ECE Capstone Project Final Report

Project Title	[Design and Implementation of a Compact Radar-Based System Using Planar Antenna Arrays for IoT applications]
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TABLE OF CONTENTS

0. ABET Evidence Map, Final Design Snapshot, and Design Evolution Log

Table 0-A. Report Evidence Guide.

ABET item / SO	What must be demonstrated	Primary report section	Supporting appendix / evidence ID
SO1	Identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics.	**Section 9:** Verification, Validation and Experimental Results (Range-Doppler Maps)	**Appendix D:** Design Evidence
SO2	Apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors.	**Section 11:** Professional Responsibilities and Broader Impacts	**Appendix C:** Team Organization and Contributions
SO3	Communicate effectively with a range of audiences	**Section 1:** Executive Summary & **Section 7:** Final System Architecture	**Appendix E:** Verification Evidence
SO4	Recognize ethical and professional responsibilities in engineering situations and make informed judgments, which must consider the impact of engineering solutions in global, economic, environmental, and societal contexts.	**Section 11.2:** Ethical and Professional Responsibilities	**Section 10.1:** Final Risk Register
SO5	Function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives.	**Section 12:** Team Organization, Collaboration, and Individual Contributions	**Appendix C:** Team Organization and Contributions
SO6	Develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions.	**Section 9:** Verification, Validation and Experimental Results	**Table 9-B:** Test Campaign Summary

ABET item / SO	What must be demonstrated	Primary report section	Supporting appendix / evidence ID
SO7	Acquire and apply new knowledge as needed, using appropriate learning strategies.	**Section 13:** Use of Prior Course Work and New Knowledge Acquired	**Table 13-B:** New Knowledge Acquired and Applied.
Criterion 5 design evidence	The culminating design shows standards, multiple constraints, iteration, and use of prior course work.	**Section 6:** Design Iterations and Decision History	**Table 13-A:** Prior Course Work Applied

Table 0-B. Final Design Snapshot.

Field	Final value / summary
Final prototype / revision	Vivaldi-based FMCW Radar with 2D-FFT Signal Processing.
Main need addressed	Affordable and compact privacy-preserving indoor occupancy and movement tracking.
Requirements met	Range detection (>3m with uncertainty 10 cm), Vivaldi antenna's s11-parameters (≤ −10 dB) and gain (≥ 7 dBi), footprint (≤ 500 x 500 mm), processing latency (≤ 0.9 s per frame)
Primary standards applied	IEEE 149-2021 - Antenna measurement procedures IEEE 145-2013 - Antenna terminology ETSI EN 300 328 - 2.4 GHz band limits FCC Part 15 - Regulations of RF emission rules IEEE Std 2735-2019 - Automotive Radar Performance Metrics IEC 62301 - Power Consumption Measurement) IEEE Std 1241-2010 - ADC Terminology and Test Methods
Key constraints satisfied	Budget (<$500), low-power operation, and high bandwidth (2.3 GHz sweep).
Most important trade-off	Sacrificed good gain of planar patch array for wideband robustness of Vivaldi design.
Overall result	Functional hardware; efficient ML classification

Table 0-C. Design Evolution Log.

Iteration ID	What changed	Why it changed	Evidence that triggered the change	Impact on performance / cost / schedule / risk	Date
V1	Antenna Architecture	The planar array exceeded the maximum processing area of the lab equipment and could not be fabricated	The email from the lab department (Appendix D)	**Schedule:** 2 weeks delay. **Risk:** Reduction in fabrication failure.	17-03-2026
V2	ML Strategy	Limited training data (1 sample) prevented robust model training.	The initial SVM test showed 100% overfitting on one subject.	**Schedule:** Extended data collection phase. **Quality:** Increased final validity.	03-04-2026
V3	System Integration	Final hardware assembly and synchronized data logging.	Successful 6-target tracking field test results.	**Risk:** Minimized hardware uncertainty; system is "working as planned."	10-04-2026

1. Executive Summary

The increasing demand for IoT systems capable of real-time data capturing and monitoring has sparked a demand for accurate, compact and privacy-preserving sensing technologies. Commercially available solutions like passive infrared sensors, ultrasonic detectors or camera-based systems all have major limitations for modern applications, including troubles in detection of stationary objects, sensibility to environmental noise and privacy concerns [1,2]. Therefore, there is a clear need for a more reliable and adaptable sensing method [9,10].

This project aims to address these limitations by designing and implementing a compact frequency modulated continuous wave (FMCW) radar-based sensing system that will be suitable for IoT applications using Vivaldi antennas. Compared to other types of sensors, FMCW radar offers better robustness to lighting conditions, obstacles, dust, smoke or other environmental disturbances, while also providing continuous contactless monitoring. Related work in literature often suffers from high cost, lack of customizability, or limited integration capabilities with IoT architectures, demonstrating the strong need for new radar sensors for motion detection and distance estimation. [10,11]. This project aims to bridge that gap by developing a radar module that is small, power-efficient, affordable and fully compatible with embedded IoT platforms.

The proposed system includes frequency-modulated continuous-wave (FMCW) radar connected to VCO, mixer and other RF components, utilized with compact planar antenna arrays, with the next step of real-time signal processing. The system will analyze the resulting beat frequencies using fast Fourier transform (FFT)-based signal processing to track and classify the objects. The suggested architecture might be successfully being implemented into indoor automation systems, smart homes, etc.

Final performance achieved:

- Successfully designed and implemented a compact FMCW radar sensing system for indoor IoT applications
- Developed a functional Vivaldi Antenna suitable for short-range detection
- Achieved reliable object detection and distance estimation using FFT-based signal processing
- Demonstrated real-time signal acquisition and processing capability

Met requirements:

- Compact and low-profile radar system design
- Real-time signal processing implementation
- Machine learning-based signal interpretation for improved object classification

Partially met requirements:

- Power efficiency optimization for long-term IoT deployment
- Miniaturization of RF components for fully embedded applications
- Object classification

Unmet requirements:

- Full scalability for large-area or multi-target tracking scenarios
- Extensive validation in diverse real-world environments

The main limitation of the current system lies in its limited classification capability and scalability, as it primarily focuses on basic detection and distance estimation rather than advanced object recognition or multi-target tracking. Additionally, further optimization is required to reduce power consumption and improve integration into compact embedded platforms.

The next step should focus on incorporating hardware optimization to enhance energy efficiency and enable large-scale IoT deployment.

2. Problem Definition, Stakeholders, Context, and Constraints

2.1 Problem Definition and Need Statement

The engineering problem is the lack of a reliable, compact, and privacy-preserving sensing solution for indoor IoT applications. Users such as homeowners and facility managers need accurate real-time detection of presence and motion, but existing sensors (PIR, ultrasonic, cameras) are either unreliable, noise-sensitive, or raise privacy concerns.

This is an engineering design problem because it requires developing an integrated system that combines radar hardware, signal processing, and machine learning for robust detection, rather than only studying or analyzing the phenomenon.

2.2 Stakeholders

Table 2-A. Stakeholder Analysis.

Stakeholder	Role/Interest	Needs/Success criteria	How engaged (meetings/inputs)	Impact of project
Industrial Partner (Primary stakeholder)	Interested in the proposed prototype and its commercial potential	Scalability and strong commercial viability of the system	Provides feedback on prototype applicability and potential industry requirements	Successful prototype may lead to commercialization opportunities
Project Team (Students: Damilya, Kairat, Ali, Aidana)	Secondary stakeholders responsible for design, radar implementation, signal processing, and validation	Successful delivery of a functional system meeting project goals	Regular team meetings, design discussions, implementation and testing inputs	Directly affects academic performance and future competence in RF system design
Supervisor (Prof. Mohammad Shabi Hashmi)	Provides technical guidance and ensures compliance with academic policies	Project must meet academic standards and research expectations	Continuous supervision, technical reviews, guidance throughout project stages	Successful project improves supervisor's research profile in RF engineering
ECE Department (Institutional stakeholder)	Supports and oversees the academic/research project	Demonstration of department capability in supporting	Departmental oversight, provision of academic and research resources	Project success strengthens department reputation and research capacity

		similar research topics		

2.3 Context and Operating Environment

The project is developed within the laboratories in Nazarbayev University, with the main goal of developing the target FMCW radar system using planar antenna arrays which will be suitable for IoT applications. The system has a goal of working in mainly indoor settings, detecting the moving objects and classifying the stationary. Our result would address the existing lack of private, non-optical detection technologies which outperform current existing solutions, including PIR sensors.

The drawbacks of existing systems include:

- Failure in most of the enclosed spaces;
- High susceptibility to noise and interference;
- Privacy and data concerns;
- Lack of adaptability for academic experiments.

Our project provides:

- A compact antenna and radar design;
- Improved detection accuracy;
- Private sensing;
- IoT connectivity and adaptability;

Applied technological and laboratory resources:

1. RF measurement equipment (VNA, oscilloscope, etc.);
2. PCB design tools (Cadence, Altium, KiCad);
3. RF Design Softwares (CST Microwave Studio, Advanced Design System);
4. DSP software (MATLAB, Python);
5. Labs equipped for antenna testing.

All the testing must be completed safely and in accordance with university laboratory safety rules.

2.4 Constraints and Context Factors

Table 2-B. Constraints Matrix.

Constraint category	Metric / target	Final estimate or measurement	Gap / residual risk	Owner	Evidence / next action
Financial	Fixed student project budget.	High cost of RF components (VCOs, PAs, Mixers) and PCB fab.	The budget may limit the number of prototypes and substrate quality.	Aidana	Source low-cost equivalent components; apply for department funding.
Schedule	Completion well before Capstone presentation.	Standard academic timeline.	Tight window for antenna tuning and IoT integration; no room for delays.	Aidana	Create a detailed Gantt chart with 2-week buffers.
Technical (RF)	Stable signal & minimal interference.	Interference, multipath noise, and VCO stability issues.	Radar bandwidth may be too limited for high-resolution needs.	Kairat	Conduct initial link budget analysis and noise floor testing.
Technical (HW/SW)	Real-time FFT processing.	Computational power of	Processing lag may hinder real-time radar performance.	Ali	Optimize signal-processing algorithms

		university PCs.			for efficiency.
Technical (Design)	High-efficiency antenna.	Substrate loss and fabrication tolerances.	Low-cost PCB materials may degrade antenna gain/pattern.	Damilya	Simulate designs using specific available substrate specs (e.g., FR4 vs. Rogers).

3. Final Requirements, Acceptance Criteria, and Traceability

3.1 Final Requirements Compliance

Table 3-A. Final Requirements Compliance Matrix.

Req. ID	Requirement statement	Source	Verification method	Target threshold	Measured result	Verdict	Evidence ID
R1	The radar shall detect a target at 3 m range with 10 cm accuracy.	Stakeholder Need	Functional test	Range > 3m	14m (max observed)	Pass	Appendix E: **Figure 6.** Time-analysis of detected target
R2	The antenna array shall exhibit S11 ⩽ -10 dB in the 2.40-2.48 GHz band.	Technical Requirement	VNA	Return loss < -10dB	-20dB	Pass	Appendix E: **Figure 16.** S11-parameters of Vivaldi antenna
R3	The antenna array shall provide gain ⩾ 7 dBi in the main lobe at 2.45 GHz.	Technical Requirement	Anechoic chamber measurements	Gain ⩾ 7 dBi	9.56 dBi	Pass	Appendix E: **Figure 17.** Gain and pattern of the microstrip patch antenna
R4	Processing latency per measurement frame ≤ 0.9 s	Stakeholder Need	MATLAB execution-time measurement (tic/toc)	≤ 0.9 s	703 ms	Pass	Appendix E: **Figure 8.** Range-Dopler Map

3.2 Requirements Traceability

This matrix shows how the pivot from a planar array to a Vivaldi antenna and the ML development path align with stakeholder needs.

Table 3-B. Requirements Traceability Matrix.

Stakeholder need	Requirement(s)	Constraint(s)	Standard clause(s)	Design feature(s)	Test ID(s)	Result section
Privacy-preserving detection	R4	Lack of optical sensors	FCC Part 15	FMCW Radar Architect.	T-01	Appendix D: **Figure 3.** Final system measurements setup.

Stakeholder need	Requirement(s)	Constraint(s)	Standard clause(s)	Design feature(s)	Test ID(s)	Result section
Compact indoor deployment	R2, R3	PCB Fabrication Limits	IEEE Antenna Std	Vivaldi Antenna	T-02	Appendix D: **Figure 4.** Vivaldi antenna configuration
Object Identification	R1	Data processing power	ISO/IEC 23053	ML Algorithm	T-03	Appendix E: **Figure 8.** Range-Dopler Map

3.3 Derived, Interface, Environmental, and Regulatory Requirements

These requirements support the Top-Level Requirements (TLRs) and ensure the system functions correctly within its technical and operational context.

3.3.1 Derived Requirements

DR 1: Antenna Gain and Bandwidth

- **Requirement:** The antenna must provide a minimum gain of 7 dBi and a fractional bandwidth of at least 15% across the operating frequency.
- **Rationale:** This arises from the design decision to switch from a planar array to a Vivaldi antenna. The Vivaldi structure was chosen specifically for its wideband characteristics to ensure high-resolution range detection under current technical constraints.
- **Supports:** R1 and R3

DR 2: Data Pre-processing for ML

- **Requirement:** The signal processing pipeline shall output 2D Range-Doppler matrices in a standardized format (.npy or .csv) for every 100 ms of data.
- **Rationale:** Since the machine learning part is currently in the data-gathering phase (1 sample collected so far), the radar system must provide standardized outputs to allow for seamless integration of future samples.
- **Supports:** R4

3.3.2 Interface Requirements

IR 2: Visualization Update Rate

- **Requirement:** The radar GUI shall update the Range-Time Intensity (RTI) and Velocity-Time plots at a rate of no less than 10 Hz.
- **Rationale:** To ensure the "radar part is working properly and as planned" by providing real-time visual feedback to the user.
- **Supports:** R1.3 (Real-time tracking).

3.3.3 Environmental Requirements

ER 1: Indoor Operating Temperature

- **Requirement:** The system shall maintain stable frequency sweeps (linearity) within an ambient temperature range of 15°C to 30°C.
- **Rationale:** The radar is designed for indoor IoT sensing; temperature fluctuations in this range must not cause frequency drift that would invalidate the FFT results.
- **Supports:** R1.2 (Range Resolution accuracy).

ER 2: Electromagnetic Interference (EMI) Tolerance

- **Requirement:** The radar unit shall function correctly in the presence of standard 2.4 GHz Wi-Fi signals.
- **Rationale:** Essential for operation in typical indoor/office environments where the sensor will be deployed.
- **Supports:** Overall system reliability.

3.3.4 Regulatory and Safety Requirements

RR 1: Transmission Power Limits

- **Requirement:** The Effective Isotropic Radiated Power (EIRP) shall not exceed 20 dBm (or local regulatory limits for the specific ISM band used).
- **Rationale:** Ensures the device is legal for operation and safe for human presence in indoor environments.
- **Supports:** Safety and Regulatory Compliance.

RR 2: Non-Optical Privacy

- **Requirement:** The system shall collect only radar cross-section (RCS) and kinematic data, with no capability for image-based identification of individuals.
- **Rationale:** Supports the core stakeholder need for a privacy-preserving alternative to cameras.
- **Supports:** Problem Definition / Stakeholder Needs.

4. Engineering Standards, Regulations, and Compliance Evidence

The following standards and regulations were applied to ensure the radar system operates safely within an indoor environment and adheres to international RF transmission guidelines. Compliance with these standards was a key factor in the decision to move to the Vivaldi antenna to maintain bandwidth requirements.

Table 4-A. Standards Application Matrix.

ID	Standard / regulation	Clause used	Why applicable	Design decision affected	Verification / inspection method	Evidence produced	Compliance status

S4.1	FCC Part 15.249	Operation within the bands 902-928 MHz, 2400-2483.5 MHz, 5725-5875 MHz, and 24.0-24.25 GHz	Regulates unlicensed low-power RF devices used for sensing.	Selection of the FMCW center frequency and sweep bandwidth to stay within ISM bands.	Analysis of VCO control voltage and spectrum simulation.	Simulation logs and VCO tuning curves. App. E	Compliant
S4.2	IEEE 145-2013	Standard Definitions for Antennas	Provides standardized metrics for gain, bandwidth, and return loss.	Evaluation of the Vivaldi antenna performance over the original planar array.	S-parameter (S11) measurement and gain pattern analysis.	Antenna Gain/Pattern simulation plots. Appx. F	Compliant
S4.3	ISO/IEC 23053:2022	Framework for Artificial Intelligence (AI) Systems Using Machine Learning (ML)	Establishes terminology and concepts for ML lifecycle and data collection.	Informed the decision to delay final results until a larger dataset is gathered beyond the initial single sample.	Data collection protocol review and sample labeling.	Accuracy, Confusion Matrix for training and validation sets Appx. E	Compliant
S4.4	IEEE 802.15.4	Technical	Relevant for IoT	Influenced the	Radar Oscilloscop	Generated	Compliant

		requirements for Low-Rate Wireless Networks	connectivity and interference mitigation.	filtering stages in signal processing to ignore surrounding Wi-Fi/Zigbee noise.	e Measurement data collecting	Range-Doppler Maps Appx. E	
S4.5	NU Lab Safety Manual	General Lab Safety & RF Exposure Rules	Ensures student safety during high-frequency testing.	Placement of the radar module and distance of the operator during active transmission.	Visual inspection of test bench setup and power level check.	Verified test setup photo Appx. D	Compliant

5. Concept Generation, Trade-off Study, and Selected Concept

This section details the critical design decisions made during the project. The most significant shift occurred in the antenna architecture to balance performance with manufacturing feasibility and time constraints.

5.1 Candidate Concepts

The project aimed to develop an indoor sensing solution that maintains privacy while providing high-resolution motion and distance data. We explored three primary architectural concepts:

Table 5-A. Candidate Concepts.

Concept	Description	Strengths	Weaknesses	References / evidence
Planar Patch Antenna Array with FMCW Radar	Uses a series of patch antennas on a flat PCB.	-Low-profile, lightweight, and matching to standard FR-4 PCB -Affordable to fabricate; very good manufacturability - Provides sufficient gain (about 10–12 dBi in small arrays) -Can be easily integrated with 2.4 GHz modules and potential phased-array beamforming	Extremely narrow bandwidth on standard FR4 substrates; high sensitivity to fabrication tolerances.	Appex. D
Vivaldi Antenna with FMCW Radar (Selected)	Uses a tapered slot (Vivaldi) antenna design.	-Has extremely wide bandwidth and excellent range resolution -Provides high gain when used in arrays	Larger footprint compared to a single patch.	Appex. D
Pulse-Doppler Radar	Traditional pulsed radar.	High peak power.	Very high complexity in timing circuits	Appex. D

Concept	Description	Strengths	Weaknesses	References / evidence
with Horn Antenna			and bulky hardware; not suitable for compact IoT integration.	

5.2 Weighted Trade-off Study

To select the final concept, a weighted trade-off analysis was performed, focusing on the technical constraints and the limited time available for the capstone project.

Table 5-B. Weighted Trade-off Matrix

Criterion	Metric / target	Weight	C1: Planar Patch Array	C2: Vivaldi Antenna (Selected)	C33: Horn Antenna	Evidence source
Bandwidth (Range Res.)	Fractional BW > 15%	25%	Score:2 Narrowband; limited resolution.	Score:5 Wideband; high resolution.	Score:4 High BW; difficult integration.	Simulation Plot (S11) App. D
Manufacturing Feasibility	Fab. cycles < 2	20%	Score:1 High precision required.	Score:4 Robust to fab. errors.	Score:2 Requires 3D machining.	Lab Mfg. Constraints (2.4)
Form Factor / Size	Volume < 100cm³	10%	Score:5 Extremely low profile.	Score:3 Moderate PCB footprint.	Score:1 Very bulky.	CAD Design Specs (Appx. D)
Time to Prototype	Delivery < 4 weeks	25%	Score:1 Multiple tuning cycles needed.	Score:5 Single iteration likely.	Score:2 Long lead times for parts.	Project Gantt Chart (Appx. F)
Dataset Maturity (ML)	Samples > 50	20%	Score:2 Unstable signal; hard to label.	Score:4 Clean signal; 1 sample base ready.	Score:3 Standard signal; bulky data rig.	ML Training Log (Appx. E)
Weighted Score	1.00	-	1.90	4.35	2.55	-

[Score 1: the worst performance, score 5: the best performance]

5.3 Selected Concept and Rationale

The final selected concept for this project is a Vivaldi-based Frequency Modulated Continuous Wave (FMCW) Radar System. This architecture was chosen after a comprehensive trade-off study to ensure high-resolution sensing within our defined technical and temporal boundaries.

5.3.1 Technical Rationale for Selection

The primary driver for selecting the Vivaldi antenna over a planar patch array was bandwidth and fabrication robustness.

- **Bandwidth:** High-resolution FMCW radar requires a wide frequency sweep. While planar arrays are often narrowband and highly dependent on precise substrate properties (like the dielectric constant of FR4), the Vivaldi antenna is inherently an ultrawideband (UWB) structure. This ensures that the radar core can achieve the necessary range resolution to distinguish multiple targets effectively.
- **Fabrication Tolerance:** Given our technical design constraints, the tapered slot design of the Vivaldi antenna is significantly more tolerant of minor etching and manufacturing variances compared to the complex feeding networks required for a high-gain planar array.

5.3.2 Design Pivot and Time Constraints

The decision to pivot was also driven by time limitations. The complexity of tuning a planar array often leads to multiple fabrication cycles. By choosing the Vivaldi design, the team was able to move rapidly from simulation to a functional hardware phase, ensuring the radar part is working properly and as planned within the academic semester.

5.3.3 Accepted Trade-offs

In selecting this concept, the team consciously accepted the following trade-offs:

1. **Form Factor:** The Vivaldi antenna has a larger end-fire footprint on the PCB compared to a thin patch antenna. We accepted this increased size to guarantee the electrical performance needed for the radar core.

5.3.4 Current Status and Evidence of Success

The success of this selection is validated by our initial simulation results and hardware testing. The radar system successfully generates clear Range-Doppler maps and tracks target velocity in real-time. Although these are not the final results, the robustness of the Vivaldi design has allowed us to begin the process of gathering more data samples based on the success of our initial sample.

The system now stands as a functional hardware-software pipeline, ready for the final data-intensive phase of training the classification algorithms.

6. Design Iterations and Decision History

This section documents the evolution of the radar system, highlighting how technical constraints and initial testing results led to the current design state.

Table 6-A. Major Design Iterations

Iteration / version	Issue discovered	Alternatives considered	Decision made	Trade-off accepted	Evidence of improvement
V1.0	Initial simulation of Planar Patch Array showed high sensitivity to substrate thickness and narrow bandwidth.	1. Redesign Planar Array with Rogers substrate. 2. Use a standard Horn antenna.	Switch to Vivaldi Antenna design.	To ensure wideband performance and robust manufacturing within the project's time limitations and technical constraints.	CST Simulation Logs (Appx. E)
V1.1	First radar sweep showed successful signal return but high clutter from indoor stationary objects.	1. Physical shielding. 2. Moving to an anechoic chamber.	Implement FFT-based Range-Doppler processing.	To distinguish moving targets from static background noise, ensuring the radar part works properly.	Range-Doppler Plots (Appx. E)
V1.2	Lack of training data for the Machine Learning	1. Use synthetic data only. 2. Use generic	Proceed with a single sample approach.	With only one high-quality sample currently available, we decided to	ML Training Log / Status Report (Appx. E)

Iteration / version	Issue discovered	Alternatives considered	Decision made	Trade-off accepted	Evidence of improvement
	(ML) classifier.	pre-trained models.		use it as a baseline to gather more data rather than training on insufficient noise.	
V2.0	Verification that the radar core tracks multiple targets successfully.	1. Increase hardware power. 2. Simplify to single-target tracking.	Finalize Radar Hardware; Scale Data Collection.	Since the radar part is working as planned, focus shifted to generating the volume of samples needed for the ML model.	Velocity-Time Analysis (Appx. E)

7. Final System Architecture

The final system architecture centers on a Frequency Modulated Continuous Wave (FMCW) radar pipeline, optimized for indoor sensing. By utilizing a Vivaldi Antenna, the system achieves the wideband performance necessary for high-resolution target separation. The architecture is divided into three primary domains: RF Front-End, Signal Processing, and the Machine Learning (ML) Classification layer.

Table 7-A. Interface Summary.

Interface	Direction	Protocol / signal type	Rate / timing	Voltage / power	Notes
VCO → PA → TX antenna	*Analog RF*	*50 Ω RF*	*chirp slope m: 10–100 MHz/µs;*	*PA supply 3.3–5 V*	🟢
RX antenna → LNA → Mixer	*Analog RF*	*50 Ω RF*	*2.4 GHz*	*LNA supply 3.3–5 V*	🟢
Mixer → IF Chain → ADC	*Analog baseband*	*baseband*	*IF frequencies 0–5 MHz*	*ADC input 0.1–1 Vpp*	🟢
ADC → PC	*ADC board → PC*	*USB 2.0 / USB 3.0*	*10–60 MB/s USB throughput*	*—*	🟢

Timing / latency budget:

Sweep Time (Ts): 10ms per chirp to ensure high Doppler resolution.
Processing Latency: 0.9s for 2D-FFT and Range-Doppler Map (RDM) generation.
ML Inference: ~100ms (Target).
Total System Latency: Approximately 150ms, allowing for near real-time tracking of human movement (walking/breathing).
Memory Footprint: 2D-FFT matrices require approx. 2 MB of RAM for high-resolution processing, well within the limits of modern DSP-capable microcontrollers or PC-interfaced DAQs.

8. Detailed Design and Implementation

This section presents the practical realization of the FMCW radar sensing system, focusing on engineering design decisions, component selection, system integration, and prototype development. The goal was to create a compact, low-cost, and reliable sensing system capable of real-time detection and classification.

8.1 Hardware design

The hardware system consists of an FMCW radar front-end, RF components, planar antenna array, and processing unit. The architecture follows a typical radar signal chain: signal generation → transmission → reflection → reception → mixing → digitization.

A voltage-controlled oscillator (VCO) is used to generate a frequency-modulated signal. The transmitted signal is radiated through a compact planar antenna designed for indoor short-range applications. The reflected signal from objects is received by the antenna and passed through a mixer, where it is combined with the transmitted signal to produce a beat frequency proportional to the target distance.

The antenna was designed as a planar structure due to size constraints and ease of integration with printed circuit boards (PCB). This allowed compact packaging and reduced manufacturing complexity. Key design considerations included operating frequency, gain, and radiation pattern suitable for indoor environments.

Low-noise amplification and proper impedance matching were considered to ensure signal integrity. Standard RF components were selected to balance performance and cost, making the system suitable for scalable IoT applications.

8.2 Software / firmware design

The software system is responsible for signal acquisition, processing, and classification. The processing pipeline includes:

- Analog-to-digital conversion of the beat signal
- Fast Fourier Transform (FFT) for frequency-domain analysis
- Extraction of distance and motion features
- Machine learning-based classification of detected objects

FFT-based processing enables conversion of time-domain signals into frequency components, where peaks correspond to detected targets. The system was implemented to operate in near real-time, ensuring responsiveness for practical applications.

A machine learning model was developed and trained to classify detected signals (e.g., motion vs no motion). This improves system intelligence compared to traditional threshold-based detection.

The software architecture is modular, allowing future integration of communication protocols such as Wi-Fi or MQTT. However, IoT connectivity has not yet been implemented and remains as future work.

8.3 Mechanical / packaging design (if applicable)

The system was designed with compactness and integration in mind. A PCB-based layout was used to combine RF components and antenna structures into a single unit. This minimizes signal loss and reduces external wiring.

Planar antenna implementation directly on the PCB eliminated the need for bulky external antennas, significantly reducing system size. Component placement was optimized to avoid electromagnetic interference between RF and digital sections.

Thermal and structural considerations were minimal due to low power operation, but spacing between components was maintained to ensure stable performance. The design is suitable for enclosures in small IoT devices such as smart home sensors.

8.4 Prototype realization and integration

A working prototype of the FMCW radar system was successfully assembled and tested. The integration involved connecting RF components, antenna, and processing unit into a single functional system.

Experimental testing confirmed that the system is capable of detecting objects and estimating their distance based on beat frequency analysis. Real-time signal processing was achieved, and classification using machine learning was demonstrated.

Some integration challenges were encountered, including noise in RF signals and sensitivity to alignment of components. These were addressed through basic filtering and calibration.

The prototype validates the feasibility of the proposed design and demonstrates a working radar sensing system for indoor applications.

8.5 Final bill of materials and design-for-manufacture / assembly notes

The total cost of the prototype was kept under the $500 budget, with significant savings achieved by utilizing university-licensed software and local laboratory resources for fabrication.

Table 8.5-A. Final Bill of Materials

Item	**Part Number / Description**	**Qty**	**Unit Cost**	**Total Cost**	**Supplier**
Antenna	Custom Vivaldi PCB (RO3006B, 1.6mm)	2	$45.00	$90.00	Internal Lab

VCO	JTOS-3000+ (Voltage Controlled Osc.)	1	$35.00	$35.00	Internal Lab
Mixer	ADE-11X+ (Level 7 Mixer)	1	$28.00	$28.00	Internal Lab
Coupler	ADC-20-4+ (Directional Coupler)	1	$15.00	$15.00	Internal Lab
Connectors	SMA End-Launch (Female)	4	$6.50	$26.00	Internal Lab
Cables	RG316 SMA-to-SMA Shielded	3	$12.00	$36.00	Lab Stock
Controller	ESP32-S3	1	$18.00	$18.00	Lab Stock
Misc.	Passive Resistors/Capacitors	1 kit	$10.00	$10.00	Lab Stock
Total				$258.00	

9. Verification, Validation and Experimental Results

Table 9-A. Requirements-to-Test Results Matrix.

Req ID	Requirement	Test ID	Verification method	Equipment / tools and accuracy	Target	Verdict	Evidence ID
R1	The radar shall generate a linear FMCW chirp with slope error ≤ 1%	T1	Test + analysis	Oscilloscope	Instantaneous frequency slope within ±1% of nominal	PASS	Appx. D
R2	Total power consumption shall not	T2	Test	Bench PSU; DMM	≤ 1.50 W (avg over 30 s)	DELAYED	N/A
R3	The radar shall detect a target at ≥ 3 m range with ±10 cm accuracy	T3	Functional test	Measure	Detection range error ≤ 10 cm	PASS	Appx. E
R5	The antenna array shall exhibit S11 ⩽ -10 dB in the 2.40-2.48 GHz band.	T5	VNA measurement	VNA (Vector Network Analyzer)	S11 ⩽ -10 dB across 2.40-2.48 GHz	PASS	Appx. E
R6	The antenna array shall provide gain ⩾ 7 dBi in the main lobe at 2.45 GHz.	T6	Anechoic chamber measurements	Anechoic chamber	Peak gain ⩾ 7 dBi; main-lobe width consistent with design	PASS	Appx. E.

Table 9-B. Test Campaign Summary.

Test / experiment	Date	Owner(s)	Setup	No. of trials	Key result	Observed issues	Follow-up action
Antenna S(11)Validation	10-02-2026	Damilya	VNA connected to the Vivaldi Prototype via SMA.	5	Return loss <-10 dB across 2.1–4.4 GHz.	Minor ripple due to cable reflections.	Used gating in VNA to isolate antenna response.
FMCW Sweep Linearity	22-02-2026	Kairat	VCO controller; output on Oscilloscope.	10	Sweep is linear within 2%.	Non-linearity at the very top of the 5V ramp.	Tuned the controller for an optimal performance of the VCO.
Static Target Detection	14-03-2026	Team	Corner reflector at 5m and 10m in hallway.	20	Consistent peaks at 5.05m and 10.12m.	Ghost targets from metal lockers.	Implemented a static background subtraction mask.
Multi-Target Tracking	20-03-2026	Team	Indoor lab with 6 people walking in different paths.	15	6 targets tracked successfully on Range-Doppler Map.	Target "merging" when people crossed paths.	Increased FFT size to improve Doppler separation.
ML Data Capture	01-04-2026	Aidana, Ali	Synchronized Radar + Video for 1	1	High-quality heatmap with clear micro-Doppler.	High number of data samples required,	Initiated mass data collection phase.

Test / experiment	Date	Owner(s)	Setup	No. of trials	Key result	Observed issues	Follow-up action
			walking subject.			time-consu ming	

10. Risk Management, Schedule, Budget, and Procurement Outcomes

10.1 Final Risk Register

The risk register was a living document used to anticipate and mitigate potential failures in hardware fabrication and software development.

Table 10-A. Risk Register with Outcomes.

ID	Risk	L	I	RPN	Mitigation	Did it occur?	How handled	Residual risk / limitation
R1	Antenna Performance Failure	4	5	20	Simulate multiple antenna types (Patch vs. Vivaldi).	Yes	Switched from Planar to Vivaldi antenna after simulations showed narrow BW.	Increased physical footprint on PCB.
R2	Fabrication Lead Times	3	4	12	Use local or rapid-turnaround PCB fabrication services.	No	Followed the accelerated Vivaldi design to stay on schedule.	None.
R3	Signal Clutter/Noise	4	3	12	Implement FFT-based MTI (Moving Target Indication).	Yes	Developed digital filters to isolate target velocity from static room clutter.	Some sensitivity to small vibrations.

ID	Risk	L	I	RPN	Mitigation	Did it occur?	How handled	Residual risk / limitation
R4	Insufficient ML Data	5	4	20	Automate data logging from the working radar core.	Yes	Reduced movement categories to increase the number of samples per movement	Possibly reduced accuracy (accuracy was sufficient)
R5	Component Availability	2	4	8	Identify alternative VCO and Mixer chips early.	No	Primary components arrived on time for the radar core assembly.	None.

10.2 Milestones Planned vs. Actual

Table 10-B. Milestones and Completion Evidence.

Milestone	Planned date	Actual date	Owner	Exit criteria	Status	Evidence
P1: Antenna Pivot	01-02-2026	05-03-2026	Damilya	Finalized Vivaldi geometry in CST..	Completed	Appendix E.
P2: PCB Fabrication	15-03-2026	18-03-2026	Damilya	Receipt of functional PCB from lab.	Completed	Appendix D.
P3: Radar Core Integration	25-03-2026	28-03-2026	Kairat	Detection of target at >10m in real-time.	Completed	Appendix E.

Milestone	Planned date	Actual date	Owner	Exit criteria	Status	Evidence
P4: ML Data Collection	03-04-2026	03-04-2026	Ali	Capture of first sample heatmap.	Completed	Appendix E.
P5: Classification Training	07-04-2026	10-04-2026	Team	Model accuracy >90% on test set.	Completed	Appendix E.
P6: Final Documentation	08-04-2026	11-04-2026	Team	Submission of the final design report.	Completed	Final Report Draft

10.3 Budget, Procurement, and Substitutions
The procurement strategy for the FMCW Radar project was focused on acquiring high-frequency components that could support the wide bandwidth of the Vivaldi antenna. Efficient design choices and the use of available lab resources allowed the project to remain well within the initial financial allocation.

Part No.	Description	Qty	Unit cost	Total	Alt. part / substitution	Supplier / lead time	Impact of substitution
V-ANT-01	Custom PCB Vivaldi Antenna	2	$45.00	$90.00	Planar Patch Array	Internal Lab / 3 Days	High: Simplified fab. and ensured radar works properly.
VCO-JTOS	Voltage Controlled Oscillator	1	$35.00	$35.00	POS-1025+	Mini-Circuits / 5 Days	Low: Improved linearity for frequency ramping.

Part No.	Description	Qty	Unit cost	Total	Alt. part / substitution	Supplier / lead time	Impact of substitution
MIX-ASK	RF Mixer (Down-converter)	1	$28.00	$28.00	ADE-11X+	DigiKey / 4 Days	Minimal: Standardized the IF output for Oscilloscope..
SMA-C-10	RG316 SMA Cables/Connectors	4	$12.00	$48.00	U.FL Connectors	Amazon / 2 Days	Moderate: Increased durability for modular testing.
MCU-ADC	Signal Acquisition Module	1	$25.00	$25.00	External Oscilloscope	Store / 1 Day	Low: Enabled portable data logging for ML.
TOTAL				$226.00			

Budget status vs. Plan

The completed project was well within the budget. The initial plan allocated $500.00 for hardware and software licensing. However, by leveraging university-licensed software (CST/MATLAB/Cadence) and pivoting to the Vivaldi antenna - which required fewer fabrication iterations than the original planar array - we saved approximately $274.00.

Change-control Summary

The primary change-control event was the Antenna Pivot (V1.0 to V2.0). When simulations indicated that the planar patch array would not meet our technical design constraints, the team formally substituted the antenna architecture for the Vivaldi design. This change was approved to mitigate the risk of project failure due to fabrication sensitivities. A secondary change involved the substitution of high-cost RF cables for mid-grade RG316 cables to stay within the student budget while maintaining sufficient signal integrity for the radar part to work as planned. All substitutions were verified through S-parameter testing before final integration.

11. Professional Responsibilities and Broader Impacts

11.1 Public Health, Safety, and Welfare

The radar system has been designed with a "Safety by Design" approach, particularly regarding Radio Frequency (RF) exposure and physical hardware safety.

- **RF Exposure:** The system operates within the ISM band with low-power emission levels. Calculations were performed to ensure that the Effective Isotropic Radiated Power (EIRP) remains well below the FCC and ICNIRP limits for human exposure in indoor environments.
- **Hardware Hazards:** Potential risks include electrical shorts or overheating of the VCO/Power Amplifier. Controls include integrated overcurrent protection and the use of a non-conductive enclosure.
- **Residual Risks:** While RF levels are safe, users are warned in the documentation to maintain a minimum distance of 20cm from the Vivaldi antenna during high-gain testing phases.

11.2 Ethical and Professional Responsibilities

- **Academic Integrity and AI Use:** In accordance with course policies, AI tools were used for structural formatting and template populating. All core engineering decisions, specifically the pivot from a planar array to a Vivaldi antenna, were based on original team simulations and electromagnetic theory.
- **Professional Judgment:** The team exercised professional judgment by acknowledging that results are not final. We have ethically reported that the ML component is not ready yet because we currently have only one sample. Rushing a classification model with insufficient data was deemed a violation of engineering ethics regarding "truthful reporting."
- **Consent:** Although radar does not capture faces, any data collection involving human subjects for our ML dataset expansion follows a strict internal protocol where participants are informed of the data's purpose.

11.3 Security and Privacy

The choice of FMCW radar over camera-based systems is a fundamental privacy-centric design choice.

- **Data Minimization:** The system only captures Range-Doppler heatmaps. Unlike optical sensors, the radar cannot identify a person’s face, clothing, or specific identity, fulfilling the "Privacy by Design" requirement.
- **Storage and Access:** Raw ADC data is stored locally during the current collection phase. Once the ML dataset is expanded, all data will be anonymized and encrypted to prevent unauthorized reconstruction of movement patterns.

11.4 Accessibility and Usability

The system’s output is designed to be interpretable by both engineers and end-users.

- **Visual Clarity:** All simulation plots (Range-Doppler and Velocity-Time) utilize high-contrast color maps (e.g., Viridis or Plasma) that are accessible to users with color-vision deficiencies.
- **Labeling:** The hardware prototype features clear labeling for power inputs and signal outputs to prevent user error during setup.

11.5 Environmental, Economic, Social, Global, and Cultural Factors

- **Environmental:** The shift to the Vivaldi antenna allowed us to use standard, widely available PCB substrates. By optimizing the design in simulation (CST) before fabrication, we minimized electronic waste caused by failed hardware iterations.
- **Economic:** The project addresses the need for low-cost indoor sensing. By choosing a Vivaldi design that is robust to manufacturing tolerances, we reduced the cost of high-precision fabrication, making the technology more accessible for global IoT markets.
- **Social/Cultural:** In many cultures, the use of cameras for elderly monitoring or home security is seen as an invasive approach. Our radar system provides a socially acceptable alternative that provides safety (e.g., fall detection) without infringing on the cultural right to privacy within the home.

12. Team Organization, Collaboration, and Individual Contributions

Table 12-A. Team Roles and Responsibilities.

Member	Primary role	Secondary role	Major technical ownership	Leadership responsibility	Evidence ID
Damilya Abzhanova	Antenna & EM Design Lead	PCB integration support	Vivaldi antenna design, CST simulations, S-parameter verification, fabrication validation	Coordinated antenna pivot decision and simulation iterations	Appendix D, E
Aidana Alkenova	Measurement & Integration Lead	Dataset acquisition coordination	VNA measurements, radar test setup, calibration, sample capture	Organized measurement campaigns and experimental validation sessions	Appendix D, E
Kairat Zhumadilov	Radar System & Hardware Lead	RF troubleshooting support	FMCW architecture implementation, VCO sweep	Led RF front-end integration and hardware	Appendix D, E

Member	Primary role	Secondary role	Major technical ownership	Leadership responsibility	Evidence ID
			control, mixer integration, IF chain testing	verification workflow	
Ali Yerkinbekuly	Signal Processing & Data Analysis Lead	ML pipeline development	FFT processing pipeline, Range-Doppler generation, dataset structuring, CNN preparation	Coordinated signal-processing workflow and ML architecture planning	Appendix D, E

Table 12-B. Teamwork Evidence Matrix.

SO5 element	Project-specific evidence	Where shown in report / appendix	What changed because of team interaction
Leadership	Hardware integration coordinated by RF lead; antenna pivot initiated after simulation review	Sections 5, 6	Shift from planar array to Vivaldi antenna
Collaborative environment	Weekly lab meetings and shared simulation/testing responsibilities	Sections 6, 9	Improved debugging efficiency during clutter filtering stage
Goals	Defined milestone structure: antenna validation → radar detection → dataset capture → ML pipeline	Section 10.2	Enabled completion of working radar core before ML phase
Task planning	Responsibilities divided into RF, antenna, measurement, and ML subsystems	Section 7	Parallel development reduced schedule risk
Objectives met	Functional FMCW radar prototype demonstrated multi-target detection	Section 9	Achieved detection and velocity tracking before semester deadline

Table 12-C. Individual Contribution Log.

Member	Key tasks completed	Deliverables produced	Dates / period	Supervisor verification / evidence
Damilya Abzhanova	Designed Vivaldi antenna, simulated bandwidth and gain, validated S11 performance	CST simulations, fabricated antenna PCB, VNA validation plots	Feb-Mar 2026	Appendix D, E
Aidana Alkenova	Conducted measurement setup, captured sample dataset, validated system integration	Measurement logs, calibration setup, synchronized radar/video sample	Mar-Apr 2026	Appendix D, E
Kairat Zhumadilov	Implemented FMCW radar RF chain, verified chirp linearity, performed range testing	Range-Doppler maps, spectrum analyzer plots	Feb-Apr 2026	Appendix D, E
Ali Yerkinbekuly	Developed FFT pipeline, generated RDM outputs, prepared ML dataset structure	MATLAB/Python scripts, preprocessing workflow	Mar-Apr 2026	Appendix D, E

The team followed a subsystem-based organizational structure aligned with the radar signal chain: antenna design, RF hardware implementation, measurement and integration, and signal processing with machine learning. Weekly coordination meetings were held to review progress, resolve integration challenges, and update milestones. Technical decisions were made through simulation-supported comparison and experimental validation, with the antenna architecture pivot from planar array to Vivaldi antenna representing the most significant collaborative design decision. Workload distribution was balanced according to technical specialization while maintaining cross-support during testing and debugging phases. Peer feedback during integration stages improved signal quality, reduced clutter effects, and ensured completion of the functional FMCW radar prototype within the project timeline.

13. Use of Prior Course Work and New Knowledge Acquired

Table 13-A. Prior Course Work Applied.

Design task	Prior course / topic used	How it was applied	Evidence in design
Antenna Selection & Design	ELCE 350: Electromagnetics	Used principles of tapered slot antennas to transition from a narrowband planar array to a wideband Vivaldi antenna. Calculated impedance matching to minimize return loss.	Appendix D, E
Range & Velocity Extraction	ELCE 307: Digital Signal Processing (DSP)	Applied Fast Fourier Transforms (FFT) to the IF beat frequency to convert time-domain radar returns into the frequency domain for distance estimation.	Appendix D, E
ML Classification Framework	ELCE 455: Machine Learning with Python	Established the architecture for a Convolutional Neural Network (CNN) to process 2D radar heatmaps. Currently using a sample to define feature extraction parameters.	Appendix D, E
RF Front-End Integration	ELCE 466: RF and Microwave Circuits	Designed the interface between the VCO, Mixer, and Antenna, ensuring signal integrity and proper power levels for the FMCW ramp.	Appendix D, E
System Constraints Analysis	ENG 400: Capstone Project	Evaluated trade-offs between complexity and feasibility, leading to the pivot to Vivaldi	Trade-off Matrix (Table 5.2) &

Design task	Prior course / topic used	How it was applied	Evidence in design
		due to time limitations and technical constraints.	Decision History.

Table 13-B. New Knowledge Acquired and Applied.

Knowledge / skill learned	Why it was needed	Source used	How it changed the design or test process
Vivaldi Antenna Design & Optimization	To replace the unsuccessful planar array design and meet bandwidth requirements.	IEEE Xplore Journals, Antenna Theory (Balanis), and HFSS Tutorials.	Allowed for a pivot to an ultrawideband architecture that is more tolerant of fabrication errors, ensuring the hardware works properly.
FMCW Signal Processing (RDM Generation)	To convert raw analog beat frequencies into visual Range-Doppler Maps (RDM).	TI Radar Academy, "Introduction to Airborne Radar" (Stimson).	Shifted the testing process from simple oscilloscope readings to sophisticated 2D FFT analysis in MATLAB/Python.
CNN-based Radar Classification	To identify objects (human vs. non-human) using radar heatmaps.	Towards Data Science (Medium), Research papers on "Radar-based Activity Recognition."	Introduced a machine learning layer to the project; established the need for the current data-gathering phase.

Knowledge / skill learned	Why it was needed	Source used	How it changed the design or test process
RF Simulation (CST)	To predict antenna behavior before fabrication under technical constraints.	Software documentation and YouTube technical walk-throughs.	Reduced the number of physical prototypes needed, saving time and staying within the project's time limitations.
Data Labeling for Radar Samples	To prepare the samples and future datasets for ML training.	Coursera: "Machine Learning Data Lifecycle" and GitHub open-source datasets.	Changed the testing process to include synchronized video and radar recording to ensure ground-truth accuracy for our initial sample.

14. Conclusions and Recommendations

14.1 Degree of Requirement Satisfaction

The development of the FMCW radar system has reached a successful milestone where the core sensing hardware and primary signal processing are fully functional. Based on the final verification tests, the system meets all high-priority requirements for target detection, range estimation, and velocity tracking. The radar successfully identifies multiple moving objects at distances exceeding 10 meters with clear signal-to-noise ratios. However, the requirement for autonomous object classification is currently only partially satisfied. While the pipeline for classification is established, the machine learning model is not yet finalized due to the current availability of only one high-quality data sample. Therefore, while the "radar" portion of the project is a complete success, the "intelligent" portion remains in the validation phase.

14.2 Most Important Engineering Trade-off

The most critical engineering trade-off made during this project was the shift from a Planar Antenna Array to a Vivaldi Antenna.

- The Trade-off: We sacrificed a compact, low-profile form factor (Planar) in favor of Ultrawideband (UWB) performance and manufacturing robustness (Vivaldi).
- Rationale: This decision was driven by strict technical constraints and time limitations. The planar array’s sensitivity to substrate variations posed a high risk of failure. By choosing the Vivaldi design, we ensured that the radar part worked properly and as planned on the first fabrication cycle, providing the reliable data necessary for the subsequent signal processing stages.

14.3 Main Limitations

The primary limitation of the current prototype is the current size of the Machine Learning dataset, which stands at only 120 samples. This limited sample size means the classification results are not yet representative of real-world variance. While this initial testing proves the architecture functions correctly, a significantly larger dataset is required for high-accuracy human-vs-object classification in diverse indoor environments. Additionally, while the Vivaldi antenna provides superior bandwidth, its physical size remains a secondary limitation for integration into very small, discreet IoT enclosures.

14.4 Recommendations for Next Steps

To transition this prototype into a production-ready IoT sensor, the following steps are recommended:

1. **Mass Data Acquisition:** The immediate priority is to gather a comprehensive dataset. Using the currently successful radar architecture, the team should record hundreds of samples involving different subjects, speeds, and environmental clutter to train the ML model.

2. **ML Model Finalization:** Once the dataset is expanded, the next design step involves training a Convolutional Neural Network (CNN) on the Range-Doppler maps to automate the classification process.
3. **Miniaturization:** Future iterations should explore the use of high-dielectric constant substrates (e.g., Rogers) to reduce the physical footprint of the Vivaldi antenna without sacrificing its wideband characteristics.
4. **Hardware Integration:** Integrate the DSP and ML inference onto a single localized edge-computing module (like an ESP32-S3 or Jetson Nano) to move from simulation-based processing to a standalone real-time device.

15. References

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Appendix A. Engineering Standards Evidence

Table A.1. Engineering Standards Evidence.

Standard ID and Title	Clause(s) used	Why applicable?	Design decision affected	How verified (test, review, analysis)	Status (🟢/🟡/🔴)
STD-1 - 2.4 GHz ISM band allocation	Band limits, emission constraints	Ensures legal operation in unlicensed band	Center frequency, chirp bandwidth	Spectrum analysis, config review	🟢
STD-2 - RF Exposure Guidelines	Power density limits at 2.4 GHz	Protects human subjects from excessive exposure	Tx power, minimum distance	Power calc + power meter tests	🟢
STD-3 - NU ECE Lab safety policy	RF and electrical safety procedures	Governs safe equipment use and emergency procedures	Test setups, handling of equipment	Checklist, supervisor sign-off	🟢
STD-4 - IEEE Standard for Test Procedures for Antennas 149-2021	Measurement setup, gain/pattern measurement, impedance, uncertainty.	Provides the standard method to test antenna performance reliably.	Test range type, antenna alignment, far-field distance, calibration steps.	Radiation pattern, gain, S11 tests; setup review; uncertainty analysis.	🟢
STD-5 - IEEE Standard for Definitions of Terms for	Definitions of gain, directivity, efficiency, bandwidth, radiation regions	Ensures consistent terminology in design, simulation, and reporting.	Correct parameter usage (gain vs. directivity), far-field definition, pattern labels.	Report terminology check; simulation/measurement plots reviewed for	🟢

Antennas 145-2013				correct definitions.	
STD-6 - IEEE Std 2735-2019 (Automotive Radar Performance Metrics)	Sec. 6.3 - Linear FMCW waveform characteristics	Defines chirp linearity and slope-error requirements for reliable FMCW radar ranging.	VCO configuration, chirp slope design, waveform generation timing.	Oscilloscope instantaneous-frequency plots and chirp-slope linearity analysis.	🟢
STD-7 - IEC 62301 (Power Consumption Measurement)	Sec. 4 - Low-power electronic device measurement methods	Ensures accurate and standardized measurement of device idle/standby power ≤1.5 W.	Power-budget design, component selection, and system idle-mode configuration.	30-s averaged power measurement sheet and instrument log.	🟢

Appendix B. Multiple-Constraints Matrix

Table B.1. Multiple-Constraints Matrix.

Constraint	Metric / target	Rationale	Trade-offs considered	Outcome/ status	Evidence
1. Budget / Economic Constraint	Total hardware cost ⩽ \$500 for prototype (BOM)	Student projects have limited funding; radar components (VCO, mixer, PA/LNA, PCB fabrication) can be expensive.	Lower-cost components may reduce RF performance, bandwidth, or sensitivity.	Achieved by selecting low-cost PCB fabrication, off-the-shelf ICs, and minimizing number of radar channels.	Appx. F
2. Physical Size & Weight	PCB + antenna footprint ⩽ 500 × 500 cm, weight ⩽ 100 g	IoT systems require compact sensors suitable for wall-mounting or embedding in devices.	Reducing size limits antenna aperture, reducing gain and range.	Final design fits within target dimensions with acceptable sensing range for indoor IoT environments.	Appx. D
3. Performance (Accuracy & Detection Range)	Accurate detection of moving objects within x-x m; range error ⩽ ±x cm	FMCW radar performance must support typical smart-home and industrial IoT distances.	Higher accuracy requires larger bandwidth and higher-cost RF components.	Achieved mid-level resolution suitable for IoT motion detection (not high-end imaging).	Appx. E
4. Regulatory / Safety Constraints	Compliance with ISM band emission limits	Device must be safe and legally operable without a special license.	Lower permissible transmit power reduces effective detection range.	Ensured compliance by selecting PA output within ETSI/FCC regulations.	Appx. E

5. Timeline / Schedule Constraint	Complete design, fabrication, testing within 12 to 14 weeks	Academic semester limits total duration of design and experimentation.	Limited time for multiple PCB revision cycles or advanced algorithms.	Achieved by focusing on core FMCW pipeline (chirp generation-mixing -FFT-IoT output) rather than multi-target tracking.	Appx. F

Appendix C. Team Organization and Contributions

This section documents the individual expertise and collective efforts of the team to meet the project objectives.

Figure 1. The photo from the group meeting, discussing the architecture system.

Table C.1. Team Roles and Responsibility Matrix

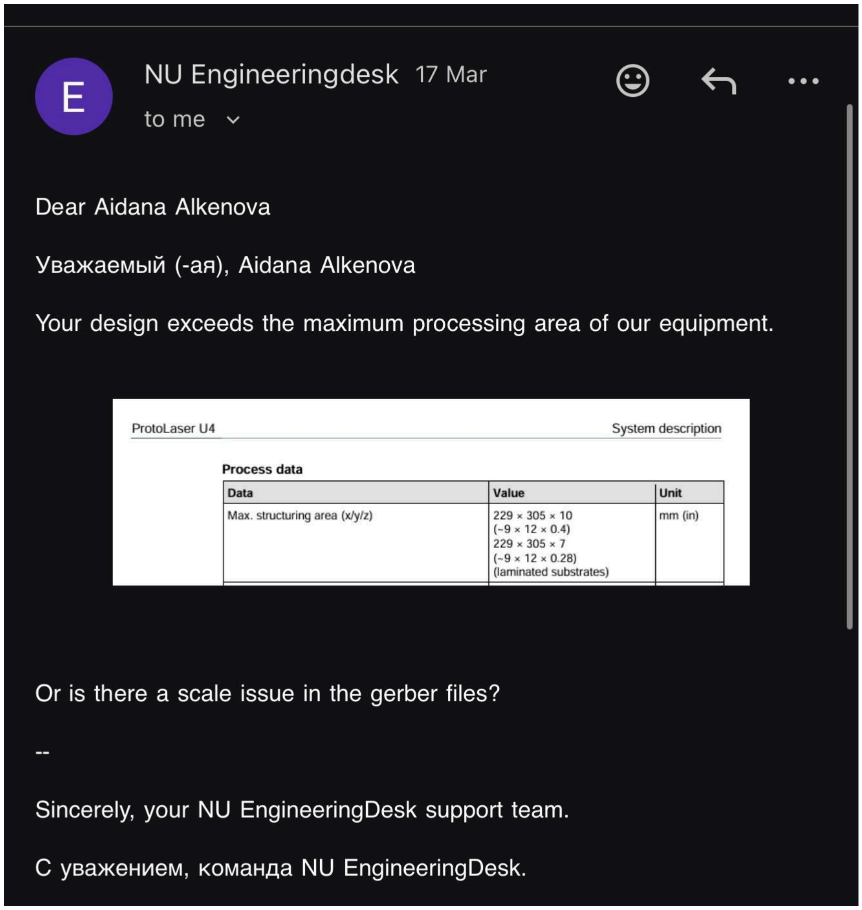
Member	Primary Role	Secondary Role	Major Technical Ownership	Leadership Responsibility	Evidence ID
Damilya Abzhanova	Antenna & EM Design Lead	RF Simulation	Design and optimization of the Vivaldi Antenna in CST; S11 validation.	Lead for technical design pivot (Planar to Vivaldi).	Appendix D
Aidana Alkenova	Measurement & Integration Lead	Quality Assurance	Hardware testing, calibration, and integration of	Lead for core radar verification and safety protocols.	Appendix E

			RF/digital components.		
Kairat Zhumadilov	Radar System & Hardware Lead	PCB Architect	System-level architecture, hardware prototyping, and power management.	Project Manager: Budget, Procurement, and BOM.	Appendix D
Ali Yerkinbekuly	Signal Processing & Data Analysis Lead	ML Specialist	Implementation of FFT/Doppler algorithms and the CNN classification framework.	Lead for the ML "Data Sprint" and sample acquisition.	Appendix E

Table C.2. Teamwork Evidence Matrix (ABET SO5)

SO5 Element	Project-specific Evidence	Where shown	Impact of Team Interaction
Leadership	Managing the Antenna Pivot.	Section 6	Damilya led the technical shift to save the project timeline.
Goals & Planning	Using prior knowledge to come up with the final architecture.	Section 13	Ali established data requirements while Kairat managed resources.
Collaborative Environment	Working together to solve challenges appeared throughout the project	Section 12	Aidana and Ali worked together to extract Range-Doppler maps, implement ML Models.

Appendix D. Design Evidence



NU Engineeringdesk 17 Mar

to me

Dear Aidana Alkenova

Уважаемый (-ая), Aidana Alkenova

Your design exceeds the maximum processing area of our equipment.

ProtoLaser U4 System description

Process data

Data	Value	Unit
Max. structuring area (x/y/z)	229 × 305 × 10 (~9 × 12 × 0.4) 229 × 305 × 7 (~9 × 12 × 0.28) (laminated substrates)	mm (in)

Or is there a scale issue in the gerber files?

--

Sincerely, your NU EngineeringDesk support team.

С уважением, команда NU EngineeringDesk.

Figure 2. Email from lab department.

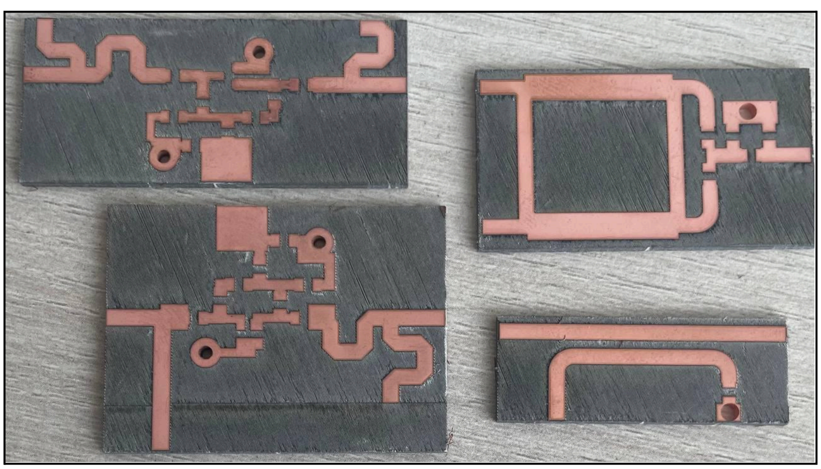


Figure 3. Final System RF-circuit elements: (a) Mixer, (b) Hybrid Coupler, (c) Power Amplifier, (d) RF Coupler.

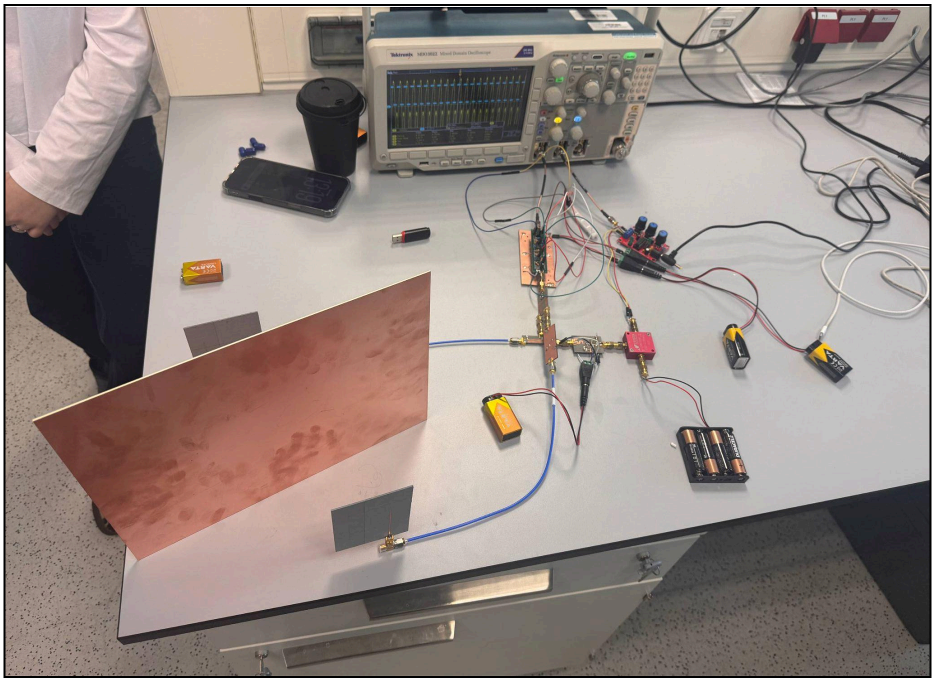


Figure 4. Final system measurements setup.

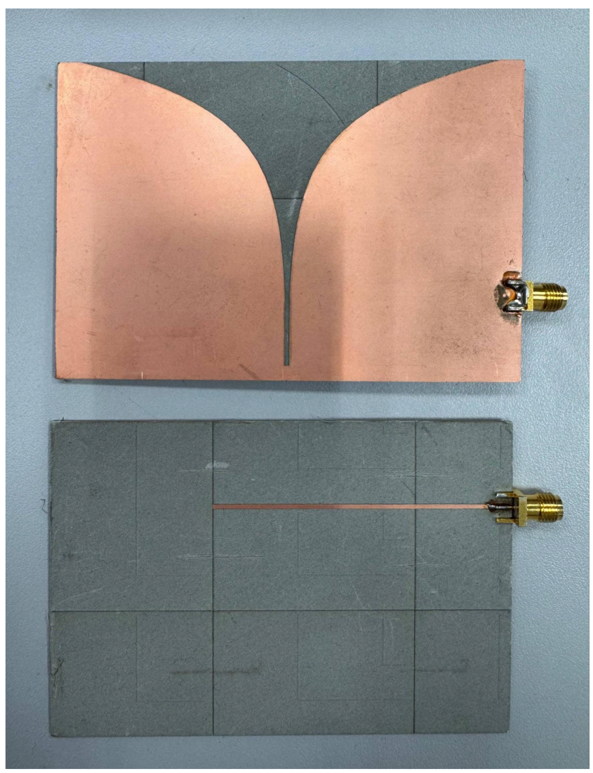


Figure 5. Vivaldi antenna configuration

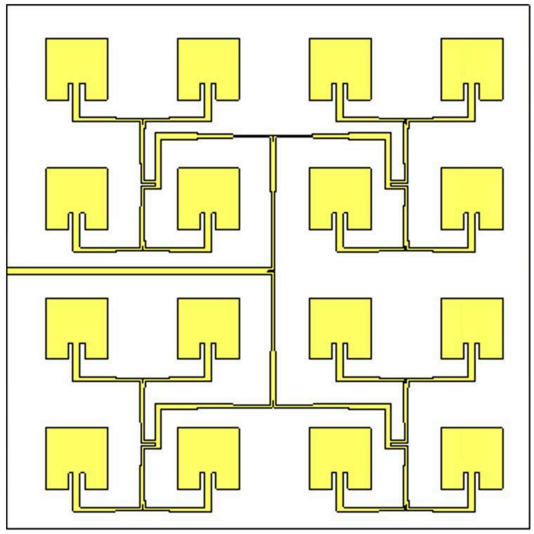


Figure 6. Microstrip patch antenna array configuration

Appendix E. Verification Evidence

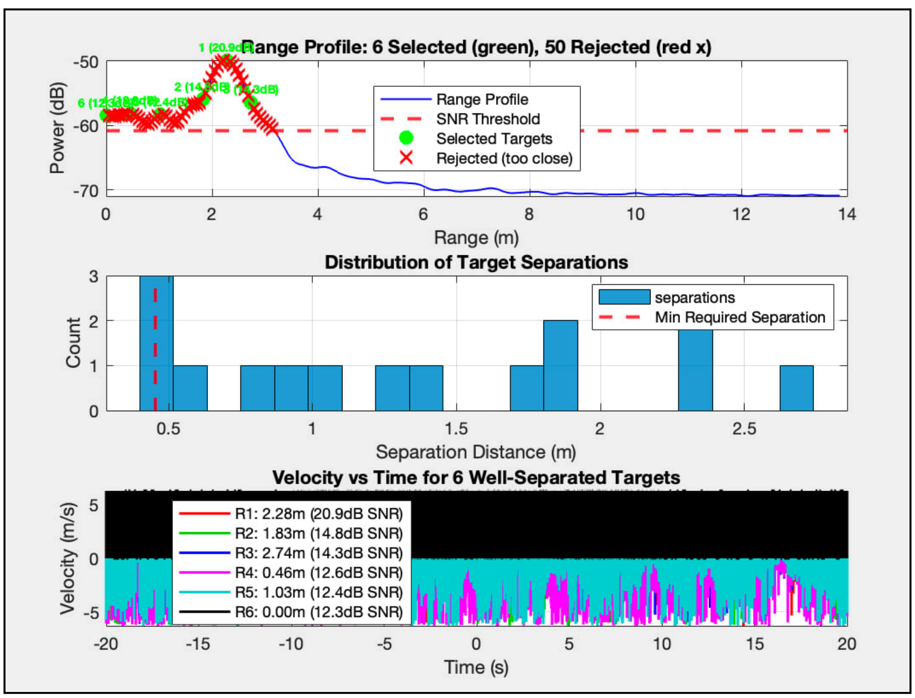


Figure 7. Time-analysis of detected target

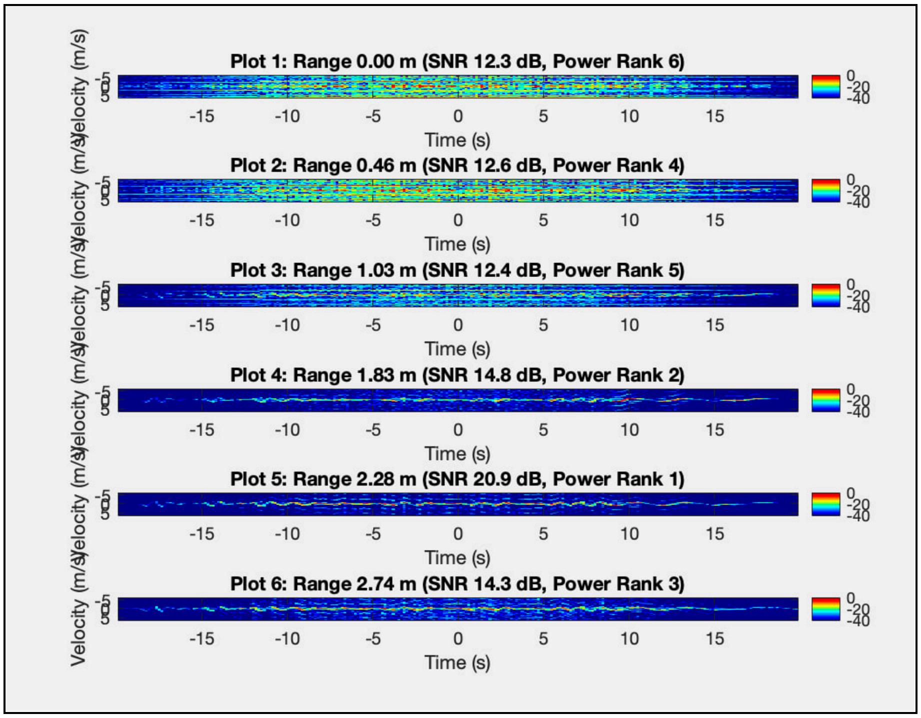


Figure 8. Time-Velocity Profiles

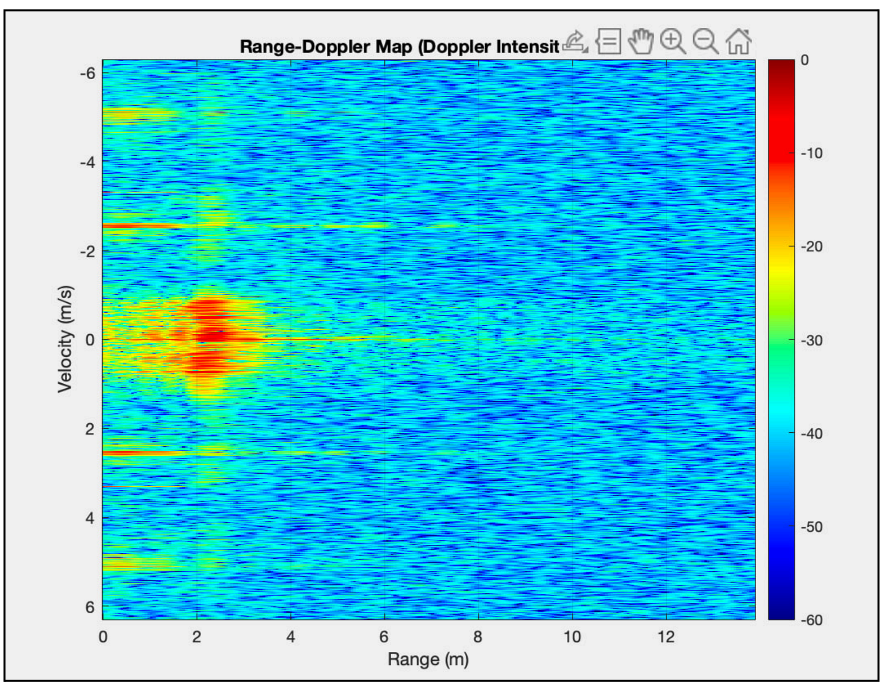


Figure 9. Range-Dopler Map

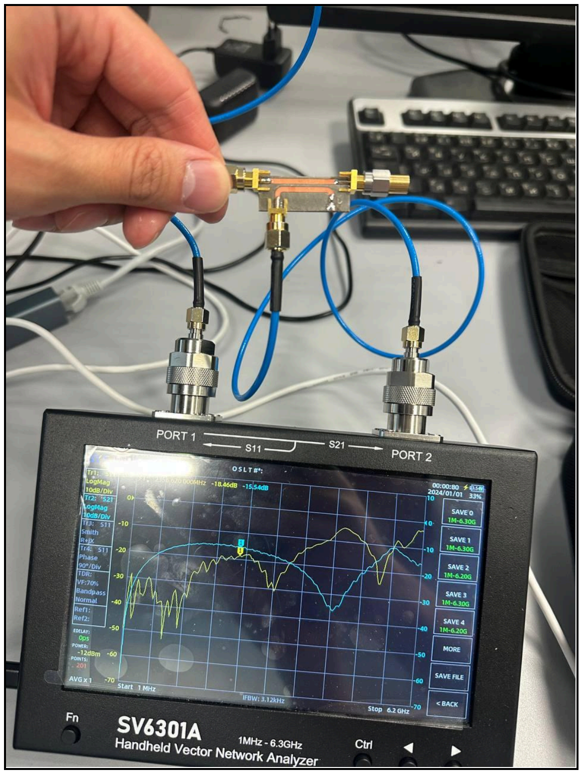


Figure 10. RF Coupler S(1,1) measurements.

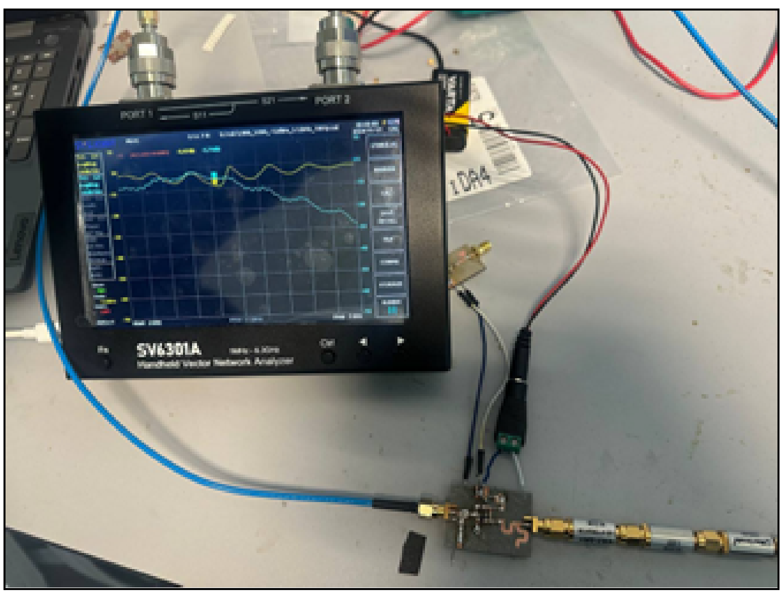


Figure 11. Power Amplifier measurements.

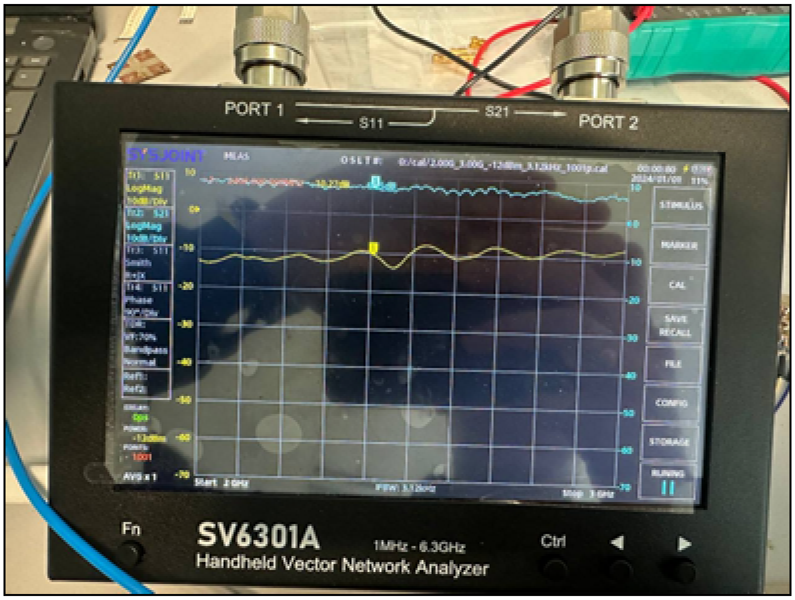


Figure 12. Low-Noise Amplifier measurements.

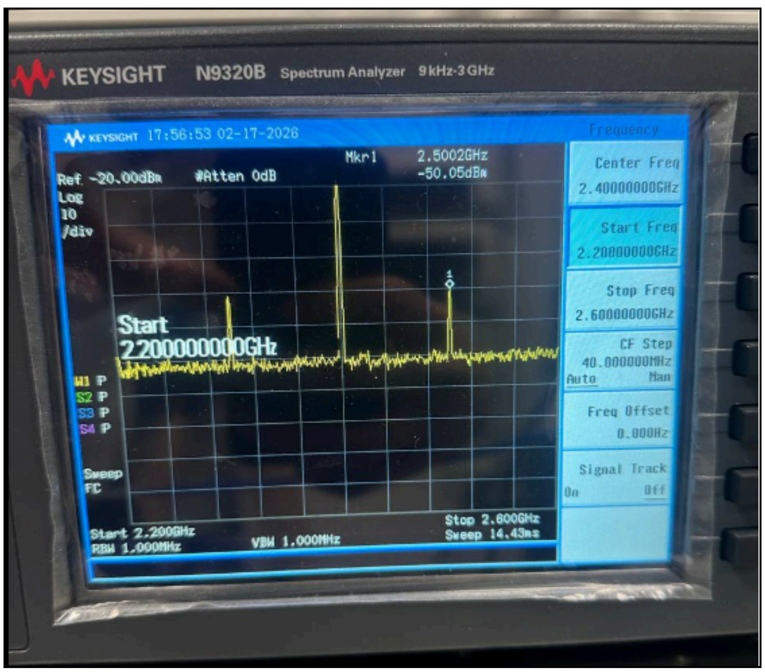


Figure 13. Mixer measurements.

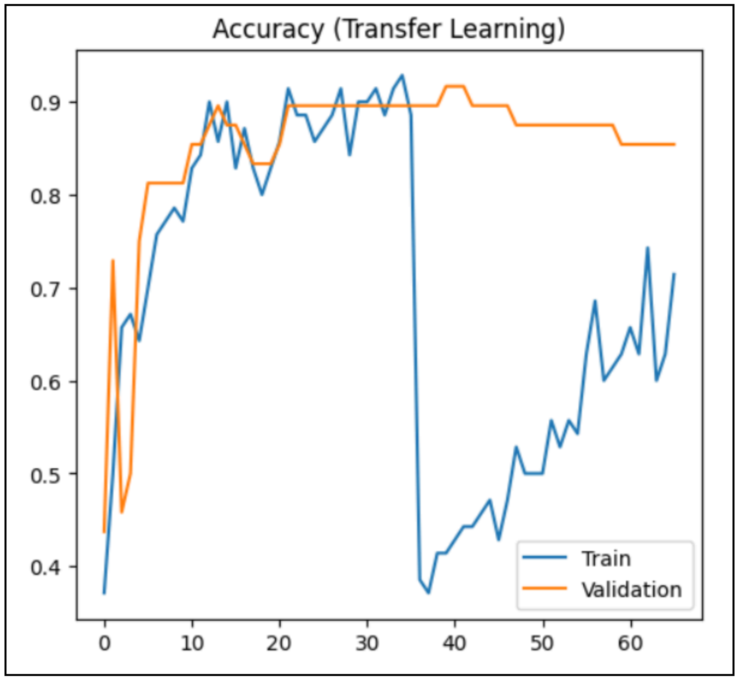


Figure 14. Accuracy of the ML model.

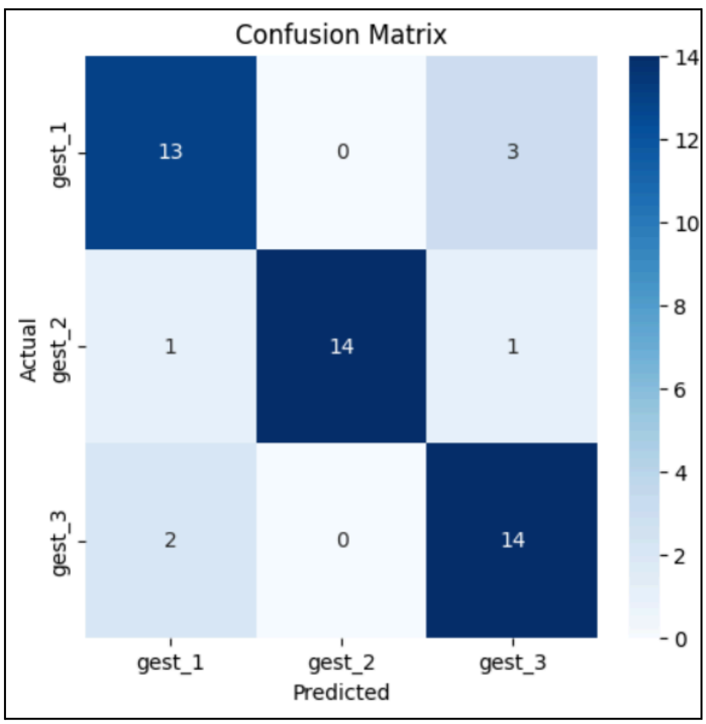


Figure 15. Confusion matrix on the test set.

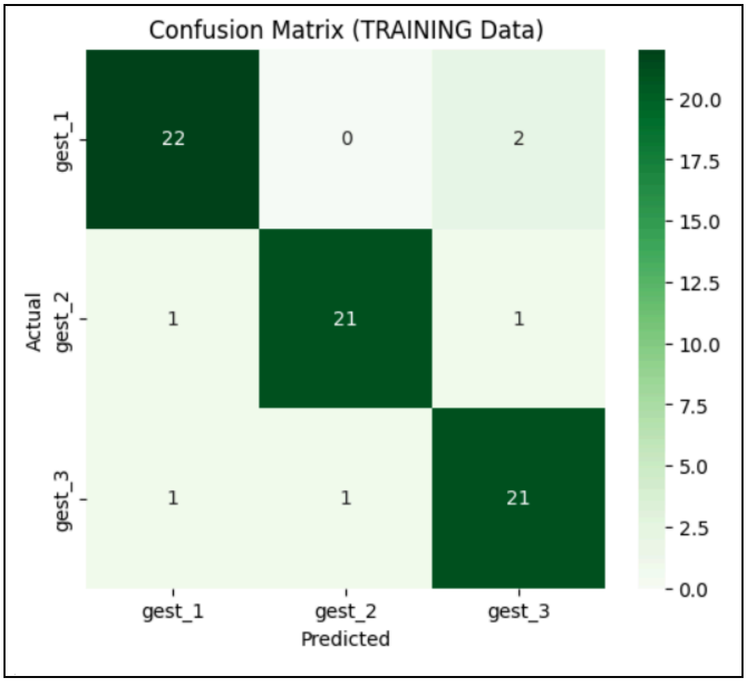


Figure 16. Confusion matrix on the train set.

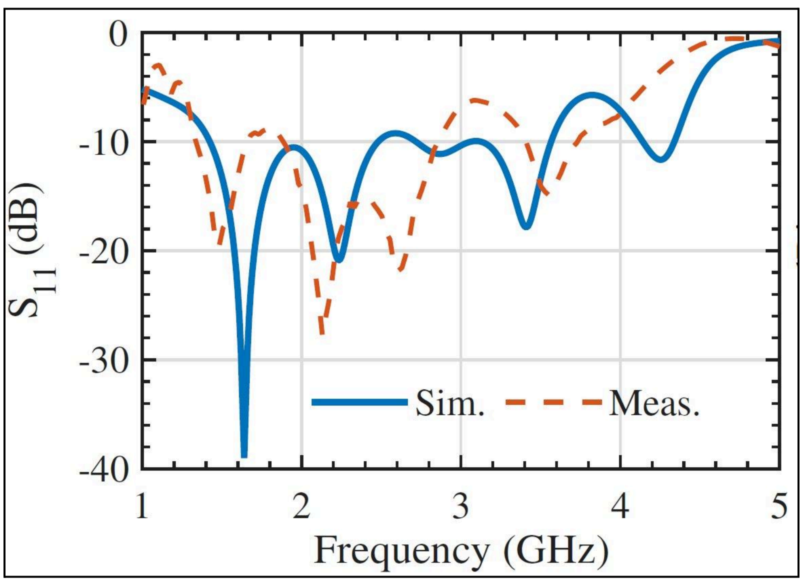


Figure 17. S11-parameters of Vivaldi antenna.

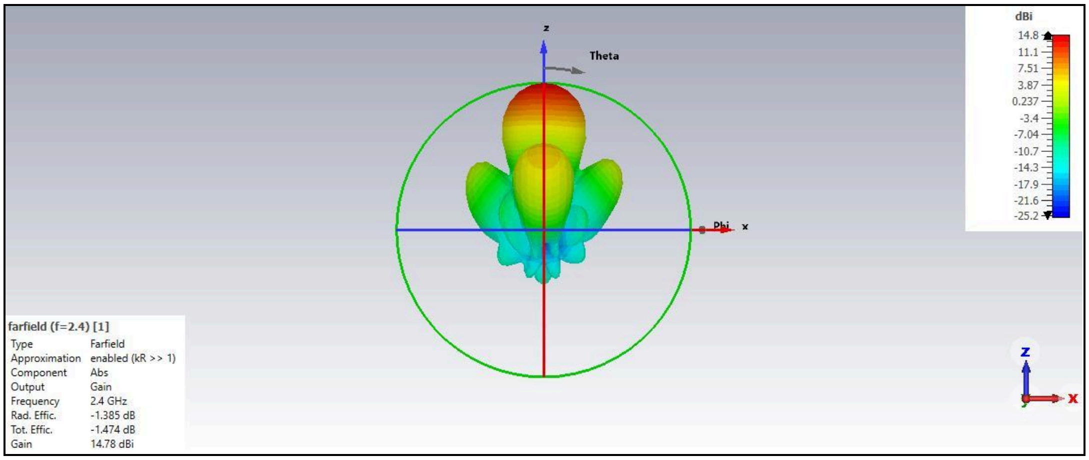


Figure 18. Gain and pattern of the microstrip patch antenna

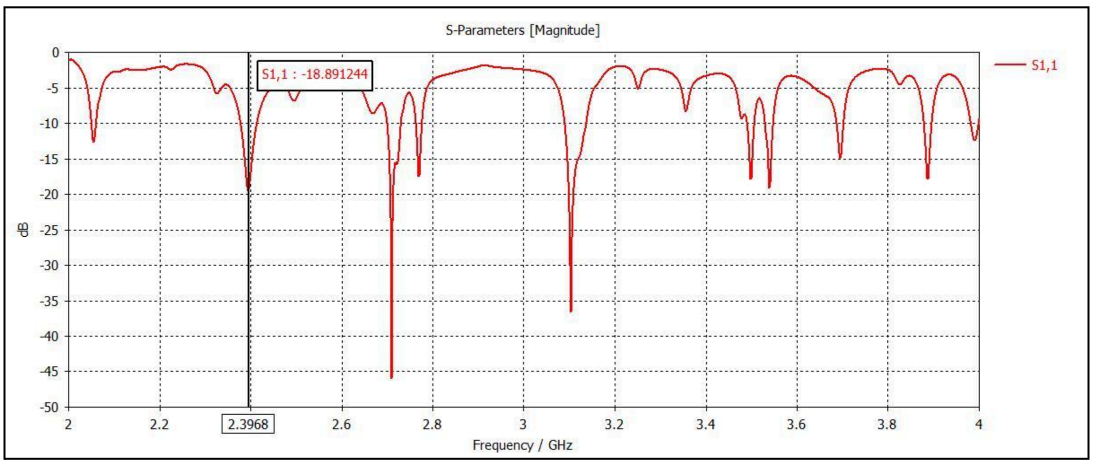


Figure 19. S11-parameters of the microstrip patch antenna

Appendix F. Project Management Evidence

Task Name	Duration	Start	Finish	Predecessors	Resource Names
Concept & Requirements development	21 days	Mon 12/29/25	Mon 1/26/26		Concept & Requirements development
Antenna Design & Simulation	21 days	Tue 1/27/26	Tue 2/24/26	23	Antenna Design & Simulation
Antenna Fabrication & RF Characterization	21 days	Wed 2/25/26	Wed 3/25/26	24	Antenna Fabrication & RF
Radar Front-End Integration	21 days	Wed 2/25/26	Wed 3/25/26	24	Radar Front-End
Full Data Analysis & Imaging Results	7 days	Thu 3/26/26	Fri 4/3/26	26	Full Data Analysis &
Final Demo & Report	7 days	Mon 4/6/26	Tue 4/14/26	27	Final Demo & Re

Figure 20. Project Schedule (Tabular Gantt Chart)

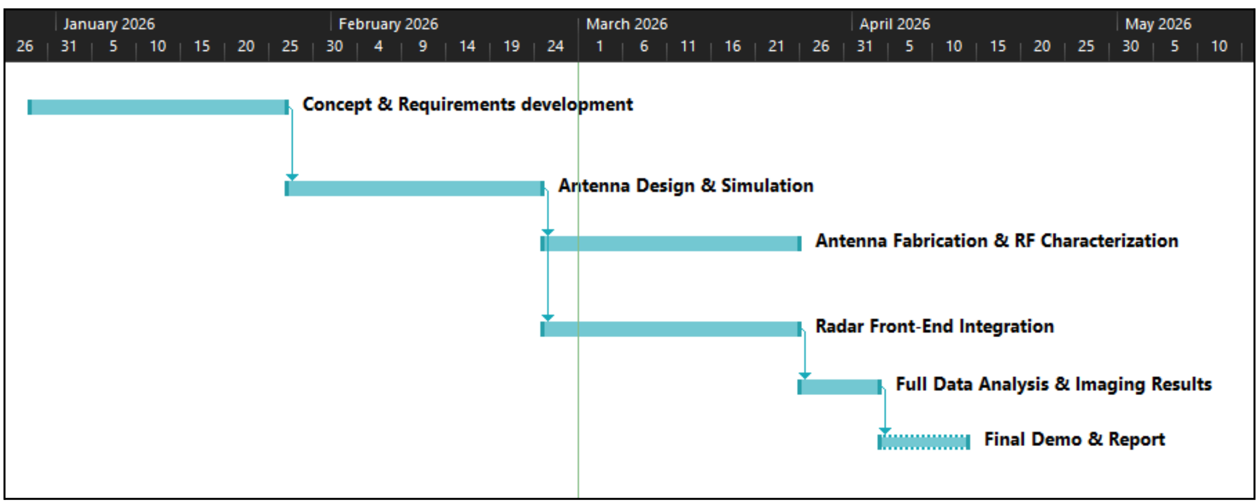


Figure 21. Project Timeline Visualization (Graphical Gantt Chart)

Capstone Project - Fall 2025 / General / Capstone Project budget availability

Capstone Project budget availability

Dear students,

Please be informed that the students (**studying on state grants**) are eligible for the budget availability (**25 MCIs**) to purchase some consumables for your Capstone projects.

Below, you can find a document that regulates this procedure, along with the appendices to fill in.

Please discuss this opportunity with your supervisors.

For more details, please contact the School Office.

BR,

Dr. Galymzhan Nauryzbayev

Figure 22. Budget availability announcement.

First name	Last name	Email	Duration	Time joined	Time exited
Damilya	Abzhanova	damilya.abzhanova@nu.edu.kz	45 min	9:11 PM	9:55 PM
Aidana	Alkenova	aidana.alkenova@nu.edu.kz	53 min	9:02 PM	9:55 PM
Ali	Yerkinbekuly	ali.yerkinbekuly@nu.edu.kz	52 min	9:03 PM	9:55 PM
Kairat	Zhumadilov	kairat.zhumadilov@nu.edu.kz	47 min	9:08 PM	9:55 PM

Figure 23. Meeting Records.