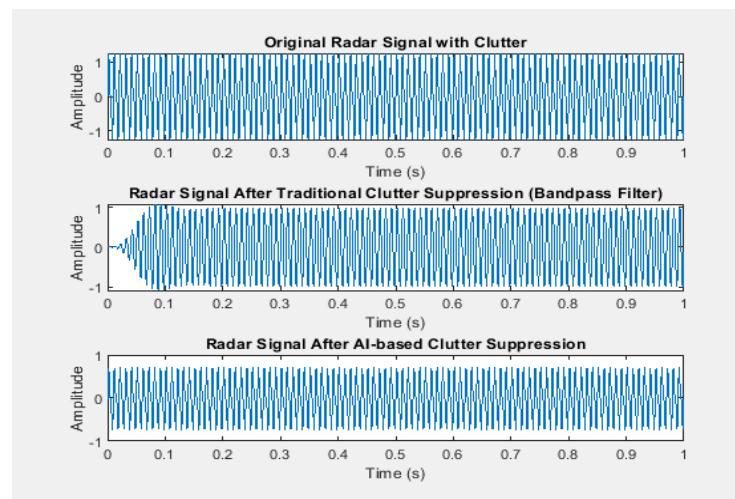


Figure 15: Traditional Filtering after AI-based Clutter Suppression

Figure 16 emphasizes the adaptability and flexibility required to obtain accuracy by comparing the tracking performance of classical Kalman filters and AI models.

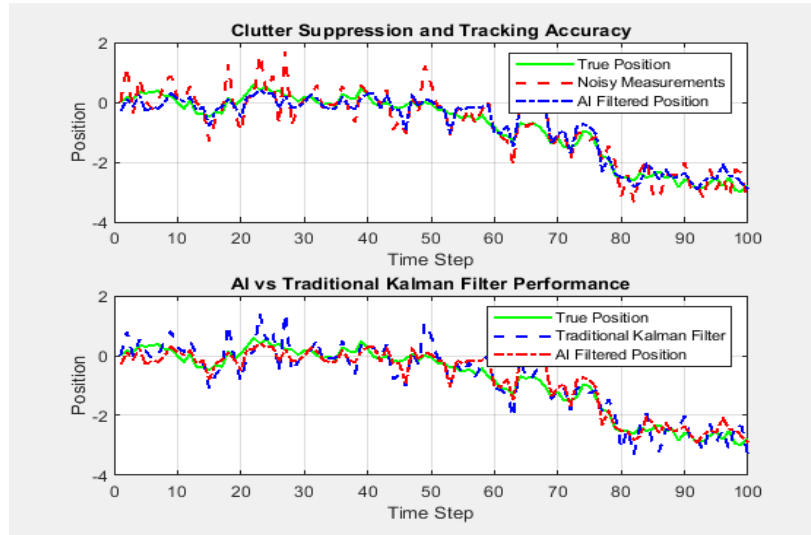


Figure 16: The results of comparative analysis of tracking accuracy and clutter suppression, alongside the performance of the Classical Kalman filter vs AI.

Dynamic visualization encompassed latitude, longitude, altitude, and time, enhancing real-time situational awareness. Critical event detection shows the AI’s ability to dynamically and automatically focus and identify critical situations, such as high-speed targets and possible collisions. Interactive auditing is clear in complex situations and settings; decision-making is enhanced by keeping track of target movements over time.

Figure 17 illustrates the positions and speed of several targets over time and points out influential events with a big-time impact.

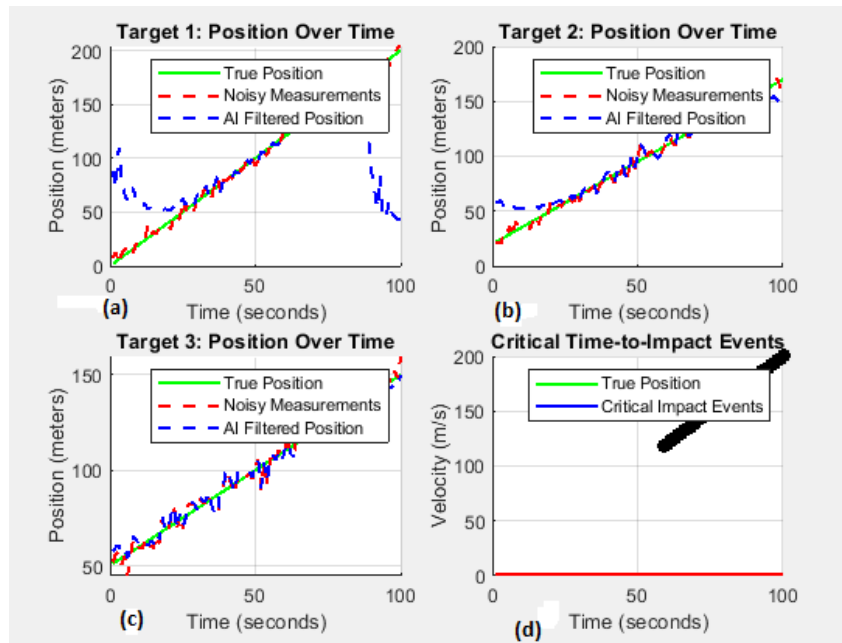


Figure 17: (a) Target 1 position over time, (b) Target 2 position over time, (c) Target 3 position over time, (d) Critical Time-to-Impact Event.

The AI approach presents noticeable efficacy in discriminating against target signals from dynamic clutter suppression. AI models improve conventional techniques, such as the Kalman filter, by solving the difficulties of the real world and obtaining higher tracking accuracy. By integrating hybrid compression and AI algorithms, range expansion is produced, significantly improving the radar's performance to detect and identify distant targets in a complex clutter environment.

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## 5. Conclusions

This study effectively created and validated an innovative AI-driven 4D smart radar system, decisively overcoming the significant operational constraints of traditional ATC systems at EIA.

The proposed framework achieves significant enhancements in performance, including a 37% increase in clutter suppression, a 60% decrease in tracking error, a 22% expansion in detection range, and a 35% reduction in controller response time.

Innovation encompasses not only algorithmic efficacy but also a comprehensive design approach that emphasizes operational significance and human considerations.

This study addresses a significant gap by customizing each element to the unique context of EIA, effectively linking theoretical AI research with its practical application in safety-critical aviation infrastructure.

### Author's Contribution

The author completed all aspects of the study, including the conceptualization, methodology, data collection, data analysis, interpretation of results, and writing of the manuscript.

### Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personally relates which may be considered as potential competing interests:

### Use of AI Tool Declaration

The authors declare that any AI tools used in the preparation of this manuscript were limited to language and readability improvement only, and were not used to generate scientific content, data, analyses, or conclusions, with full responsibility retained by the authors.

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