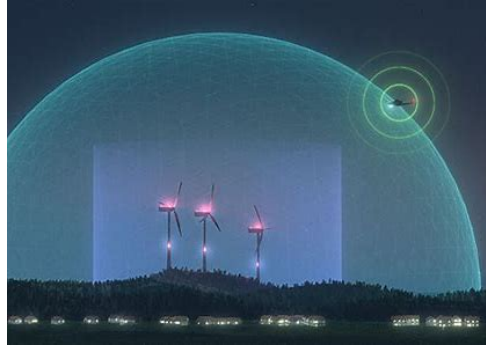


Low Cost Passive Aircraft Detection System for Remote Areas

Divide and Conquer Document

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Table of Contents

Chapter 1 Executive Summary.....	1
Chapter 2 Project Description.....	2
2.1 Motivation and Background.....	2
2.2 Existing Products.....	3
2.2.1 General Applications.....	3
2.2.2 Proprietary Applications.....	3
2.2.3 Comparison of Our Design to Available Products.....	4
2.3 Goals and Objectives.....	4
2.3.1 Basic Goals.....	4
2.3.2 Advanced Goals.....	5
2.3.3 Stretch Goals.....	5
2.3.4 Objectives.....	5
2.4 Features and Functionalities.....	6
2.4.1 Design Implementations.....	6
2.4.2 Customer Input.....	6
2.5 Specifications.....	6
2.5.1 System Specs.....	6
2.5.2 Component Specs.....	7
2.6 House of Quality.....	8
2.7 Block Diagrams.....	10
2.7.1 Hardware Block Diagram of Node Array.....	10
2.7.2 Hardware Block Diagram of Individual Node.....	10
2.7.3 Software Flow Chart:.....	11
2.7.3.1. System Initialization.....	12
2.7.3.2. Signal Pre-Processing.....	13
2.7.3.3. Independent RF Signal Detection.....	13
2.7.3.4. Data Fusion & Analysis in the Main Unit.....	13
2.7.3.5. Validity Check for Detection.....	13
2.7.3.6. Cloud-Based Storage & API Access.....	13
Chapter 3 Research and Investigation.....	14
3.1 Hardware Technologies.....	14
3.1.1 Central Processor.....	14
3.1.1.1 MPU vs. SBC.....	14
3.1.1.1.1. Pros and Cons of SBCs.....	14
3.1.1.1.2. Pros and Cons of MCUs.....	14

3.1.1.1.3. Why SBC could be a best fit?	15
3.1.1.1.4. Choosing between MCU and SBC	15
3.1.1.2 SBC Selection	17
3.1.1.2.1. Raspberry Pi Series	17
3.1.1.2.2. Raspberry Pi Zero	19
3.1.1.2.3. Raspberry Pi Compute Module Series	19
3.1.1.2.4. Qualcomm Snapdragon	20
3.1.1.2.5. NXP i.MX	20
3.1.1.2.6. Intel Atom, Core, and Xeon	21
3.1.1.2.7. Texas Instruments Sitara	21
3.1.1.2.8. SBC Comparison	22
3.1.1.3 SBC Selection	24
3.1.2. Antenna	24
3.1.2.1 Choosing the Antenna	24
3.1.2.1.1. Log-Periodic Dipole Array (LPDA) Antennas	24
3.1.2.1.2. Yagi-Uda Antenna	25
3.1.2.1.3. Dipole Antennas	25
3.1.2.1.4. Phased Array Antennas	26
3.1.2.1.5. Monopole Antennas	26
3.1.2.1.6. Phased Array Antennas	26
3.1.2.1.7. Antenna Comparison	27
3.1.2.2 Signal Hound BB60D Spectrum Analyzer	28
3.1.2.3 Setup with Spectrum Analyzer	29
3.1.2.4 Antenna Selection	30
3.1.3 Android Cellular Phone Handset	30
3.1.3.1 Samsung	31
3.1.3.2 Google Pixel	32
3.1.3.3 Motorola	33
3.1.3.4 Cellular Phone Selection	34
3.1.4 Starlink Mini Terminal	35
3.1.5 Laptop PC (Core i7)	36
3.1.5.1 Dell	36
3.1.5.2 HP	37
3.1.5.3 Lenovo	37
3.1.5.4 Laptop Part Selection	38
3.2. Power Supply System	39
3.2.1 Batteries	40
3.2.1.1 Choosing a Battery	40

3.2.1.2 Available Battery Options.....	40
3.2.1.3 Battery Option Chart.....	41
3.2.1.4 LiFePO4 Battery Choices.....	42
3.2.2 Solar Panels.....	43
3.2.2.1 General Types of Panels.....	43
3.2.2.2 Pros and Cons.....	43
3.2.2.3 Specific Models.....	45
3.2.3 Charge Controllers.....	46
3.2.3.1 Purpose of Charge Controller.....	46
3.2.3.2 Types of Charge Controllers.....	46
3.2.3.3 Charge Controller Options.....	46
3.2.4 Wiring Setup.....	47
3.2.4.1 For a Single Unit.....	47
3.2.4.2 For Multiple Unit.....	47
3.2.4.3 Additional Recommendations.....	47
3.2.5 Power Supply Part Selection.....	47
3.3 Communication Technologies.....	49
3.3.1. Mobile services.....	49
3.3.1.1 AT&T.....	49
3.3.1.2 Verizon.....	49
3.3.1.3 T-Mobile.....	49
3.3.1.4 Mobile Service Selection.....	50
3.3.2. Communication Methods.....	51
3.3.2.1 Zigbee.....	51
3.3.2.2 Z-Wave.....	53
3.3.2.3 Near Field Communication (NFC).....	54
3.3.2.4 Bluetooth.....	55
3.3.2.5 Wi-Fi.....	56
3.3.2.6 Starlink Satellite Communication (SATCOM).....	58
3.4 Software Technologies.....	60
3.4.1. C/C++.....	60
3.4.2. Java.....	61
3.4.3. Python.....	62
3.4.4. Development Environment: Languages and Repositories.....	64
3.4.5 Language Selection.....	64
3.4.6 Data Transfer Mechanism.....	65
3.4.7 Data Transmission Process.....	65
3.4.8 Data Structure and Storage.....	67

3.4.9 Software Architecture and System Workflow.....	68
Chapter 4 Standards and Design Constraints.....	68
4.1 Software.....	68
4.1.1 Software Standards.....	68
4.1.1.1 IEEE 12207 – Software Life Cycle Processes.....	69
4.1.1.2 ISO/IEC 27001 – Information Security Management.....	70
4.2 Hardware.....	71
4.2.1 Hardware Standards.....	72
4.2.2 Hardware Design Constraints.....	73
4.2.3 Non-Technical Constraints.....	75
Environmental Constraints.....	76
Chapter 5. Comparison of ChatGPT with Similar Platforms.....	78
5.1 Case study 1: ChatGPT vs Microsoft Copilot.....	78
5.2 Case study 2: ChatGPT vs Google Gemini.....	79
5.3 Case study 3: ChatGPT vs Grok.....	80
Chapter 6. Hardware Design.....	81
6.1 Power Supply System.....	81
6.2 RF Detection Subsystem.....	82
6.2.1 Antenna Schematic (Active/Passive).....	82
6.2.2 Spectrum Analyzer Connections.....	82
6.3 Data Processing and Communications System.....	83
6.3.1 Raspberry Pi.....	83
6.3.1.1 Power Schematic.....	83
6.3.2 Samsung S24.....	83
Power Wiring:.....	83
Data Connection:.....	83
Chapter 7. Software Design.....	84
7.1 Use Case Diagram.....	84
7.3. User Interface (UI) Design.....	86
7.4 Entity-Relationship Diagram (ERD).....	86
7.5 Activity Diagram.....	87
7.6 Localization diagram.....	88
Chapter 8: Prototyping and Testing.....	90
8.1 Hardware Testing.....	90
8.2 Software Testing.....	91
8.3 Integration Testing.....	92
8.4 Enclosure and Environmental Housing.....	93
9.1 Raspberry Pi as the Target Hardware Platform.....	94
9.2 ASUS NUC as a Prototyping Platform.....	94

9.3 Software Migration and Compatibility Testing.....	95
9.4 Additional Testing Strategies.....	95
9.5 Detailed Development and Testing Plan.....	95
Chapter 10. Administrative Content.....	96
10.1 Project Budget and Financing.....	96
10.2 Bill of Materials.....	97
10.3 Work Distribution.....	97
10.4 Schedule and Milestones.....	98
10.4.1 Senior Design 1.....	98
10.4.2 Senior Design 2.....	99
Chapter 11: Conclusion.....	100
APPENDIX A REFERENCES.....	103
APPENDIX B.....	108
5.1. ChatGPT vs Copilot.....	108
5.2 Case Study - ChatGPT.....	111
Step 1: Solar Panel to MPPT Charge Controller.....	112
Step 2: Battery Connection.....	112
Step 3: Voltage Regulation for Each Component.....	112
12V to 5V Conversion (For Raspberry Pi, Samsung S24, LNA, etc.).....	112
Direct 12V Connection (For Signal Hound BB60D).....	112
5.3 ChatGPT vs Grok.....	114
7.4 ERD Overview.....	120

List of Figures

Figure 2.1 House of Quality Diagram.....	9
Figure 2.2 Hardware Block Diagram of Node Array.....	10
Figure 2.3 Hardware Block Diagram of Individual Node.....	11
Figure 2.4 Software block diagram.....	12
Figure 6.1 Wiring Diagram	77
Figure 6.2 Passive Antenna Setup	78
Figure 6.3 Cell Phone to Laptop Connection	79
Figure 7.1 Software Use Case Diagram by Authors	80
Figure 7.2 Software State Diagrams by Authors	81
Figure 7.3 ERD Diagram.....	83

Figure 7.5: Activity Diagram	84
Figure 7.6.1: Localization diagram.....	84
Figure 7.6.2: Localization flowchart	86
Figure 7.6.1: Localization diagram.	84
Figure 10.1 BOM	93

List of Tables

Table 2.1 System Specifications	6
Table 2.2 Component Specifications	7
Table 3.1 Comparison between MCU and SBC.....	15
Table 3.2 MPU Comparison by Authors	22
Table 3.3 Antenna Types	27
Table 3.4 Power Supply Requirements	39
Table 3.5 Battery Types.....	41
Table 3.6 Battery Models	42
Table 3.7 Solar Panel Types	44
Table 3.8 Solar Models with Features.....	45
Table 3.9 Charge Controller Models.....	46
Table 3.10 Mobile services comparison by Authors	50
Table 3.11 Data Transfer Protocols	60
Table 3.12 Storage Solutions	63
Table 7.1 UI Breakdown	82
Table 10.1 Budget	92
Table 10.2 Table of Work Distributions	93
Table 10.3 SD1 Schedule	94
Table 10.4 SD2 Schedule	95

Chapter 1 Executive Summary

Unauthorized border incursions by aircraft operating in remote areas without conventional air traffic control radar systems pose significant threats to the security and sovereignty of nations within the U.S. SOUTHERN COMMAND Area of Responsibility. These regions often lack radar coverage due to the high cost of implementing and maintaining such infrastructure, which is frequently beyond the financial capabilities of the affected nations. To address this challenge, the Low-Cost Passive Aircraft Detection System for Remote Areas offers an innovative solution that utilizes a passive RF detection approach with Commercial Off-The-Shelf (COTS) components. Unlike traditional active radar systems, this passive system "listens" for aircraft signals through open RF receivers arranged in an array along border areas. The detected information is then transmitted in real-time via Starlink SATCOM to a secure live-streaming website, enabling global access for users to monitor activity and take timely action as needed. By relying on passive RF detection rather than emitting radar waves, the system significantly reduces costs, energy consumption, and detectability, making it an ideal solution for remote and resource-constrained environments.

The system is designed with advanced Digital Signal Processing (DSP) and machine learning algorithms, which ensure a high detection accuracy rate of over 95% while maintaining false positive rates below 5%. Its weatherproof and solar-powered design enables continuous operation for over a decade, even in harsh environmental conditions, while its plug-and-play setup simplifies deployment and maintenance. With a prototype budget of approximately \$8,000, this cost-effective solution provides a viable alternative to expensive existing systems, such as Raytheon's Silent Sentry and FlightAware Global. Unlike these systems, the proposed design emphasizes scalability, affordability, and flexibility, offering enhanced real-time data access, improved anomaly detection, and the ability to expand coverage as needed.

Phase 2 will expand the system from a single detection unit to a fully functional multi-unit network, improving accuracy and coverage. These units will be placed across a designated area and will communicate with each other and a central hub using timing differences between detected signals to estimate an aircraft's exact location. This setup ensures a more precise and reliable tracking system capable of monitoring larger regions effectively. Phase 2 will also refine real-time data transmission and synchronization, making sure all units stay in sync and work together seamlessly. The system will continue to use Starlink SATCOM for communication, ensuring reliable and efficient data transmission even in remote areas. By transitioning to a distributed network of detection units, Phase 2 will significantly strengthen the system's ability to monitor remote areas while maintaining affordability and scalability for future expansions.

The initial prototype, created by the other group, will include a single working unit comprising of a remote sensor with a PC and battery power supply, enabling a field test to validate its performance in detecting aircraft using passive RF methods. The system's phased development includes research, design, testing, and in our case, a transition to a fully solar-powered configuration of multiple nodes in the second phase. Beyond technical development, the project will conduct a comprehensive business analysis to explore the potential for producing and deploying arrays of these passive sensors on a global scale. This analysis will consider the scalability of the solution, its integration into existing monitoring infrastructures, and its potential

to address similar challenges in other regions. By offering an affordable and sustainable alternative to conventional radar systems, the Low-Cost Passive Aircraft Detection System represents a transformative approach to securing remote border areas and enhancing global monitoring capabilities.

Chapter 2 Project Description

2.1 Motivation and Background

In many remote areas, keeping track of aircraft is a big challenge because traditional radar systems are not always available. Setting up radar requires a lot of money, infrastructure, and maintenance, which makes it hard for many regions to afford. Without proper monitoring, unauthorized aircraft can fly undetected, which could be a serious security risk. Some of these aircraft may be used for illegal activities like smuggling, while others might be operating without proper clearance. Governments and security agencies need a reliable way to detect these planes, but existing radar systems are often too expensive or impractical to install in remote locations.

Our project is designed to solve this problem in a more affordable and efficient way. Instead of using active radar, which sends out signals to detect aircraft, our system passively listens for signals that planes naturally emit. This method makes it harder for unauthorized aircraft to hide or interfere with the detection process. By using commercial off-the-shelf components, we can keep costs low while still creating a system that works well. The system will also be connected to Starlink SATCOM, allowing real-time transmission of detected aircraft data to a secure online platform where authorities can access it from anywhere in the world. This means that security teams don't have to be near the detection units to see the data—they can monitor everything remotely.

The project is being developed in two main phases, each with different responsibilities. In the first phase, another group is building and testing the aircraft detection hardware. This includes setting up RF receivers and antennas that will listen for aircraft signals and developing a program that can recognize and classify those signals. Their job is to make sure the detection system works and can reliably identify aircraft. Our team is focused on what happens after the detection process—making sure multiple detection units can work together.

In the second phase, our team takes the working detection units from the first phase and expands them into a larger system. Instead of just one unit detecting aircraft, we will deploy multiple units over a wide area and ensure they all communicate with each other. This is important because a single detection unit can only confirm that an aircraft is nearby, but multiple units working together can determine the exact location of the aircraft. Our job is to develop the networking and coordination system that allows these units to share data in real time. We will also create software that processes this information, using multiple signals to calculate the aircraft's position. Another key part of our work is testing and optimizing the system to ensure it works well in different environments.

Additionally, we will develop a centralized monitoring platform that will allow security teams to track detected aircraft, view alerts, and analyze movement patterns. This platform will act as a user-friendly interface where all detection data is displayed in one place. To make sure the

system is reliable, we will also create failover mechanisms, meaning that if one unit stops working, the other units will still function without disruption.

By the end of the second phase, our system will be able to detect aircraft, determine their exact location, and send this information in real-time to security teams. Compared to traditional radar, our solution is cheaper, harder to detect, and requires less maintenance, making it ideal for use in remote areas. Because it can be easily expanded by adding more detection units, it provides a flexible and scalable way to monitor large regions.

Looking ahead, this system could be expanded to monitor entire borders or other high-security areas where radar is not practical. If successful, it could provide an affordable alternative to expensive radar-based systems while still offering highly accurate aircraft tracking. By combining passive RF detection, multi-unit coordination, and real-time satellite communication, our project aims to improve aircraft monitoring in areas that currently lack proper surveillance.

2.2 Existing Products

2.2.1 General Applications

Active Radar Systems:

- Traditional active radar systems are easily detectable through many different methods.
- While they provide excellent detection, their detectability will hinder the usefulness of the device for detecting enemy aircraft.

Commercial RF Monitoring Devices:

- Existing RF monitoring tools inspired the use of Digital Signal Processing (DSP) and machine learning algorithms for accurate signal classification and a low false-positive rate.
- However, these commercial tools are not designed for scalable border monitoring, which is a unique aspect of this project.

Satellite Communication Solutions:

- Current surveillance systems often lack real-time global access.
- By incorporating Starlink SATCOM, this project ensures that detection data is instantly accessible from anywhere, making it more versatile and scalable than many existing solutions.

2.2.2 Proprietary Applications

Raytheon - Silent Sentry:

- Raytheon's Silent Sentry is a passive radar system similar to the one we are trying to design.
- It uses the same application of passive RF analysis to detect aircrafts and flights, with a proprietary focus on surveillance and monitoring.
- The biggest downfall of Silent Sentry is that it is not commercially available, and it requires a "headquarters" or central operation point.
- Additionally, it is not expandable, with no access to Starlink for widespread use.

FlightAware Global:

- This system is less similar than the Raytheon Silent Sentry, as it is not passive. However, the communications side of this system is more in-line with our design.

- FlightAware Global uses ADS-B, which is compulsory of the aircrafts to give. This means that dangerous or uncooperative flights are not detected by this system.
- The big plus for this system is its UI and modularity, allowing many users to access the info once the aircrafts are detected.

2.2.3 Comparison of Our Design to Available Products

Our design stands out from existing solutions due to its affordability, flexible access via Starlink communication, modular expandability, and fully passive detection capabilities. Unlike traditional active radar, our system eliminates the need for active signal transmission, making it undetectable and ideal for covert surveillance applications.

As we move into phase two, our system's advantage becomes even more pronounced. By incorporating multiple detection nodes, we enable triangulation for more precise information regarding the aircraft location—a feature lacking in many existing passive detection systems. This provides a scalable, border-monitoring solution that is both cost-effective and globally accessible.

Additionally, our design helps to bridge the gap between high-end proprietary solutions like Raytheon's Silent Sentry and commercial RF monitoring tools by offering a modular, expandable network without requiring a centralized headquarters. Unlike FlightAware Global, which relies on ADS-B transmissions, our system can detect uncooperative or hostile aircraft without requiring their participation in signal broadcasting.

This second-phase development transforms our project from a simple detection tool into a robust, networked surveillance system, capable of monitoring large areas with high accuracy and minimal infrastructure requirements.

2.3 Goals and Objectives

2.3.1 Basic Goals

The primary goal of our project is to integrate multiple passive aircraft detection units into a unified system capable of determining the general location, speed, and direction of detected aircraft. This phase builds upon the initial prototype by ensuring all units function together effectively in a networked array, utilizing passive RF detection and real-time data transmission via Starlink SATCOM.

- Deploy an array of multiple detection units to collectively determine aircraft location and movement.
- Establish real-time communication between all units and a base station via Starlink SATCOM.
- Ensure the system operates independently with a solar power supply for remote deployments.
- Utilize commercially available, low-cost components to maintain affordability and scalability.
- Conduct extensive field tests to verify detection accuracy and overall system reliability.

This phase ensures that a multi-unit detection system can accurately track aircraft movement in areas without traditional radar coverage. The use of passive RF detection and commercial

off-the-shelf (COTS) components makes this system an affordable alternative to high-cost radar infrastructure, while Starlink SATCOM guarantees global accessibility of the detection data.

2.3.2 Advanced Goals

Once the basic system is operational, the next phase of development will focus on optimizing performance, refining detection capabilities, and improving system durability. These enhancements will increase system effectiveness and reliability over extended periods of use.

- Improve detection accuracy through refined signal processing techniques and data fusion.
- Optimize unit placement and coverage area to enhance aircraft tracking precision.
- Implement error-detection and correction methods to improve data reliability.
- Develop a modular hardware and software design to support future upgrades.
- Increase system efficiency by reducing power consumption and enhancing solar integration.

These improvements will ensure the system operates reliably in real-world conditions and can be scaled up for larger deployments. By refining data processing and optimizing energy efficiency, the detection network will become more robust, minimizing false positives while maximizing tracking accuracy.

2.3.3 Stretch Goals

Beyond the required system capabilities, additional features may be explored to improve long-term system performance and adaptability. These goals focus on increasing automation, security, and future scalability.

- Implement automated self-calibration and unit synchronization for simplified deployment.
- Enhance system durability for sustained operation in harsh environments.
- Develop predictive tracking algorithms to estimate aircraft movement based on detection patterns.
- Strengthen data security protocols to protect transmitted and stored information.
- Explore future expansion by integrating additional detection technologies or alternative communication methods.

These stretch goals are not necessary for initial system deployment but would enhance the detection network's longevity, adaptability, and efficiency. The ability to predict aircraft movement and self-calibrate will reduce manual intervention, making the system more user-friendly and scalable for broader applications.

2.3.4 Objectives

- Passive Detection Implementation
- Each unit will use software-defined radios (SDRs) and RF receivers to detect aircraft signals like ADS-B. Digital signal processing (DSP) will filter noise and extract relevant data for classification.
- Real-Time Communication Implementation
- Detection data will be transmitted via Starlink SATCOM to a base station. Units will send timestamped data packets for real-time tracking through a web-based interface.
- Aircraft Positioning and Data Fusion

- Detection units will synchronize via GPS-disciplined clocks for accurate time difference of arrival (TDOA) calculations. A data fusion algorithm will refine aircraft positioning and estimate speed and direction.
- Power and Remote Deployment

Units will be solar-powered with battery storage, housed in weather-resistant enclosures. Power efficiency will be optimized to extend operational longevity.

2.4 Features and Functionalities

2.4.1 Design Implementations

- Passive Detection: The system passively "listens" for RF emissions from aircraft, eliminating the need for active radar signals. This reduces costs and energy consumption compared to traditional radar systems.
- Starlink SATCOM Integration: Detected data is transmitted via the Starlink satellite communication network to a live-streaming website, enabling global monitoring and analysis.
- Digital Signal Processing (DSP) and Machine Learning: Advanced DSP techniques and machine learning algorithms are employed to analyze RF signals, ensuring high accuracy (>95%) and a low false-positive rate (<5%).
- Scalable Deployment: The system design supports scalability, allowing for arrays of sensors to cover vast remote areas effectively.
- Ease of Setup: A plug-and-play setup process ensures quick and seamless deployment in under one hour.
- Durability: Weatherproof enclosures and solar-powered operations enhance reliability, enabling a lifespan of over 10 years in remote and harsh conditions.

2.4.2 Customer Input

- Affordability: Customers in remote areas, particularly governments or agencies with limited budgets, emphasized the importance of keeping costs low while maintaining functionality. This directly influenced the decision to use Commercial Off-The-Shelf (COTS) components, ensuring ease of access and a unit cost under \$8,000.
- Ease of Use: End users requested a system that does not require extensive training or specialized skills for setup and operation. This led to the implementation of an entirely self-sufficient design to minimize maintenance.
- Reliability in Harsh Environments: Stakeholders working in remote and extreme conditions needed a system that could withstand tough weather. This prompted the integration of weatherproof enclosures and solar-powered functionality to enhance durability.

2.5 Specifications

2.5.1 System Specs

Table 2.1 System Specifications

Parameter	Specifications	Description
Cost	< \$8000 USD	Cost for single unit will not exceed this price
Bandwidth	9kHz - 3GHz	The bandwidth of signals detected and analyzed by the processor
Power Generation	> 100W	Power Supply output for the system
Battery Life	9-10 months	Time for which the battery can sustain before being replaced
System Accuracy	> 95%	Detects the presence of at least 95% of aircrafts that pass through the operational region
Time to detect aircraft and process data	<10s	Time from aircraft passing over node to data transmitted to base station
Localization Density	2–10km	Maximum recommended spacing for full coverage of detection zone to allow localization
Node Range	4km	Radius of detection for each node
Unit Dimensions	$\leq 1\text{m} \times 1\text{m} \times 1\text{m}$	Dimensions per unit (excluding battery and solar panel)
Unit Weight	$\leq 25\text{ kg}$	Weight per unit

2.5.2 Component Specs

Table 2.2 Component Specifications

Component(s)	Parameter	Specifications
Wideband Antenna	Frequency Range	300 - 3000MHz
	Antenna Gain	$\geq 6\text{ dBi}$
RF Spectrum Analyzer	Frequency Range	9kHz - 6GHz
	Noise Level	$\leq 2\text{ dB}$
Detection Software	Latency	< 1S for local processing < 5S for cloud transmission
Solar Panel	Power Output	100W

Starlink SATCOM	Encryption	AES-256
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2.6 House of Quality

The House of Quality for the Low-Cost Passive Aircraft Detection System clearly maps customer requirements to measurable engineering specifications, facilitating a structured approach to product development. The matrix is centered around aligning five primary customer needs—Affordability, Ease of Use, Real-Time Monitoring, Energy Efficiency, Reliability, and Adaptability to Region—with critical engineering metrics like Cost, Power Consumption, Localization, Detection Software, Time to Detect, Bandwidth, and System Accuracy.

Affordability strongly influences cost, as indicated by the black circle, showing a strong correlation. The goal is to stay below the \$8,000 target, which ensures the system remains accessible for wide-scale deployment, particularly in developing or remote areas. This is supported by using COTS components and open-source software.

Ease of Use relates moderately to system software and detection time. The project targets a plug-and-play design that enables setup in under one hour. The software interface is designed to be intuitive, reducing the learning curve and ensuring non-specialists can operate the system effectively in the field.

Real-Time Monitoring has direct connections to detection software, bandwidth, and system accuracy. The system aims to capture, process, and transmit aircraft signals in near-real-time, leveraging digital signal processing and cloud integration via Starlink. Bandwidth allocation and efficient data compression are optimized to maintain fast and secure updates without overwhelming the system.

Energy Efficiency is tied closely to power consumption and detection software. The system employs solar-powered operation with intelligent sleep cycles and lightweight edge computing to reduce energy draw. This ensures 24/7 functionality in isolated locations where grid power is unavailable.

Reliability shows strong relationships with localization and system accuracy. Using techniques like Time Difference of Arrival (TDoA) and signal triangulation from multiple RF nodes, the system can pinpoint aircraft locations with a target accuracy exceeding 95%. Environmental durability and weatherproof housing ensure long-term reliability.

Adaptability to Region is related to all engineering characteristics to some extent. The design is modular, scalable, and climate-resilient—able to be deployed in forests, deserts, coastlines, or mountainous regions without requiring region-specific redesigns.

At the top of the matrix, correlations between engineering characteristics are explored. For example, improving accuracy might increase cost or power consumption, so trade-offs must be considered carefully during design optimization. Positive and negative correlations are marked to guide these design decisions.

This House of Quality ensures that customer expectations drive technical priorities while allowing for traceability from requirements to design metrics, ensuring that all engineering decisions are justified and aligned with the intended mission.

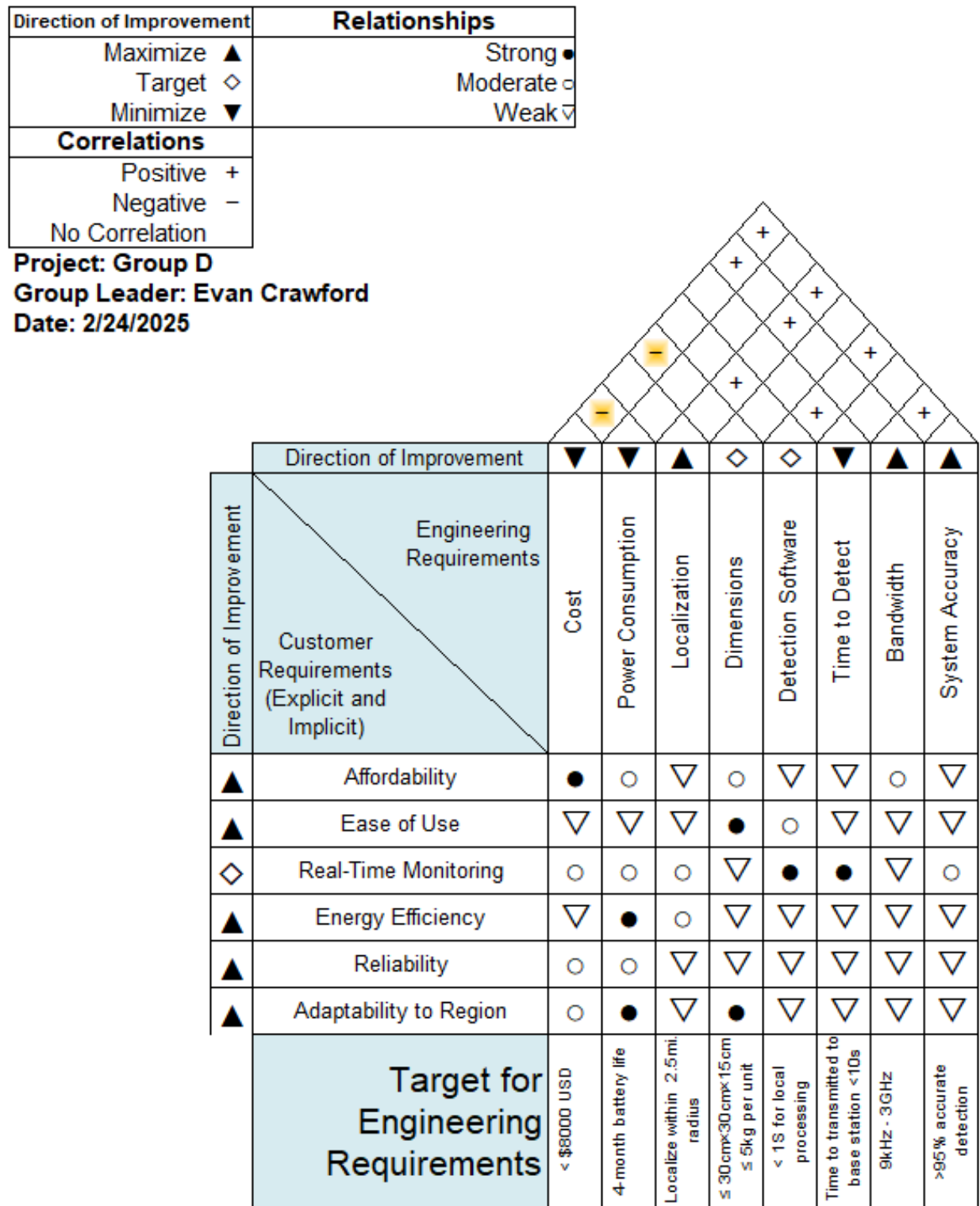


Figure 2.1 House of Quality Diagram

2.7 Block Diagrams

2.7.1 Hardware Block Diagram of Node Array

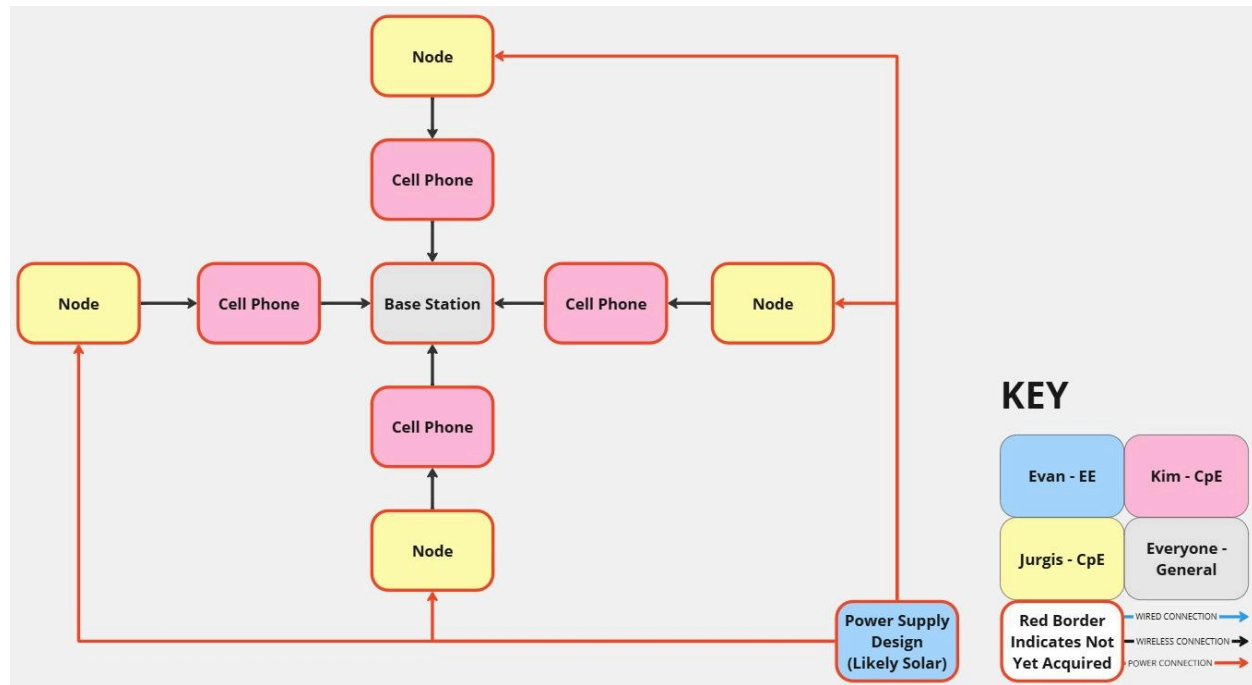


Figure 2.2 Hardware Block Diagram of Node Array

This block diagram shows the setup of phase two of our system, which consists of four nodes and the base station.

- The Base Station serves as the central hub, aggregating data from all the Nodes.
- The other nodes are connected to the base station via Cellular Device, enabling real-time data transmission and triangulation of location.
- Like in phase one, a laptop can access this data from anywhere worldwide, allowing for remote monitoring, via cellular services.
- The system is powered by a rugged power supply, likely solar-based, ensuring durability against harsh environmental conditions and reliability.
- Allows modular deployment across borders and other zones of interest.

Once multiple nodes are deployed in phase two, the system gains the ability to track the location of a detected aircraft through triangulation. Each node detects the same aircraft signal at slightly different times due to the varying distances between the aircraft and each node. By measuring these time differences of arrival (TDOA) or signal strength variations, the system can estimate the aircraft's location. This setup expands on phase one, allowing precise location data, modularity within the system, and long-term setup due to the power supply.

2.7.2 Hardware Block Diagram of Individual Node

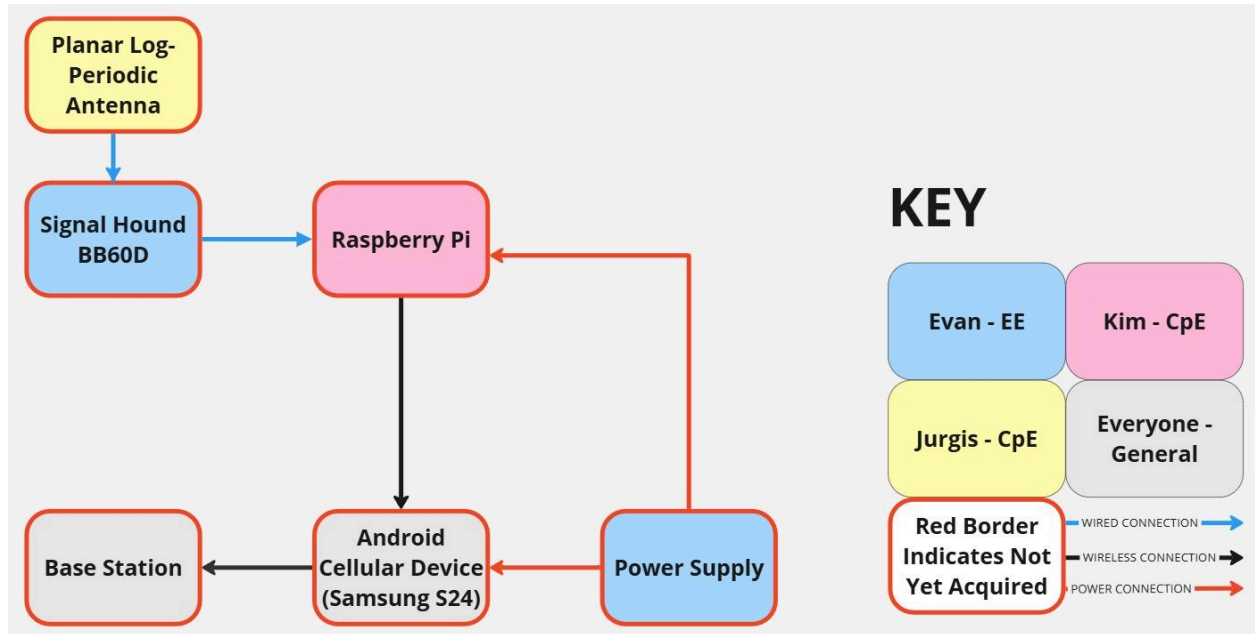


Figure 2.3 Hardware Block Diagram of Individual Node

The block diagram represents the nodes used in phase two of the passive aircraft detection system. This setup is responsible for detecting the presence of an aircraft, and when combined with other units, will be the main conduit of information to the base station. The primary components are:

- Planar Log-Periodic Antenna → Captures radio frequency signals from aircraft.
- Signal Hound BB60D → A software-defined radio that processes incoming signals and sends data to the Raspberry Pi for analysis.
- Android Cellular Device (Samsung S24) → Facilitates connectivity and data transfer. Ensures global data accessibility, allowing remote monitoring from a laptop or base station.

The core of the system is a Raspberry Pi, which serves as the central processing unit, aggregating data from the RF antenna. Because this will be completed in phase one, we do not need to focus on the specifics of this phase beyond understanding how it feeds into later multi-node deployments. This setup will validate basic detection capabilities before expanding into a network of nodes and connecting to the Cellular Device for global access.

2.7.3 Software Flow Chart:

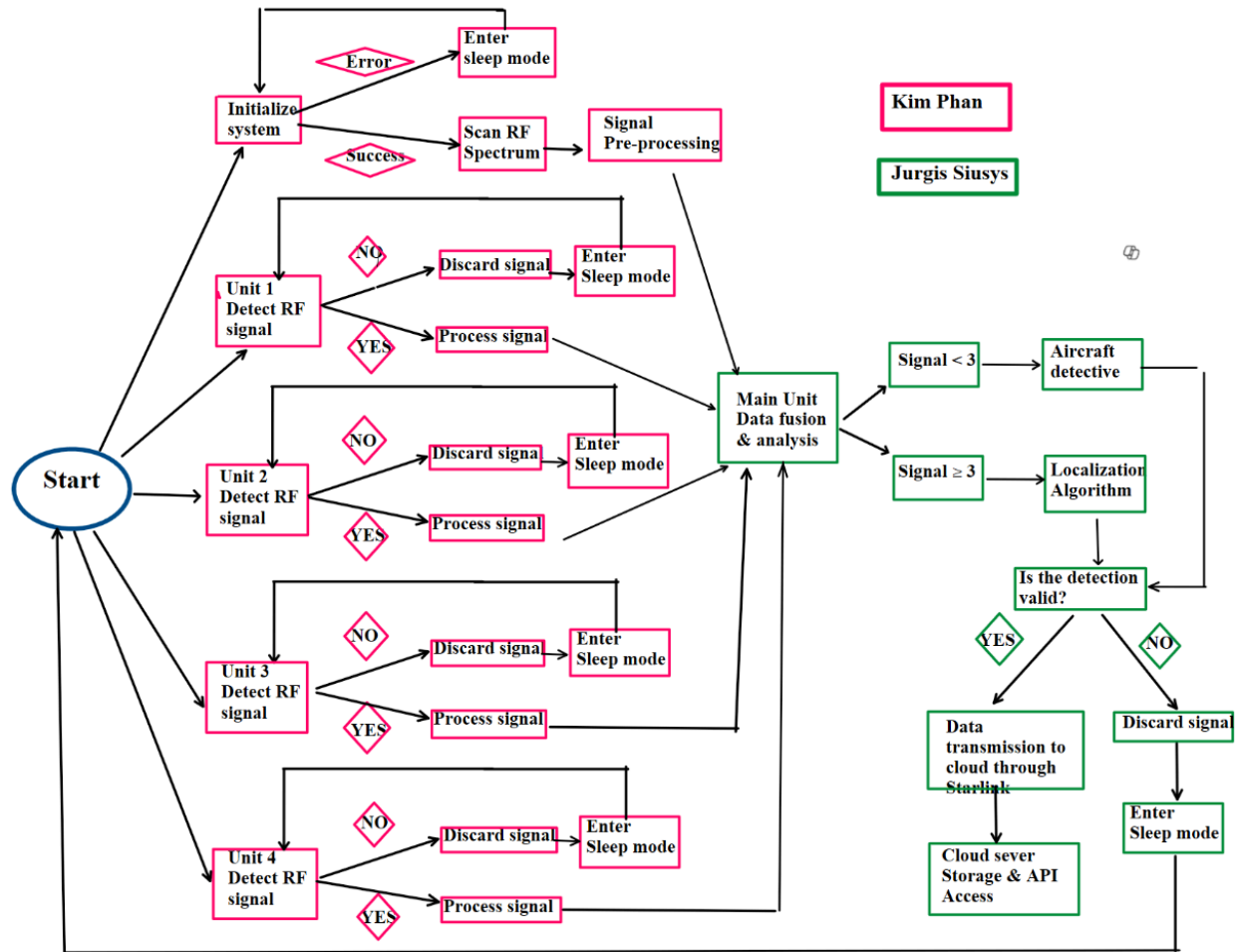


Figure 2.4 Software block diagram

This system consists of four sensor units arranged in a diamond formation around a central Main Unit. Each unit independently detects the same aircraft and transmits its measurements to the Main Unit, where the data is fused and analyzed to create an accurate aircraft profile. The Main Unit then sends the final aircraft detection report to the cloud via SATCOM, where it can be accessed by users in real-time. The system also includes a sleep mode for power efficiency, where it turns off unnecessary functions when no aircraft signals are detected.

2.7.3.1. System Initialization

- The system begins operation from the Start node.
- It first proceeds to the "Initialize System" process, where it checks for hardware readiness and ensures all components are functional.
- Decision:

If an error occurs, the system enters sleep mode to save power and prevent faulty operation.

If initialization is successful, the system proceeds to scan the RF spectrum for potential signals.

2.7.3.2. Signal Pre-Processing

- After scanning the RF spectrum, the system performs "Signal Pre-Processing", where it filters out noise and prepares the data for detection.
- The filtered signal is then forwarded to each of the four independent RF detection units.

2.7.3.3. Independent RF Signal Detection

- Each of the four RF detection units operates independently, detecting RF signals in the environment.

Per-Unit Decision Process:

Each unit detects an RF signal and makes a decision:

If NO, signal is detected: The unit discards the attempt and enters sleep mode to conserve energy.

If YES, a signal is detected: The unit processes the signal and forwards it to the Main Unit for Data Fusion & Analysis.

- This process ensures that each unit operates autonomously, reducing power consumption when no aircraft is present.

2.7.3.4. Data Fusion & Analysis in the Main Unit

- The Main Unit collects and processes data from all active detection units.
- The system checks the number of valid signal detections received:

If less than 3 signals are detected: The system cannot determine aircraft presence accurately and categorizes it as "Aircraft Detected" for further checks.

If 3 or more signals are detected: The system runs a Localization Algorithm to determine the aircraft's exact position.

2.7.3.5. Validity Check for Detection

After running the Localization Algorithm, the system determines:

- If the detection is valid: The data is sent to the SATCOM Link, which transmits the processed detection data to the cloud.
- If the detection is invalid: The system discards the detection and enters sleep mode to conserve power.

2.7.3.6. Cloud-Based Storage & API Access

- If valid data is sent via SATCOM Link, it is transmitted to the Cloud Server for storage and further processing.
- The cloud server provides API access, allowing users or other systems to retrieve and analyze the detection data.

Chapter 3 Research and Investigation

3.1 Hardware Technologies

3.1.1 Central Processor

3.1.1.1 MPU vs. SBC

3.1.1.1.1. Pros and Cons of SBCs

Single Board Computers (SBCs) are compact, all-in-one computing devices that integrate a processor, memory, storage, and input/output interfaces onto a single board. They offer a cost-effective and energy-efficient solution for various applications, including embedded systems, IoT devices, and edge computing. SBCs are highly versatile and can run full operating systems like Linux, Android, or Windows, allowing them to support a wide range of applications. They provide higher processing power than microcontrollers (MCUs), making them suitable for tasks like real-time data analysis, multimedia processing, and AI applications. SBCs also feature multiple connectivity options, including Wi-Fi, Bluetooth, Ethernet, and USB, enabling seamless integration with other devices and cloud services. Additionally, their compact size and low power consumption make them ideal for portable and remote applications.

Despite their advantages, SBCs have some limitations. They typically consume more power than MCUs, making them less suitable for ultra-low-power applications. Unlike traditional computers, they often have limited upgradeability, meaning users are restricted to the built-in CPU and memory. Additionally, SBCs require an external power source and storage (such as an SD card or eMMC), which can introduce additional failure points. For real-time processing applications, SBCs may lack the low-latency performance required compared to dedicated MCUs or FPGAs. Finally, while SBCs are more affordable than full-fledged computers, higher-end models can be costly, especially when additional components like cooling systems or external peripherals are needed.

3.1.1.1.2. Pros and Cons of MCUs

MCUs are highly integrated and self-contained, meaning they include a CPU, RAM, Flash memory, and I/O peripherals on a single chip. This integration makes them compact, power-efficient, and cost-effective, which is ideal for applications that need to run autonomously in remote locations. They consume very little power, making them perfect for battery-powered or solar-powered systems, like our aircraft detection project. Additionally, many modern MCUs come with built-in DSP (Digital Signal Processing) capabilities, allowing them to handle signal processing tasks efficiently without needing an MPU.

However, MCUs have limited processing power compared to MPUs. They typically run at lower clock speeds (tens to hundreds of MHz) and have limited memory, which can be a drawback for projects that require complex data analysis or multitasking. Additionally, because MCUs run

bare-metal code or lightweight RTOS (Real-Time Operating Systems), they lack support for full operating systems like Linux or Android, which MPUs can run.

3.1.1.1.3. Why SBC could be a best fit?

After evaluating the requirements of our passive aircraft detection system, our group decided that a Single Board Computer (SBC) would be the best fit for our project. While Microcontrollers (MCUs) offer ultra-low power consumption and real-time processing, they lack the computational power, multitasking capabilities, and extensive connectivity options required for advanced signal processing, data fusion, and cloud integration. Since our system needs to handle complex RF signal analysis, transmit data over networks, and support potential AI-based enhancements, an SBC provides the necessary balance of power and flexibility without excessive energy consumption.

One of the key reasons for our choice is that SBCs support full operating systems, allowing us to utilize multithreading, advanced networking protocols, and high-speed data storage. Unlike MCUs, which have limited memory and processing power, SBCs like the Raspberry Pi 4, Raspberry Pi Zero W, or similar models enable real-time signal filtering, data processing, and seamless communication with cloud servers. The availability of built-in Wi-Fi, Ethernet, and USB interfaces ensures reliable data transmission, which is crucial for remote deployment where network stability may vary.

Our group believes that SBCs strike the right balance between processing power, energy efficiency, and ease of integration. They allow for scalability, meaning that as our detection system evolves, we can incorporate machine learning algorithms, automated data analysis, and enhanced visualization tools without the need for extensive hardware changes. By choosing an SBC, we ensure that our system remains cost-effective, adaptable, and optimized for long-term use while still maintaining the performance necessary for real-time aircraft detection in remote environments.

3.1.1.1.4. Choosing between MCU and SBC

Developing a low-cost passive aircraft detection system for remote areas requires selecting the right processing unit to balance cost-efficiency, accuracy, and performance. Both MCUs and SBCs have their advantages, but the decision depends on the complexity of signal processing, power constraints, and scalability needs.

While MCUs are excellent for low-power, real-time applications, MCUs provide the necessary computational power and flexibility to handle advanced data processing, AI, and cloud-based enhancements. The table below compares MCUs and MPUs across key features, helping us determine why an SBC is the optimal choice for our project.

Table 3.1 Comparison between MCU and SBC

Feature	MCU ((Microcontroller Unit)	SBC (Single Board Computer)
Integration	Includes CPU, RAM, Flash storage, I/O peripherals on a single chip.	A complete computing system on a single board with CPU, RAM, storage, and I/O controllers.
Processing Power	Low to Medium (Tens to hundreds of MHz). Optimized for real-time processing	High (Above 1 GHz). Designed for multitasking and running complex applications.
Power Consumption	Very low (mW to a few watts). Optimized for battery-powered applications.	Higher (W to tens of watts). Requires a stable power supply and may need cooling.
Operating System	No OS or runs Real-Time Operating System (RTOS) like FreeRTOS, Zephyr.	Supports full OS like Linux, Android, Windows Embedded.
Programming Languages	Primarily C, C++, Assembly, and MicroPython for real-time control.	Supports Python, Java, C++, Go, Linux-based tools for high-level computing.
Memory & Storage	Fixed, built-in RAM and Flash storage (e.g., 64KB-512KB RAM, 256KB-2MB Flash).	Uses external RAM and storage (e.g., DDR4 RAM, eMMC, SD card, or SSD).
Communication Protocols	I ² C, SPI, UART, CAN (lightweight, low-power communication).	Supports high-speed data transfer and networking like Ethernet, Wi-Fi, USB, PCIe, and MIPI.
Use Case	Best for IoT, automation, motor control, medical devices, and low-power embedded systems.	Best for industrial automation, AI, multimedia, networking, and complex computing.
Real-time Processing	Designed for real-time applications, ensuring low latency.	Not optimized for real-time tasks, but supports multithreading and high-level computation.
Multitasking	Limited to simple control loops and task switching.	Supports multitasking, runs multiple applications simultaneously.
Peripheral Control	Optimized for direct hardware control (e.g., sensors, motors, displays)	Handles complex peripherals like cameras, touchscreens, GPUs, and multimedia

		interfaces.
Ease of Use	Easier to program and deploy with simple hardware requirements.	More complex, requires OS configuration and software drivers.
Cost	Low cost (\$1-\$15 per unit), minimal external components needed.	Higher cost (\$20-\$200 per unit), requires additional components.
Example Devices	Arduino (ATmega328), ESP32, STM32, PIC16F, MSP430.	Raspberry Pi (Broadcom), Qualcomm Snapdragon, Intel Atom, NXP i.MX.
Power Supply Requirement	Can run on low power (coin-cell batteries, USB, small power supplies).	Requires high power (dedicated power supply, battery packs, high-current sources).

After evaluating the requirements of our passive aircraft detection system, we have chosen to use a Single Board Computer (SBC) over a Microcontroller Unit (MCU). While MCUs offer low power consumption and real-time processing, they lack the computational power, multitasking capabilities, and advanced connectivity required for processing RF signals, transmitting data, and integrating cloud-based analytics. An SBC, such as the Raspberry Pi 4 or Raspberry Pi Zero W, provides the processing speed, operating system support, and networking options necessary for seamless data analysis and remote monitoring. Additionally, its ability to run Linux-based applications, handle large-scale data processing, and support AI-driven detection algorithms makes it a more suitable choice for the evolving needs of our project. With scalability, flexibility, and cost-effectiveness in mind, selecting an SBC ensures that our system remains powerful, adaptable, and optimized for real-time aircraft detection in remote environments.

3.1.1.2 SBC Selection

3.1.1.2.1. Raspberry Pi Series

In our project, we research and evaluate different models of Raspberry Pi to determine their suitability for RF signal processing, aircraft detection, and real-time data transmission. Each Raspberry Pi model offers unique advantages depending on our requirements for processing power, connectivity, power efficiency, and scalability. Below are some key models from the Raspberry Pi series that we consider for our system:

The Raspberry Pi series has evolved significantly from its first-generation Model 1 to the latest high-performance Model 4, making it a versatile platform for various computing applications. Each model in the series has introduced enhanced processing power, improved connectivity, and greater memory capacity, making Raspberry Pi a powerful yet cost-effective solution for embedded and IoT-based projects. Given our project's need for real-time RF signal processing, remote connectivity, and cloud-based data analysis, the Raspberry Pi stands out as an ideal choice for our passive aircraft detection system.

The Raspberry Pi Model 1 was the first-generation board designed for education and basic computing, featuring a 700 MHz single-core ARM11 processor and 256MB or 512MB RAM. It introduced basic USB, HDMI, and Ethernet (Model B only) connectivity, making it useful for DIY electronics and embedded applications. Although its processing power was limited, it laid the foundation for affordable computing and IoT development.

With the Raspberry Pi 2, significant performance improvements were introduced. It featured a quad-core ARM Cortex-A7 processor (900 MHz) and 1GB of RAM, making it far more capable for multitasking and general computing. It retained the 40-pin GPIO layout, ensuring compatibility with various peripherals. This upgrade allowed it to handle more advanced applications, such as robotics, media streaming, and IoT solutions, while still being energy-efficient.

The Raspberry Pi 3 further enhanced connectivity by incorporating built-in Wi-Fi and Bluetooth 4.2, eliminating the need for external adapters and making it an excellent platform for IoT and cloud-based applications. Its quad-core ARM Cortex-A53 processor (1.2 GHz – 1.4 GHz in Model B+) and 1GB of RAM allowed for smoother performance in industrial automation, home automation, and lightweight web servers. The Model B+ version introduced faster Ethernet and improved thermal efficiency, making it reliable for long-term deployments.

The Raspberry Pi 4 Model B represents the most significant advancement in the Raspberry Pi lineup, making it a powerful alternative to traditional computers and high-performance embedded systems. It features a quad-core ARM Cortex-A72 processor (1.5 GHz) and multiple RAM options (2GB, 4GB, and 8GB LPDDR4-3200), providing greater flexibility for memory-intensive applications. It also introduces dual micro HDMI ports supporting dual 4K displays, Gigabit Ethernet, USB 3.0, and Wi-Fi 5 (dual-band 2.4 GHz / 5.0 GHz), significantly enhancing networking, data transfer speeds, and overall performance.

For our passive aircraft detection system, Raspberry Pi is an excellent choice due to its scalability, affordability, and performance capabilities. The Raspberry Pi 4 Model B is particularly suited for real-time RF signal processing, cloud-based data integration, and AI-driven analytics, enabling us to detect, process, and transmit aircraft detection data efficiently. Its high-speed connectivity options ensure seamless communication with remote cloud servers, while its low power consumption compared to traditional computing systems makes it a cost-effective and sustainable solution.

Additionally, Raspberry Pi's support for Linux-based operating systems and programming languages such as Python, C++, and Java allows us to implement customized software solutions for data filtering, analytics, and remote monitoring. Its large community support ensures that we can continuously optimize and expand our system for future enhancements, such as machine learning-based detection, automated alerts, and improved sensor integration.

By leveraging the processing power, built-in connectivity, and software flexibility of Raspberry Pi, we ensure that our aircraft detection system remains efficient, scalable, and optimized for remote deployment. Its combination of performance, affordability, and adaptability makes it the ideal computing platform for our project.

3.1.1.2.2.Raspberry Pi Zero

Another option we can consider for our passive aircraft detection system is the Raspberry Pi Zero (Broadcom BCM2835, 1 GHz, 512MB RAM). Given its small size, lightweight design, and minimal power consumption, it serves as an excellent choice for low-power RF monitoring tasks, sensor-based data logging, and embedded remote detection units. Its compact form factor makes it easy to deploy in space-constrained environments, allowing us to set up secondary detection nodes in remote locations where power availability is limited.

The Raspberry Pi Zero W, an upgraded version with built-in Wi-Fi and Bluetooth, enhances our system by enabling wireless communication between detection nodes and central processing units like the Raspberry Pi 4 or Raspberry Pi 3. This makes it possible to transmit aircraft detection data efficiently without requiring wired connections, making it ideal for battery-powered or solar-powered units deployed in remote areas.

Although the Raspberry Pi Zero lacks the computational power for complex AI-driven detection or advanced signal processing, it remains highly useful for basic RF signal monitoring and initial data filtering before transmitting the processed data to a more powerful computing unit.

3.1.1.2.3.Raspberry Pi Compute Module Series

The Raspberry Pi Compute Module (CM) series is a specialized version of the standard Raspberry Pi designed for industrial and embedded applications. Unlike traditional Raspberry Pi boards, which come with standard USB, HDMI, and Ethernet ports, the Compute Module is a compact, stripped-down version that provides only the essential processing components while allowing custom hardware configurations via a custom carrier board. This makes it ideal for applications where size, power efficiency, and modularity are critical.

The Compute Module series includes various models, with each version corresponding to a standard Raspberry Pi counterpart. The Compute Module 4 (CM4), for example, is based on the Raspberry Pi 4 (Broadcom BCM2711) and features a quad-core Cortex-A72 processor, up to 8GB of RAM, optional eMMC storage, and PCIe connectivity for high-speed data transfer. Similarly, the Compute Module 3 (CM3) is based on the Raspberry Pi 3, offering a quad-core Cortex-A53 processor, making it suitable for less computationally demanding tasks while maintaining power efficiency.

One of the primary advantages of the Compute Module series is its flexibility in hardware design. Since it lacks built-in peripheral ports, developers can design custom carrier boards that meet specific application requirements, whether for automation, IoT, AI-based processing, or industrial control systems. Additionally, Compute Modules support long-term deployment, making them ideal for mission-critical applications that require reliability, durability, and consistent performance.

With its scalable performance, industrial-grade reliability, and customizable hardware support, the Raspberry Pi Compute Module series is widely used in embedded computing, robotics, machine learning, real-time signal processing, and automation systems, making it a powerful choice for complex and scalable projects.

3.1.1.2.4. Qualcomm Snapdragon

The Qualcomm Snapdragon series offers high-performance computing, AI acceleration, and efficient power management, making it a strong choice for AI-driven applications, industrial automation, and edge computing. However, while Snapdragon MPUs are widely used in mobile devices, IoT, and embedded systems, they are not the best fit for our passive aircraft detection system due to several factors.

Snapdragon processors such as the 8cx, 865, 888, and 820E series are designed primarily for high-performance, power-hungry applications, including smartphones, gaming devices, and AI-enhanced computing. While they provide advanced AI capabilities and high-speed connectivity, they require complex power management and additional external components, making them less suitable for energy-efficient, long-term remote deployment.

For our project, which focuses on real-time RF signal processing and remote data transmission, Snapdragon MPUs introduce unnecessary complexity. Unlike SBCs like the Raspberry Pi, which offer a fully integrated computing platform with OS support, storage, and peripheral connectivity, Snapdragon MPUs require extensive hardware customization and software optimization, increasing development time and costs. Additionally, their high processing power and advanced GPU capabilities are excessive for our low-power, lightweight aircraft detection system that does not require intensive graphics rendering or mobile AI acceleration.

While Qualcomm Snapdragon MPUs provide cutting-edge performance for AI, networking, and industrial applications, they do not align with our low-cost, energy-efficient, and scalable approach. Instead, choosing an SBC like the Raspberry Pi 4 ensures that we have the necessary processing power, wireless connectivity, and ease of integration without the added complexity and power demands of an MPU-based system.

3.1.1.2.5. NXP i.MX

The NXP i.MX series offers a range of high-performance MPUs designed for embedded systems, industrial automation, IoT, and AI-driven applications. These processors provide a balance of power efficiency, scalability, and secure computing, making them well-suited for real-time processing tasks like aircraft detection and RF signal analysis. However, despite their capabilities, they are not the most suitable choice for our project due to power consumption, complexity, and unnecessary high-end features.

The i.MX 6 series, with its integrated GPU and real-time visualization capabilities, is ideal for graphical interfaces and multimedia applications but is overly complex for our low-power, RF-based detection system that does not require extensive video processing or UI rendering. The i.MX 7 series, optimized for low-power IoT applications, offers parallel processing and power-efficient RF scanning, but it still introduces additional design complexity compared to a Single Board Computer (SBC) like Raspberry Pi, which provides a more integrated, ready-to-use solution.

The i.MX 8 series, built for AI, cloud-based analytics, and high-speed data fusion, includes advanced processing cores and high-speed interfaces like PCIe and USB 3.0, making it a strong choice for AI-driven industrial applications. However, these features are unnecessary for our system, which focuses on efficient RF signal detection and lightweight data processing.

Additionally, MPUs require custom PCB designs, external RAM, and specialized software development, making them less practical and cost-effective compared to off-the-shelf SBC solutions.

While the NXP i.MX series is powerful and versatile, it does not align with our low-cost, energy-efficient, and easy-to-deploy approach. SBCs like the Raspberry Pi offer a simpler and more efficient solution, providing sufficient processing power, built-in connectivity, and software flexibility without the additional complexity and overhead of an MPU-based design.

3.1.1.2.6. Intel Atom, Core, and Xeon

The Intel Atom, Core, and Xeon processor families offer high-performance computing for industrial automation, AI, and cloud-based applications, but they are not suitable for our passive aircraft detection system due to high power consumption, external hardware dependencies, and unnecessary computational complexity. The Intel Atom E3900 series, designed for industrial IoT and edge computing, provides real-time processing, multimedia support, and hardware-based security, making it ideal for smart city infrastructure and autonomous systems. However, its lack of built-in networking and complexity in deployment make it less practical than an SBC like the Raspberry Pi for our lightweight, energy-efficient system. The Intel Core i3, i5, i7, and i9 processors are designed for consumer and business computing, offering multi-core processing, AI acceleration, and high-speed performance. While they provide scalability from basic computing (i3) to high-performance AI workloads (i9), they require external RAM, advanced cooling, and extensive power management, making them impractical for our remote, low-power aircraft detection system. The Intel Xeon D and Scalable Processors, built for enterprise applications, are optimized for AI, deep learning, and cloud analytics. The Xeon D series is used in edge computing and networking, while Xeon Scalable Processors are designed for large-scale AI training and predictive analytics. However, their complex infrastructure requirements, high power demands, and reliance on extensive data center environments make them unsuitable for our cost-effective, energy-efficient solution. While these Intel processors offer exceptional performance for AI and industrial applications, they do not align with our project's goals. Instead, an SBC like the Raspberry Pi 4 provides the right balance of processing power, built-in connectivity, and affordability, making it the best fit for our passive aircraft detection system.

3.1.1.2.7. Texas Instruments Sitara

The Texas Instruments Sitara series offers high-performance ARM-based MPUs designed for industrial automation, IoT, and AI-driven applications. With multi-core processing, real-time industrial communication, and AI acceleration, Sitara processors like the AM335x, AM437x, and AM57x series are ideal for mission-critical systems requiring low-latency data processing and secure networking. However, despite its advanced features, it is not the best fit for our passive aircraft detection system due to higher complexity, external hardware requirements, and unnecessary AI processing capabilities.

The AM335x series, built on an ARM Cortex-A8 processor, is optimized for industrial networking, motor control, and IoT deployments but lacks built-in Wi-Fi and higher-level computing capabilities found in SBCs like the Raspberry Pi. The AM437x series, featuring a 1.5 GHz Cortex-A9 processor, offers better performance and secure boot features but is designed for networked industrial control and multimedia interfaces, making it unnecessary for our

lightweight detection system. The AM57x series, with quad-core Cortex-A15 processors and an integrated DSP, is overpowered for our project, as it is designed for AI-powered automation, real-time machine learning, and cloud-based analytics—all of which exceed our system's computational needs and power constraints.

While the Sitara MPUs provide excellent processing power, security, and industrial networking, they lack the ease of integration, affordability, and power efficiency required for our remote aircraft detection system. A Single Board Computer (SBC) like the Raspberry Pi 4 offers sufficient processing power, built-in networking, and simpler deployment, making it a more practical, cost-effective solution for our project.

3.1.1.2.8. SBC Comparison

Table 3.2 MPU Comparison by Authors

Feature	SBC (Raspberry Pi 4)	Qualcomm Snapdragon	NXP i.MX	Intel (Atom, Core, Xeon)	TI Sitara
Processing Power	Quad-core Cortex-A72 (1.5 GHz), suitable for lightweight AI and real-time processing	High-performance Kryo CPUs, AI acceleration, optimized for mobile computing.	Scalable from Cortex-A7 to Cortex-A72, good for industrial automation.	Varies: Atom (low-power), Core (high-performance), Xeon (enterprise-grade).	Ranges from Cortex-A8 (AM335x) to Cortex-A15 (AM57x) with DSP integration.
Power Consumption	Low (5V, ~3-5W), optimized for embedded and remote applications.	Moderate (optimized for mobile but still higher than SBCs).	Moderate to high, varies by series, some optimized for low-power IoT.	High (Core/Xeon consume significant power; Atom is more efficient but still higher than SBCs).	Moderate to high, varies by series, designed for industrial use.
Ease of Integration	Plug-and-play, pre-configured OS support (Linux, Raspbian).	Requires custom PCB design and external components	Needs external RAM, storage, and power management, increasing complexity.	Requires external power, RAM, and cooling, complex setup.	Requires custom hardware, industrial-specific configurations.

Connectivity	Built-in Wi-Fi, Bluetooth, Gigabit Ethernet, USB 3.0, dual HDMI.	Advanced 5G, Wi-Fi 6, Bluetooth, but requires additional integration.	Industrial communication protocols (CAN, SPI, I ² C, PCIe, Gigabit Ethernet).	High-speed connectivity with PCIe, Thunderbolt, Ethernet, but bulky.	Supports industrial networking (EtherCAT, CAN, PCIe, Gigabit Ethernet).
Real-Time Processing	Can handle lightweight real-time tasks with optimized programming but lacks dedicated real-time cores.	Optimized for multimedia and mobile AI, lacks dedicated RTOS support.	Some models include real-time cores (Cortex-M integration).	Xeon supports HPC and AI inference, but not optimized for embedded real-time systems.	Integrated DSP (AM57x) and PRU-ICSS enable industrial real-time control.
Software Support	Linux-based OS, supports Python, C++, AI frameworks like TensorFlow Lite.	Supports Android and Linux, but custom software development required.	Supports Linux, FreeRTOS, and Yocto, but needs customization.	Runs Windows, Linux, and AI frameworks, but overkill for embedded systems.	Runs Linux, TI-RTOS, and industrial frameworks, optimized for automation.
Cost	Affordable (\$35-\$100), includes all essential components.	Expensive (\$200+ for Snapdragon-based dev kits).	Mid-range (\$50-\$200), but needs additional components.	High (\$150-\$1000), depending on model.	High (\$100-\$500+), industrial-focused pricing.
Use Case in Our Project	Best fit for cost-effective, scalable, real-time RF signal processing.	Overpowered, designed for AI-driven mobile and high-speed computing.	Good for industrial automation, but adds complexity and cost.	Too complex and power-hungry for our lightweight, remote system.	Industrial-grade real-time control, but not necessary for our needs.

In conclusion, after comparing SBCs, Qualcomm Snapdragon, NXP i.MX, Intel Atom/Core/Xeon, and TI Sitara, we found that SBCs like the Raspberry Pi 4 provide the best balance of performance, power efficiency, ease of integration, and cost-effectiveness for our passive aircraft detection system. While MPUs offer higher processing power and industrial-grade features, they come with greater complexity, higher costs, and increased power

consumption, making them less suitable for our lightweight, remote deployment needs. The Raspberry Pi 4 ensures seamless real-time processing, built-in networking, and simple software compatibility, making it the most practical and scalable solution for our project.

3.1.1.3 SBC Selection

For our project, we require an SBC that balances processing power, scalability, energy efficiency, and cost-effectiveness. After evaluating various options, we have chosen the Raspberry Pi series, which is provided by our sponsor, as the best fit for our project. This sponsorship significantly reduces hardware costs, allowing us to focus on developing and refining our aircraft detection algorithms without worrying about budget constraints. Raspberry Pi SBCs offer a versatile platform with strong community support, a low-cost structure, and sufficient processing capabilities for real-time signal processing and cloud-based data transmission.

Specifically, models like the Raspberry Pi 4 (Broadcom BCM2711) and Raspberry Pi Compute Module 4 (CM4) provide quad-core ARM Cortex-A72 processors, delivering the necessary computational power for RF signal analysis, data fusion, and AI-driven detection enhancements. Unlike traditional MPUs, which require external memory and additional peripherals, Raspberry Pi integrates storage, networking, and GPIO support, making it an ideal choice for embedded applications and IoT-based deployments. Additionally, Raspberry Pi's compatibility with Linux-based operating systems enables us to leverage existing software tools, machine learning frameworks, and real-time data processing applications with minimal customization.

Another critical factor in our decision is expandability and connectivity. The Raspberry Pi 4 and Compute Module 4 support high-speed USB, PCIe interfaces, Gigabit Ethernet, and Wi-Fi 5, ensuring seamless integration with remote monitoring systems, cloud services, and external sensors.

By utilizing Raspberry Pi as our SBC, we ensure an efficient, cost-effective, and scalable solution that meets the real-time processing, and remote deployment needs of our passive aircraft detection system.

3.1.2. Antenna

The antenna plays a critical role in the success of our project, as it is responsible for capturing the RF signals emitted by aircraft in remote areas. To ensure effective and reliable detection, the antenna must meet specific criteria, including a wide frequency range to cover various aircraft communication and navigation signals, high directional gain for accurate localization, and durability for harsh environmental conditions. Additionally, ease of deployment and cost-effectiveness are key considerations, given the limited resources available for these remote installations. There are several types of antennas that could meet these requirements, including Log-Periodic Dipole Array (LPDA) antennas, Yagi-Uda antennas, dipole antennas, phased arrays, monopoles, and microstrip patches. Each type offers different advantages in terms of frequency range, size, and directivity, and selecting the most appropriate one is essential for ensuring the system's overall performance and scalability.

3.1.2.1 Choosing the Antenna

3.1.2.1.1. Log-Periodic Dipole Array (LPDA) Antennas

Log-Periodic Dipole Array (LPDA) antennas are ideal for detecting a wide range of RF signals emitted by aircraft due to their broad frequency reception capabilities. These antennas feature a series of elements arranged in a periodic structure, allowing them to cover a large spectrum of frequencies, typically ranging from 100 MHz to several GHz. The LPDA's excellent gain and directivity make it well-suited for passive RF detection systems, as it can efficiently capture signals from various aircraft communication systems, including VHF, UHF, and both civilian and military frequencies. Its directional nature further enhances the ability to pinpoint the source of signals, improving the accuracy of detection.

However, LPDA antennas have some limitations, such as their larger size, which could impact portability and ease of installation in remote locations. Additionally, to effectively cover a wide area, careful positioning may be required, which can add complexity to deployment. Despite these challenges, the LPDA antenna's wideband performance, high gain, and directional sensitivity make it an excellent choice for applications like aircraft monitoring in areas with limited radar infrastructure.

3.1.2.1.2. Yagi-Uda Antenna

The Yagi-Uda antenna is a highly directional antenna known for its high gain and narrow beamwidth, making it ideal for long-range signal reception. It excels at targeting specific aircraft RF signals over large distances, particularly in low-frequency bands commonly used by aircraft communication systems. Its compact design and ease of deployment make it well-suited for distributed sensor networks, where multiple antennas can be strategically placed for enhanced coverage. The Yagi-Uda antenna is effective at detecting particular signals, such as aircraft transponders, radar, and communication systems.

However, the Yagi-Uda antenna has some limitations. Its bandwidth is narrower compared to other options like the LPDA, which may require multiple antennas to cover a broader frequency range. Additionally, its directional nature means that careful alignment is essential to achieve optimal reception, making installation and maintenance a bit more challenging. Despite these constraints, the Yagi-Uda antenna remains a strong choice for applications requiring precise, long-range signal detection.

3.1.2.1.3. Dipole Antennas

A dipole antenna is one of the simplest and most cost-effective antenna designs, consisting of two conductive elements typically half a wavelength long. When used for passive RF detection, dipole antennas are suitable for applications such as monitoring aircraft communications, navigation, and surveillance signals. Their simplicity and low cost make them easy to construct with readily available materials, and they are relatively omnidirectional, providing good general reception over a broad area.

However, due to their simple design, dipole antennas experience some drawbacks when compared to the other antennae. Their directional capability is more limited compared to antennas like the LPDA or Yagi, resulting in lower gain and reduced detection range. Additionally, to ensure optimal reception, careful placement is required, particularly in remote areas where environmental factors may interfere with signal clarity. Despite these drawbacks,

dipole antennas are effective for detecting signals in specific communication bands such as VHF and UHF and remain a cost-effective option for simpler detection needs.

3.1.2.1.4. Phased Array Antennas

Phased array antennas are a more advanced antenna option that consists of a grid of individual antenna elements. The primary advantage of phased array systems is their ability to electronically steer the beam without physically moving the antenna. By adjusting the phase of the signal received by each element, the antenna can rapidly detect the location and direction of aircraft, providing flexible and precise coverage without the need for manual orientation.

However, phased array antennas come with some limitations. They are more complex and costly compared to simpler antennas like dipoles or Yagi, which may make them less suitable for budget-constrained applications. Additionally, they require advanced signal processing and specialized hardware to manage and interpret the data from multiple elements. Despite these challenges, phased array antennas offer exceptional precision, flexibility in target tracking, and high reliability in harsh environments, making them ideal for high-performance aircraft detection and tracking applications.

3.1.2.1.5. Monopole Antennas

A monopole antenna is a simple and cost-effective antenna that consists of a single conductive element mounted vertically. Known for its omnidirectional characteristics, monopole antennas are commonly used in applications that require 360-degree signal reception, including aircraft communication and navigation systems. When used for passive RF detection, monopoles can capture signals from aircraft across a wide frequency range, making them versatile for various monitoring tasks.

However, monopole antennas have some limitations. Their gain and directivity are lower compared to more specialized directional antennas, which can affect detection range and signal accuracy. Additionally, monopoles may struggle with sensitivity in noisy environments or when detecting aircraft at greater distances. Despite these drawbacks, their low cost, simple construction, and ease of installation make them ideal for budget-conscious systems and field deployments in remote or challenging locations.

3.1.2.1.6. Phased Array Antennas

Microstrip patch antennas are flat, low-profile antennas commonly used in compact systems for satellite communication and RF detection. Their lightweight and compact design make them ideal for integration into portable, low-cost sensor units, where space is limited. Microstrip patch antennas can be tailored to detect specific frequency bands, such as those used by aircraft communication and navigation systems, providing flexibility for specialized applications. Additionally, they are relatively low-cost and easy to manufacture using standard processes, making them an attractive option for budget-conscious projects.

However, microstrip patch antennas have some limitations. They typically offer lower gain than other antennas like LPDA or Yagi, which can reduce their detection range and precision. Furthermore, they are not as effective at wideband frequency reception, making them less

suitable for applications that require monitoring a broad range of frequencies. Despite these drawbacks, their compact size and customization options make them a solid choice for specific, space-constrained RF detection systems.

3.1.2.1.7. Antenna Comparison

Table 3.3 Antenna Types

Antenna Type	Frequency Range	Gain	Directional	Size	Advantages	Limitations
LPDA	Wide	High	Yes	Larger	Wide bandwidth, high gain	Larger size, complex positioning
Yagi-Uda	Narrow to medium	High	Yes	Moderate	High gain, long-range detection	Requires precise alignment
Dipole	Medium	Med	No	Small	Simple, low cost, omnidirectional	Lower range and gain
Phased Array	Wide	Very High	Yes	Larger	High precision, electronic beam steering	Complex, expensive
Monopole	Medium	Low	No	Small	Low cost, omnidirectional	Lower gain and range
Microstrip Patch	Narrow	Med	Yes	Very small	Compact, easy to integrate	Lower gain, limited range

LPDA antennas are the best fit for our design due to their ability to cover a wide frequency range. Aircraft emit RF signals across various frequencies, from VHF and UHF to more

specialized bands, and LPDA antennas are designed to capture this broad spectrum. This wideband capability ensures that our system can detect signals from a variety of aircraft systems without the need to switch or tune antennas for different frequencies, simplifying the detection process and ensuring lots of coverage.

In addition to their broad frequency range, LPDA antennas are directional with high gain, making them ideal for pinpointing aircraft locations along remote borders. Their directional nature allows them to focus on specific areas, improving signal detection accuracy and location estimation, which is crucial for monitoring aircraft in large, remote areas. This level of precision helps ensure that our system can effectively track aircraft, even in regions lacking conventional radar infrastructure.

Another advantage of LPDA antennas is their scalability. As our system expands in Phase 2, multiple detection units can be deployed using LPDA antennas to improve network coverage. By arranging these antennas in an array, the system can synchronize the units and enhance its ability to triangulate aircraft positions. This scalability is key for the success of a large-scale, distributed monitoring network.

Finally, LPDA antennas strike an excellent balance between performance and cost-effectiveness. While more expensive options, such as phased array antennas, offer higher performance, LPDA antennas provide a more affordable solution without compromising on the necessary sensitivity and directional capabilities. Their durability also makes them well-suited for deployment in harsh environmental conditions, ensuring long-term reliability in remote border areas. These factors make LPDA antennas a strong choice for our detection system.

3.1.2.2 Signal Hound BB60D Spectrum Analyzer

For our Low-Cost Passive Aircraft Detection System, we are using the Signal Hound BB60D Spectrum Analyzer, a decision made by our sponsor due to its performance and suitability for our specific needs. This high-performance, compact spectrum analyzer covers a frequency range from 9 kHz to 6 GHz, which is essential for detecting the wide variety of signals emitted by aircraft. Aircraft typically transmit signals in this frequency range, including navigation and communication signals, making the BB60D an ideal tool for our system. By utilizing this broad frequency coverage, we can ensure that our system captures and analyzes the relevant signals to track aircraft in remote regions.

One of the key advantages of the BB60D is its high dynamic range, which allows us to detect weak aircraft signals even in environments with high levels of RF interference. Since aircraft may transmit faint signals, especially when distant or operating at low altitudes, the BB60D's dynamic range ensures that even these signals are captured with high accuracy. This is particularly important for our system, as we need to reliably detect aircraft across large and potentially noisy areas.

The real-time spectrum analysis capability of the BB60D is another crucial feature for our project. This allows us to monitor and capture signals continuously, without having to rely on traditional sweep modes. The ability to analyze signals in real-time is essential for our passive detection approach, as it enables us to track aircraft movements as they occur. Additionally, the

BB60D's low noise floor further enhances its ability to detect weak RF signals, which is essential for our passive detection system to identify aircraft emissions, even when they are operating without strong signals.

Chosen for its portability and compactness, the BB60D is perfectly suited for deployment in remote areas, which is a core component of our system's design. Its small size and lightweight nature make it easy to transport and install, while its energy efficiency ensures that it can run continuously without excessive power consumption—important for our solar-powered system. The analyzer's compatibility with other hardware components, such as RF antennas and processors, makes it easy to integrate into our network of detection units.

For data analysis, the BB60D works seamlessly with SpectraVue, Signal Hound's software, which provides a comprehensive interface for signal analysis. This software offers advanced tools like spectral analysis and signal classification, which will allow us to efficiently process and interpret the data collected by the BB60D. Moreover, its integration with our Starlink SATCOM system ensures that real-time data can be transmitted to our centralized monitoring platform, giving security teams worldwide access to live detection data.

Ultimately, our sponsor's choice of the Signal Hound BB60D is an excellent fit for our aircraft detection system. It provides the necessary performance, reliability, and cost-effectiveness to make our system both scalable and efficient. By using this analyzer, we can ensure accurate and continuous monitoring of aircraft in remote areas while maintaining the affordability that is essential for the success of our project.

3.1.2.3 Setup with Spectrum Analyzer

If we are going to use an LPDA antenna, we must know how to connect it to our spectrum analyzer, specifically the Signal Hound BB60D. We want to use best practices to ensure proper signal transmission and minimal loss. Start by selecting an LPDA antenna that covers the frequency range of interest, such as 1090 MHz for ADS-B or the VHF aviation bands. The antenna should be positioned to maximize gain in the intended direction, ideally at an elevated location with minimal obstructions. We'll use a high-quality, low-loss coaxial cable like LMR-400 or RG-6 for shorter runs to reduce signal attenuation. Since the BB60D has an SMA (female) RF input, we may need an adapter if our LPDA antenna uses an N-type or other connector. Proper shielding and secure connections are essential to maintain signal integrity and prevent unwanted interference.

There's also additionally circuitry we can employ to boost our quality. To improve signal quality, a preamplifier (LNA) can be used to boost weak signals before they reach the spectrum analyzer. Additionally, if we decide to focus on a specific frequency range, a bandpass filter can help eliminate out-of-band noise and interference, improving signal clarity. Conversely, if the incoming signal is too strong, an inline attenuator (such as 10 dB) can prevent overloading the BB60D's input. The configuration of the spectrum analyzer in Signal Hound's Spike software is a key aspect of our research, with careful adjustments made to frequency range and resolution bandwidth (RBW) to balance detection accuracy and noise reduction. Enabling real-time spectrum analysis helps capture transient signals effectively as well.

Environmental and operational factors play a crucial role in the system's long-term functionality. Antenna placement must minimize external RF interference while maintaining a clear line of sight for optimal signal reception. For field deployments, weatherproofing the antenna and connectors is necessary to ensure durability in harsh conditions.

3.1.2.4 Antenna Selection

For our antenna, our sponsor has selected the Aventas Inc. Planar Log-Periodic Antenna 8 as the key component in the signal detection network. This antenna is designed to cover a wide frequency range, from 500 MHz to 8 GHz, making it well-suited for capturing the diverse range of signals emitted by aircraft. Aircraft typically operate in communication and navigation bands that fall within this frequency range, so the Planar Log-Periodic antenna is an ideal choice for ensuring comprehensive signal coverage in our system.

One of the key advantages of the Planar Log-Periodic Antenna is its ability to provide high gain across a broad range of frequencies, which enhances the detection capabilities of our system. Its wideband performance ensures that it can detect signals from various types of aircraft, whether they are using high-frequency communications or lower-frequency navigation systems. The antenna's directional nature also allows it to focus on specific regions of interest, improving the system's ability to pinpoint signals from aircraft even in environments with high levels of background noise.

The antenna is designed to be lightweight and compact, which is crucial for our remote and distributed deployment strategy. The system will be using multiple detection units spread across large areas, so the antenna's size and ease of installation make it a practical choice for integration into our solar-powered, energy-efficient system. Despite its small form factor, the antenna maintains high performance, which is important for ensuring the system's reliability in detecting aircraft signals over vast, challenging terrain.

Additionally, the Planar Log-Periodic Antenna 8 is weatherproof, which is essential for deployment in harsh environmental conditions. Our system is designed to operate autonomously in remote locations, where it could be exposed to extreme weather. The antenna's durability ensures that it will continue to function effectively, even in regions with harsh environmental conditions, thus supporting the long-term sustainability of the detection network.

The antenna's ability to provide stable and reliable signal reception across a wide range of frequencies makes it a key enabler of our system's passive detection capabilities. By coupling it with our Signal Hound BB60D Spectrum Analyzer and Starlink Mini Terminal, we can ensure that the signals detected by the antenna are analyzed, processed, and transmitted in real-time to our base station anywhere in the world. This combination of components allows us to create a comprehensive system capable of detecting aircraft in remote regions and providing timely, actionable data to security teams worldwide.

3.1.3 Android Cellular Phone Handset

For our project, an Android-based cellular phone handset will serve as a user interface for monitoring, managing, and interacting with system data. The phone will be used to display aircraft detection data, communicate with other system components, and provide real-time access

to system information. When selecting a handset, key factors include processing power, battery life, software compatibility, and network connectivity to ensure smooth and reliable operation.

This section evaluates three potential Android phone options—Samsung, Google Pixel, and Motorola—comparing their performance, usability, and suitability for our project’s needs. After analyzing these options, we will explain why the Motorola handset was chosen, as indicated in our tentative part list.

3.1.3.1 Samsung

Overview:

Samsung is one of the biggest names in the smartphone industry, known for making high-performance Android phones that come with powerful processors, high-quality displays, and advanced features. Their phones range from premium flagship models like the Galaxy S series to budget-friendly options in the Galaxy A lineup. Samsung devices run on One UI, which adds extra software features on top of Android, making them user-friendly and highly customizable (The Verge, 2023).

Pros:

- **Great Displays:** Samsung’s Super AMOLED and Dynamic AMOLED 2X displays are regarded as some of the best in the industry, offering vibrant colors, deep blacks, and high brightness levels. These displays enhance readability, especially outdoors, and support high refresh rates (up to 120Hz), providing smoother visuals and improved touch responsiveness.
- **Strong Performance:** Equipped with powerful chipsets and ample RAM (up to 16GB in flagship models), Samsung phones excel in multitasking, gaming, and running demanding applications. Their internal optimization ensures fast performance and efficient power consumption, even under heavy usage.
- **Smart Features & AI Integration:** Samsung integrates artificial intelligence in several areas, including adaptive battery usage, scene optimization in photography, and voice commands via Bixby. Features like DeX mode also allow users to connect their phones to monitors and use them as desktop computers, adding to their versatility.
- **Ecosystem Compatibility:** Seamless integration with other Samsung devices (TVs, wearables, smart appliances) enhances productivity and convenience through features like Samsung SmartThings and Link to Windows.
- **Durability & Innovation:** Many Samsung phones, especially flagships, come with IP68 water and dust resistance, Gorilla Glass protection, and even foldable screens in advanced models.

Cons:

- **Expensive:** Samsung's flagship phones like the Galaxy S24 Ultra or Z Fold series can be significantly more expensive than mid-range or budget devices, often exceeding \$1,000. This price point may not align with the cost constraints of our project, especially since advanced smartphone features are not critical to system performance.
- **Pre-Installed Apps (Bloatware):** Samsung devices frequently come pre-loaded with third-party apps and duplicate software (e.g., Samsung Internet, Samsung Email alongside Google’s equivalents), which can consume storage and occasionally affect

system performance. These apps may not be relevant to the project's use case and may require manual disabling or removal.

- **Overhead Features:** The range of smart features, while impressive, may introduce unnecessary complexity for users who only need the device for basic data access and monitoring functions.

Suitability for Our Project:

Although Samsung smartphones offer exceptional performance, display quality, and feature sets, they may be excessive for the needs of our aircraft detection project. The primary function of the handset is to act as a reliable and portable interface for accessing system data, managing device settings, and enabling communication via mobile or Wi-Fi networks. A Samsung flagship would exceed the necessary specifications and introduce avoidable cost overheads. Additionally, extra features and apps not needed for our task could introduce complexity or increase maintenance.

Given our focus on affordability, efficiency, and simplicity, a more cost-effective device like the Motorola Moto G 5G—which provides solid performance, long battery life, and a near-stock Android experience—is a more suitable choice. Therefore, while Samsung phones are undoubtedly capable and premium, they are not the optimal fit for this project's requirements from a practical and financial perspective.

3.1.3.2 Google Pixel

Overview

Google's Pixel smartphones are known for their clean Android experience, as they are developed and maintained directly by Google. This means faster software updates, better security, and no unnecessary pre-installed apps. One of the latest models, the Pixel 7, features a 6.3-inch OLED display with a 90Hz refresh rate, a Google Tensor G2 processor, 8GB of RAM, and storage options of 128GB or 256GB. It also has a 50MP main camera, 12MP ultra-wide lens, and a 10.8MP front camera, making it one of the best phones for photography. The 4,355 mAh battery supports fast charging and wireless charging, ensuring all-day battery life (GSMArena, 2023).

Pros:

- **Fast Software Updates:** Being the first to receive Android version upgrades and security patches ensures long-term device support and the latest features, which is critical for secure and stable system integration.
- **Smooth Performance:** The Google Tensor G2 chip, paired with a clean, unmodified Android OS, ensures fast, lag-free performance across apps, multitasking, and cloud-connected tasks.
- **Great Camera Quality:** Pixel phones are known for their class-leading photo quality thanks to Google's AI-powered image processing—ideal for documenting field deployments or capturing on-site setup for system validation.
- **Enhanced Security:** Pixel phones come with the Titan M2 security chip, designed to protect sensitive system data and ensure device integrity, which could benefit sensitive or field-based operations.

Cons:

- **No Expandable Storage:** The lack of a microSD card slot limits the ability to expand storage, which may be a concern if large amounts of media, sensor logs, or app data need to be stored offline.
- **Fewer Hardware Customization Options:** Unlike brands like Samsung or Motorola, Google offers fewer variants or form factors, which might limit flexibility in selecting a device that aligns precisely with budget or performance needs.
- **Higher Price Point:** Pixel devices tend to be priced at a premium, especially new models like the Pixel 7 or Pixel 7 Pro, which could strain a project budget—particularly when the handset’s full capabilities may not be necessary.

Suitability for Our Project:

Although the Google Pixel 7 offers exceptional performance, reliable software support, and robust security features, its higher price point and limited customization options may not align with the cost-efficiency goals of our passive aircraft detection system. Since the phone will primarily serve as an interface for accessing system data, performing remote diagnostics, and facilitating mobile communication, many of the Pixel’s high-end features—such as its camera capabilities and premium display—may be underutilized.

Additionally, the absence of expandable storage and fewer available hardware variants might limit flexibility if future project needs evolve. Given these constraints, a more economical and adaptable option like the Motorola Moto G 5G, which offers reliable performance, microSD support, and long battery life, is a more suitable fit for our deployment. The Motorola device balances essential functionality with affordability, helping us meet project goals without unnecessary expenditure.

3.1.3.3 Motorola

Overview:

For our project, we will be using the Motorola Moto G 5G (3rd Gen), which is provided to us by our sponsor. This device is known for its affordability, reliable performance, and clean Android experience, making it a great fit for our needs. The Moto G 5G features a 6.7-inch LTPS IPS LCD display, a Qualcomm Snapdragon 750G processor, 4GB or 6GB of RAM, and 128GB of internal storage, which can be expanded using a microSDXC card. It also has a 5000 mAh battery, ensuring long usage times, and a triple-camera setup with a 48MP main sensor, 8MP ultra-wide lens, and 2MP macro lens (GSMArena, 2023).

Pros:

- **Cost-Effective:** Offers solid hardware for its price, making it a smart solution for budget-conscious engineering projects where device replication across multiple units is needed.
- **Clean Stock Android Experience:** Reduces the need to uninstall or disable unnecessary software, minimizing background usage and improving responsiveness.
- **Long Battery Life:** With a 5000 mAh battery, the Moto G 5G can operate for extended periods without needing frequent recharging—ideal for long-term monitoring in off-grid setups.

- **Expandable Storage:** Unlike some modern smartphones, this device supports microSDXC cards, making it easy to increase storage without relying solely on cloud-based access.
- **Reliable Connectivity:** With 5G support, dual-band Wi-Fi, and Bluetooth 5.1, the device can stay connected to local networks, hotspots, or Starlink satellite systems for seamless data upload and remote access.

Cons:

- **Mid-Range Processor:** The Snapdragon 750G is capable of smooth performance for most applications, but may lag behind flagship processors in intensive tasks such as AI-based processing or heavy multitasking.
- **Average Display:** The IPS LCD display lacks the vibrant contrast and color depth of OLED screens, which might affect visibility in very bright outdoor environments.
- **Slow Charging:** Although the battery lasts long, the lack of fast charging above 20W may lead to longer charging downtime, especially when rapid redeployment is needed.

Suitability for Our Project:

The Motorola Moto G 5G (3rd Gen) is a highly suitable choice for our low-cost passive aircraft detection project. Its affordability makes it scalable for use across multiple units, especially in distributed deployments. It satisfies essential technical requirements—such as long battery life, reliable connectivity, storage flexibility, and smooth operation—without burdening the project budget with high-end features that are unnecessary for our goals.

Furthermore, its Android-based platform supports custom app development, allowing us to tailor the phone's functionality to serve as a remote terminal for data viewing, system alerts, and diagnostic control. With its clean software, power efficiency, and practical design, the Moto G 5G enables a smooth field experience for our engineering team, helping bridge real-time data with intuitive user access.

3.1.3.4 Cellular Phone Selection

For our project, we will be using the Motorola Moto G 5G (3rd Gen), which is provided by our sponsor. This phone is a great balance of performance, reliability, and affordability, making it a solid choice for system monitoring and mobile data access. With 5G connectivity, it ensures fast and stable communication, which is important for real-time data transfers and remote access to our system.

The phone runs on a Qualcomm Snapdragon 480+ 5G processor, which provides smooth performance for everyday tasks. It comes with 4GB or 6GB of RAM, which is enough for multitasking and running essential system applications, and 128GB of internal storage, which can be expanded with a microSD card. This gives us plenty of space for storing system data, logs, and any necessary software.

The 6.5-inch LCD display has a 120Hz refresh rate, making it smooth and responsive when scrolling through data and notifications. The 5000 mAh battery provides all-day usage, reducing the need for frequent charging, and with 15W fast charging, it can quickly power up when needed.

For connectivity, the Moto G 5G (3rd Gen) supports dual SIM, 5G networks, and Wi-Fi, making sure we always have a reliable connection to our system. It also has a USB-C port for charging, Bluetooth 5.1, and a headphone jack for added convenience. The phone runs a clean, near-stock version of Android, meaning it has minimal bloatware and is easy to use, which is helpful when setting it up for our specific project needs.

Since this phone is provided by our sponsor, it's a cost-effective yet capable solution for managing our system remotely. With 5G capabilities, a large battery, and expandable storage, it gives us everything we need for real-time monitoring and reliable mobile access. Its affordability and strong performance make the Motorola Moto G 5G (3rd Gen) the right choice for our project.

3.1.4 Starlink Mini Terminal

As part of our project, we have been provided with the Starlink Mini Terminal to use for reliable satellite communication to transmit detected aircraft data. The Starlink Mini Terminal, with its compact design and high-speed internet connectivity, plays a pivotal role in ensuring that our system can function in remote areas where traditional internet infrastructure is unavailable.

One of the primary advantages of the Starlink Mini Terminal is its ability to provide global, low-latency broadband internet coverage, even in areas without cellular or wired infrastructure. This makes it an ideal solution for our system, which needs to operate in remote regions with limited access to traditional communication networks. With its satellite-based connectivity, the Starlink Mini Terminal allows us to transmit real-time data from our detection units to a secure, centralized monitoring platform. This ensures that authorities can access the data from anywhere in the world, providing them with up-to-date information on aircraft movements in the monitored regions.

The Starlink Mini Terminal's compact size and portability are also crucial for our project. As our system will be deployed across vast areas, the ability to install the terminal in various locations with minimal setup is essential. The Mini Terminal's ease of installation and robust design make it ideal for integration with our solar-powered power supply units. Since it requires minimal power to operate, it aligns perfectly with our goal of creating a low-cost, energy-efficient system that can run autonomously for extended periods.

In addition to its portability, the Starlink Mini Terminal offers high-speed data transmission capabilities. This ensures that the data collected by our RF detection units—such as aircraft signals, location data, and alerts—can be transmitted quickly and efficiently, providing real-time updates to security teams. The low-latency communication helps in reducing delays, which is vital for rapid response times in security-sensitive situations.

The integration of the Starlink Mini Terminal into our project enhances the scalability and flexibility of our system. As our network of detection units expands in Phase 2, the Mini Terminal will allow seamless communication between these units and the central hub, ensuring that data from multiple units can be synchronized and processed efficiently. This networked communication is essential for accurately calculating the location of detected aircraft and for the real-time sharing of this data with security teams.

In all, the Starlink Mini Terminal plays a crucial role in ensuring that our design remains functional, scalable, and effective in remote and resource-limited environments. By providing reliable satellite communication, it enables the real-time transmission of data, enhances the system's overall reliability, and supports the system's deployment across vast areas where traditional communication infrastructure would be impractical or too costly to implement. This will be crucial to our success, and was a great choice by our sponsor.

3.1.5 Laptop PC (Core i7)

For our project, we need a high-performance laptop with an Intel Core i7 processor to handle data processing, system monitoring, and software development. A powerful processor, sufficient RAM, and ample storage are essential for running simulations and managing large datasets smoothly. We are considering three potential models: Dell Latitude 5440, Lenovo ThinkPad X13 Gen 6, and HP Laptop 17-cn4047nr. The Dell Latitude 5440 is a solid business laptop with a 13th Gen Intel Core i7, up to 64GB RAM, and a Full HD display. The Lenovo ThinkPad X13 Gen 6 is lightweight, durable, and supports up to 64GB RAM and 2TB SSD, making it ideal for long work sessions. Finally, the HP Laptop 17-cn4047nr, which is provided by our sponsor, has a 17-inch display and a 13th Gen Intel Core i7, offering a large workspace and reliable performance. In the next sections, we'll break down their strengths and weaknesses to find the best fit for our needs.

3.1.5.1 Dell

The Dell Latitude 5440 is a business-class laptop known for its strong performance, reliability, and professional design. Equipped with a 13th Gen Intel Core i7 processor, it is capable of handling demanding applications and multitasking workloads with ease. The laptop features a 14-inch Full HD display, which offers clear visuals for development and debugging, and its sturdy build ensures durability in everyday use. Designed for professionals, the Latitude 5440 strikes a solid balance between performance, portability, and connectivity, making it well-suited for technical and field-based applications (Dell, 2023).

Performance-wise, the Latitude 5440 can be configured with up to 64GB of RAM, allowing it to manage complex, memory-intensive tasks without slowdown. Despite its powerful specs, it remains lightweight and portable, weighing only around 3.06 lbs (1.39 kg)—a convenient option for on-the-go work or field testing. It also boasts a range of modern connectivity options, including USB 3.2, Thunderbolt 4, HDMI 2.0, and optional 5G support, offering flexibility when connecting to various peripherals or remote networks (Dell Technologies, 2023).

However, there are a couple of limitations to consider. The display, while sharp, has a maximum brightness of only 250 nits, which may be less effective in bright or outdoor environments (XDA Developers, 2023). Additionally, the integrated Intel Iris Xe graphics, although sufficient for everyday tasks, may not be capable of handling heavy graphics processing or visualization workloads.

Overall, the Dell Latitude 5440 is a practical and powerful option for our project. Its combination of solid CPU performance, ample RAM support, lightweight design, and strong connectivity makes it well-suited for data processing, system monitoring, and software development. While

not selected as the final device for this project, it remains a strong contender for similar technical environments.

3.1.5.2 HP

For our project, our sponsor is providing us with the HP Laptop 17-cn4047nr, a 17-inch laptop equipped with a 13th Gen Intel Core i7 processor. This laptop is designed for general productivity and multitasking, offering a large display, reliable performance, and respectable battery life. It is a cost-effective solution that meets the technical demands of our project, particularly in areas such as data processing, software development, and system monitoring (HP, 2023).

One of the standout features of this laptop is its 17.3-inch screen, which offers ample workspace for multitasking and analyzing large datasets. The combination of the Intel Core i7 processor and 16GB of RAM provides smooth and responsive performance across most applications. It also includes HP's Fast Charge feature, allowing the laptop to recharge quickly, which helps reduce downtime during development (HP, 2023). Since this laptop is being provided by our sponsor, it also helps us reduce overall project costs while still meeting all of our operational needs.

There are, however, a few limitations to note. Due to its large screen size, the HP 17-cn4047nr is less portable than smaller laptops, making it more cumbersome to transport. Additionally, it lacks a dedicated graphics card, meaning it is not suited for tasks that involve high-end graphics processing, such as advanced rendering or simulation.

Despite these drawbacks, the HP Laptop 17-cn4047nr is a practical and reliable choice for our project. Its performance capabilities, large display, and sponsor-provided cost advantage make it well-suited for supporting our system's software development, testing, and data analysis efforts.

3.1.5.3 Lenovo

The Lenovo ThinkPad X13 Gen 6 is a lightweight and high-performance business laptop designed for professionals who prioritize portability without compromising on capability. Weighing just 2.05 pounds, it is one of the most portable options available, making it especially useful for team members who may need to work remotely or travel with their equipment. Despite its compact size, the X13 Gen 6 supports powerful hardware configurations, including Intel Core Ultra processors, up to 64GB of RAM, and 2TB of SSD storage. Its 13.3-inch display provides a clear and efficient workspace, and the durable chassis upholds the ThinkPad's reputation for reliability and long-lasting build quality.

This laptop excels in areas such as multitasking, data management, and software development. With support for a high amount of RAM and storage, it can easily handle multiple applications and large datasets simultaneously. The ultra-lightweight design makes it particularly appealing for mobile or on-the-go development, and its rugged construction ensures it can withstand daily use in a variety of environments.

However, there are a few limitations to consider. The Lenovo ThinkPad X13 Gen 6 lacks a dedicated graphics card, which can be a drawback for projects requiring high-end graphical processing, such as rendering or visual simulations. Additionally, while its base model is

reasonably priced, fully upgraded configurations may be expensive, posing a challenge for projects with strict budget constraints.

Overall, the Lenovo ThinkPad X13 Gen 6 offers a strong balance between portability and performance. Its technical specifications make it well-suited for many aspects of our project, including system monitoring and development. Though it was not selected as the final laptop for the project, it remains a very capable alternative that could serve similar use cases effectively.

Suitability for Our Project:

The Lenovo ThinkPad X13 Gen 6 offers a compelling mix of portability and performance. Its lightweight design and robust specifications make it suitable for tasks such as data processing, system monitoring, and software development. However, the lack of a dedicated graphics card may limit its effectiveness for graphics-intensive applications. Overall, it stands as a strong candidate for our project's computing needs.

3.1.5.4 Laptop Part Selection

For our project, we will be using the HP Laptop 17-cn4047nr, which is provided by our sponsor. This laptop offers a solid balance of performance, usability, and affordability, making it a great choice for handling data processing, system monitoring, and software development. Equipped with a 13th Gen Intel Core i7-1355U processor, it has 10 cores and 12 threads, allowing for smooth multitasking and fast performance, which is essential when running multiple applications at once.

With 16GB of DDR4 RAM, the laptop can easily handle large datasets, simulations, and coding environments without lag. It also comes with a 512GB PCIe NVMe SSD, ensuring fast boot times and quick access to files, making it great for working with large amounts of data. The 17.3-inch Full HD display provides plenty of screen space, making multitasking easier, and the anti-glare coating helps reduce eye strain. While the screen is bright enough for most indoor settings, its 300-nit brightness may not be the best for outdoor use. The Intel Iris Xe Graphics is fine for general tasks but isn't designed for intensive graphics work like video editing or 3D modeling.

For connectivity, the HP Laptop 17-cn4047nr supports Wi-Fi 6 and Bluetooth 5.3, ensuring fast and reliable internet access, which is crucial for remote monitoring and data transfers. It also has multiple ports, including USB-C, USB-A, HDMI, and a headphone/microphone jack, making it easy to connect external devices, additional screens, and storage drives. One major plus is the HP Fast Charge feature, which allows for quick battery recharging, reducing downtime and keeping our workflow uninterrupted.

At 4.60 lbs, this laptop is a bit on the heavier side, but the large display and powerful performance make up for the lack of portability. It runs Windows 11, ensuring compatibility with all the necessary software tools we'll be using. The full-size backlit keyboard with a numeric keypad also makes it more comfortable for long hours of work, especially when handling data entry or spreadsheet tasks.

Overall, the HP Laptop 17-cn4047nr is a practical and capable system that meets all our project's needs. Thanks to our sponsor providing it, we have access to a high-performance, reliable laptop that will allow us to efficiently process data, develop software, and monitor system performance without exceeding our budget.

3.2. Power Supply System

Now that we have selected the primary processing and detection components, we can move forward with selecting the power delivery system. Our passive aircraft detection system requires a reliable and energy-efficient power source to sustain continuous operation in remote locations, where access to traditional power grids may be limited. Given that our system consists of multiple sensor nodes, an MPU, RF signal processing units, and wireless communication modules, we must ensure that our power supply is sufficient to support real-time data transmission, sensor monitoring, and cloud integration.

Based on our initial calculations, the peak power consumption of our detection unit is estimated to be approximately 45W. However, similar to other embedded systems, it is unlikely that all components will be operating at peak power simultaneously. To ensure consistent power availability while maintaining efficiency and cost-effectiveness, we have chosen to use a solar panel and battery combination. A 50W solar panel will serve as the primary power source, providing continuous energy during daylight hours, while a backup battery will supply power during low-light conditions or at night.

Our system has specific power distribution needs, with components operating at 3.3V, 5V, and 12V. The MCU and communication modules require 3.3V, while RF signal processors and sensors function at 5V, and certain power-intensive components like long-range communication modules may need 12V. Table X outlines the estimated peak power consumption for each component in our system:

Table 3.4 Power Supply Requirements

Device	Quantity	Voltage (V)	Peak Power (W)
MPU (Raspberry Pi 4/CM4)	1	5V	5W
RF Signal Processing Unit	1	5V	10W
Sensor Nodes	4	3.3V	8W (Total)
Communication Module (LoRa/SATCOM)	1	12V	12W
Cloud Transmission Module	1	5V	5W
Other Auxiliary Components	-	-	5W (Approx.)
Total Estimated Peak Power	-	-	45W

In addition to the solar panel, we require a battery capable of storing enough energy to keep the system operational during low-power conditions. Assuming an average standby power consumption of 0.15W per hour over two weeks, our system would need a minimum battery capacity of 50-60Wh. Considering availability and cost factors, a 12V 100Ah battery is a practical choice, as it offers high energy density, reliability, and affordability. Additionally, these batteries are commonly used in industrial and remote monitoring applications, making them well-suited for our project's needs.

One key consideration is temperature tolerance and environmental durability since our system may be deployed in remote or extreme weather conditions. To mitigate power fluctuations, we may implement power regulation circuits and voltage converters to optimize power efficiency across different system components. This approach ensures that our passive aircraft detection system remains functional and reliable, even under challenging deployment scenarios.

3.2.1 Batteries

3.2.1.1 Choosing a Battery

In remote regions where conventional radar is not viable, our node system relies on solar-powered units to operate autonomously for extended periods. A key component of this system is an efficient, long-lasting rechargeable battery that can store enough energy to power RF receivers, processing units, and satellite communication equipment. Since these units will be deployed in isolated areas with varying weather conditions, the selected battery must be high-capacity, durable, and optimized for solar charging.

For our applications, the primary criteria are reliability, efficiency, and long-term performance, as our nodes will be out in the wilderness, and should not require constant maintenance. Since the system will likely be powered by solar energy, the battery must be capable of efficiently storing and discharging energy in varying sunlight conditions, ensuring continuous operation even during periods of low light or at night. The battery must also have a high cycle life to withstand frequent charging and discharging without significant degradation, as the system may need to operate for extended durations with minimal maintenance. Additionally, the battery should be able to handle temperature fluctuations, as the detection unit could be deployed in diverse environmental conditions. We can also consider size and weight as semi-important factors for remote deployments, where space may be limited and lightweight components are desirable. Finally, cost-effectiveness is a key consideration, given the goal of maintaining a low overall cost for the detection unit while ensuring the battery is durable and reliable over time.

All these factors will guide the selection of the most suitable battery technology for this application.

3.2.1.2 Available Battery Options

When selecting a rechargeable battery for our detection nodes, several types of batteries can be considered: Lithium Iron Phosphate (LiFePO₄), Lithium-Ion (Li-Ion), Sealed Lead Acid (SLA), and Gel batteries. LiFePO₄ is known for its long cycle life, high safety, and stability, making it an excellent choice for long-term, reliable energy storage in outdoor applications. Li-Ion batteries offer higher energy density and lighter weight compared to other options, which is

advantageous for applications where space and weight are constraints. SLA batteries, while heavier and less efficient, are cost-effective and widely available, making them a budget-friendly option, though they tend to have shorter lifespans. Gel batteries are similar to SLA but feature a gel electrolyte that improves safety and performance in extreme conditions, though they are typically more expensive and heavier. Each of these battery types offers trade-offs in terms of cost, performance, and lifespan.

3.2.1.3 Battery Option Chart

Table 3.5 Battery Types

Battery Type	Capacity (Ah)	Voltage (V)	Cycle Life	Efficiency	Pros	Cons
Lithium Iron Phosphate (LiFePO4)	100	12	3000-5000	95%	High cycle life, lightweight, deep discharge	Higher cost upfront
Lithium-Ion (Li-Ion)	100	12	2000-4000	90-95%	Compact, good efficiency	Slightly lower lifespan than LiFePO4
Sealed Lead Acid (SLA)	100	12	500-1000	80-85%	Lower cost, easy to find	Heavy, shorter lifespan
Gel Battery	100	12	600-1200	85-90%	Maintenance-free, deep cycle	More expensive than SLA, lower lifespan than LiFePO4

This chart compares four types of rechargeable batteries—Lithium Iron Phosphate, Lithium-Ion, Sealed Lead Acid, and Gel Batteries—across key parameters such as capacity, voltage, cycle life, efficiency, and pros and cons. All options in the chart have similar capacities (100 Ah) and voltage (12 V), but they differ significantly in cycle life, efficiency, and cost-effectiveness. LiFePO4 offers the highest cycle life (3000-5000 cycles) and efficiency (95%), making it ideal for long-term, reliable use, though it comes with a higher upfront cost. Li-Ion provides good efficiency and compactness, with a slightly lower cycle life than LiFePO4. SLA and Gel batteries are much more affordable but come with significantly shorter cycle lives and lower efficiency. While Gel batteries offer maintenance-free operation, their lifespan is still shorter compared to LiFePO4.

For the detection nodes, a battery with a high cycle life and reliability in varying environmental conditions is crucial. Given that LiFePO₄ offers the best combination of long cycle life, efficiency, and deep discharge capabilities, it is likely the most suitable choice despite the higher initial cost. The long-term performance and reliability it provides outweigh the initial investment, especially for a system that needs to operate continuously with minimal maintenance.

3.2.1.4 LiFePO₄ Battery Choices

The following table provides a comparison of several 12V 100Ah Lithium Iron Phosphate (LiFePO₄) batteries, outlining their prices, key features, and where we can find them. These options are suitable for applications requiring reliable energy storage, such as in a solar-powered passive aircraft detection unit. Each battery varies in terms of cost, lifespan, and added features, allowing for different trade-offs based on specific needs and budget constraints.

Table 3.6 Battery Models

12V 100Ah LiFePO ₄ Lithium Battery		
Brand	Price (USD)	Key Features
Redodo	\$167.88	Budget-friendly, suitable for solar
LiTime	\$199.99	Deep cycle, designed for energy storage applications.
Eco-Worthy	\$209.99	Compact design, lifespan up to 15,000 cycles.
Battle Born	\$749.99	Known for durability and versatility, tailored for RVs and off-grid systems.
Renogy	\$709.99	Smart features with Bluetooth connectivity for monitoring.
EcoFlow	\$250.00	Low lifetime cost, 6,000 cycle lifespan.
WattCycle	\$159.99	A+ grade cells, up to 20,000 cycles.
ExpertPower	\$329.99	Flat discharge curve, lifespan of 2,500 to 7,000 cycles.

Considering the balance of price, lifespan, and reliability, the LiTime 12V 100Ah LiFePO₄ Lithium Battery emerges as the best option. Priced at \$199.99, it offers a solid combination of affordability, a reasonable lifespan, and reliability for long-term use. While more expensive

options like Battle Born and Renogy offer additional features, the LiTime battery provides a good balance without breaking the budget, making it a great fit for our system..

3.2.2 Solar Panels

3.2.2.1 General Types of Panels

When selecting a solar panel for our detection system, several factors need to be considered, including the local environmental conditions, the required power output, panel efficiency, lifespan, cost, and physical space for installation. Since the system is intended for remote areas with limited infrastructure, the ideal solar panel should be highly reliable, efficient in diverse weather conditions, and affordable to maintain. Given that the system will be powered continuously, energy efficiency will be critical to ensure long-lasting performance without requiring frequent maintenance. Additionally, ease of installation and durability are important, as the system will be deployed in harsh and often unpredictable environments, such as remote border areas.

There are four types of solar panels we will consider: Monocrystalline, Polycrystalline, Thin Film, and PERC. In selecting the type of panel, we must also account for the geographic location and the amount of available sunlight. For instance, if the system is deployed in areas with consistent sunlight, high-efficiency panels might be prioritized. Conversely, if the system is located in regions with partial shading or low sunlight, we may prioritize panels that perform better under such conditions, even if they come at a slightly higher cost. Similarly, since these systems may operate in large networks, scalability and the ability to quickly deploy additional panels will also influence the type of solar panels selected.

3.2.2.2 Pros and Cons

For our Power Supply System, we can consider several types of solar panels, each with unique advantages and trade-offs. Understanding the underlying technology and performance characteristics of each option is essential for selecting the best fit for our remote deployment.

Monocrystalline panels are known for their high efficiency, with typical energy conversion rates up to 22%. These panels are made from single-crystal silicon, which is grown in a way that allows electrons to flow more freely, enhancing performance. Their compact, space-efficient design makes them ideal for installations in areas where space is limited, such as remote monitoring stations. Monocrystalline panels also have a long lifespan, often exceeding 25 years, and perform excellently in low light conditions, ensuring continuous energy generation even during overcast or shaded periods. However, the main drawback is their higher cost compared to other panel types. Additionally, their fragility during installation can present challenges, as the panels can be brittle and require careful handling.

Polycrystalline panels are made from silicon that has been melted and poured into molds, forming multiple crystals. This process is less expensive and results in a lower cost compared to monocrystalline panels. They typically have an efficiency rate between 15% and 17%, which is sufficient for general applications, though their lower efficiency means that a larger surface area is required to generate the same amount of power as monocrystalline panels. These panels are still a solid choice for systems where cost is a significant concern, but their larger size and

relatively lower efficiency make them less ideal for applications requiring space-saving solutions or higher power output. Polycrystalline panels also have a lifespan of around 20–25 years, but their performance under low-light conditions is not as strong as that of monocrystalline panels.

Thin-film panels, made from layers of semiconductor materials such as cadmium telluride or amorphous silicon, are lightweight and flexible. This makes them versatile, allowing integration into unconventional surfaces like roofs or walls. They are typically lower in cost, which may seem appealing for budget-constrained projects. However, thin-film panels come with significant downsides. Their efficiency is the lowest of the options we considered, typically around 10% or less, meaning that much larger surface areas are required to meet energy demands. Furthermore, their shorter lifespan (approximately 10–15 years) and poor performance in low-light conditions make them less suitable for our use case, where reliability and efficiency are key to maintaining system operation in remote locations over an extended period.

PERC (Passivated Emitter and Rear Contact) panels are a more advanced version of monocrystalline panels. They employ an additional layer on the back of the cell to reduce energy losses and improve overall efficiency, reaching up to 22%. PERC technology enhances performance, particularly in low light and high-temperature conditions, making these panels more efficient and reliable than conventional monocrystalline panels. However, the increased efficiency comes with a higher cost, and the panels require more specialized installation and handling due to the advanced technology involved. This makes them a good option for situations where efficiency is paramount, but the added complexity and cost may not justify the benefits in every case.

Table 3.7 Solar Panel Types

Type of Panel	Efficiency	Cost Range	Lifespan	Best Use Case
Monocrystalline	18%-22%	High (\$0.80-\$1.00/W)	25+ years	High efficiency, small footprint, remote areas with high sunlight
Polycrystalline	15%-17%	Medium (\$0.60-\$0.80/W)	20-25 years	Budget-conscious solutions, larger area available
Thin Film	10%-13%	Low (\$0.50-\$0.70/W)	10-15 years	Large area installations, less critical for space
PERC	20%-22%	Medium-High (\$0.90-\$1.10/W)	25+ years	High-efficiency needs in low light conditions

For our Power Supply System, we have already decided that our best battery option is a 12V 100Ah LiFePO4 battery. With that in mind, along with the pros and cons of each kind of solar panels, monocrystalline solar panels are the best choice for us. Monocrystalline panels offer the highest efficiency, typically between 18% and 22%, which means they generate more power per square meter compared to other types like polycrystalline and thin-film panels, while being lower cost than the comparable PERC panels. This is particularly beneficial for our system, as maximizing energy production in a limited space is crucial, especially in remote and difficult-to-access locations as well as to avoid detection from the aircrafts. Monocrystalline panels are also known for improved performance in low-light conditions, making them a great option for areas with inconsistent sunlight or partial cloud cover. In such environments, these panels will continue to provide reliable power, ensuring the battery is charged efficiently.

Additionally, these panels boast a long lifespan of over 25 years, offering durability and reliability for a system that will likely be deployed in harsh, hard-to-reach environments where maintenance is limited. Furthermore, monocrystalline panels output a voltage that typically falls between 18V–22V, making them an excellent fit for efficient charging of our 12V battery system, when paired with a charge controller. Though polycrystalline are a cheaper option, the efficiency is lower (15-17%) making them less than ideal for low-light locations, meaning we would have to purchase more panels, which will cost a similar price to the more expensive monocrystalline panels. Thin-film panels are not viable due to their poor efficiency and shorter lifespan. PERC panels, though superior in efficiency, involve higher costs and specialized handling, which is not necessary for our application. Ultimately, monocrystalline panels strike the best balance between performance, cost, and long-term reliability, ensuring that our system can operate autonomously in remote regions with minimal maintenance. Thus, we propose using a monocrystalline panel for the design

3.2.2.3 Specific Models

Table 3.8 Solar Models with Features

Brand	Model	Cost	Key Features
Renogy	RNG-100D	\$120	100W, Monocrystalline, Compact, High-Efficiency (21%)
Goal Zero	Nomad 100	\$300	100W, Monocrystalline, Foldable, Portable, Waterproof
SunPower	SPR-X22-370	\$350	370W, Monocrystalline, PERC, Industry-leading efficiency (22%)
Eco-Worthy	Solar Panel 100W	\$100	100W, Polycrystalline, Durable, Cost-effective

ALLPOWERS	AP-100W	\$160	100W, Monocrystalline, Lightweight, Waterproof, Foldable
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3.2.3 Charge Controllers

3.2.3.1 Purpose of Charge Controller

A charge controller is a vital component of the solar power system. It regulates the voltage and current coming from the solar panels to ensure the battery is charged efficiently and safely. Charge controllers prevent overcharging, deep discharging, and allow the battery to last longer by controlling the charge flow. When evaluating charge controller options, several key factors need to be considered, including system size, efficiency, compatibility with the LiFePO4 battery, and scalability for future expansions.

3.2.3.2 Types of Charge Controllers

There are two primary types:

- PWM (Pulse Width Modulation) Charge Controllers: More affordable, suitable for smaller systems with lower power needs. However, less efficient than MPPT controllers.
- MPPT (Maximum Power Point Tracking) Charge Controllers: More expensive but highly efficient, especially in low-light conditions. MPPT controllers are ideal for larger systems where performance and energy efficiency are paramount.

Given our system's requirements (high efficiency, scalability, 12V 100Ah LiFePO4 battery) an MPPT charge controller is the best choice. An MPPT controller ensures that excess voltage from the panels is converted to the optimal charging current for the LiFePO4 battery, maximizing energy efficiency and reducing charging time, even in variable lighting conditions. This makes it particularly valuable for the remote environments where the nodes will have to be deployed. Additionally, an MPPT controller is better suited for future scalability, especially if we expand the system to include more panels. While the higher cost of MPPT controllers is a consideration, the increased efficiency and long-term reliability they offer make them the best investment for our application, ensuring the system remains operational in the most energy-efficient manner.

3.2.3.3 Charge Controller Options

Table 3.9 Charge Controller Models

Brand	Model	Type	Cost	Features	Applications
Renogy	Rover 40A	MPPT	\$125	40A, Efficient in variable sunlight, LCD display	High-efficiency, solar systems with larger panels
Victron	SmartSolar MPPT 75/15	MPPT	\$85	15A, Bluetooth monitoring, High performance	Smaller systems or remote monitoring

AllPowers	10A PWM	PWM	\$30	Affordable, Suitable for 12V systems	Budget systems or small setups
EPEVER	Tracer AN 30A	MPPT	\$75	30A, Waterproof, Battery type flexibility	Remote systems with high solar exposure

3.2.4 Wiring Setup

3.2.4.1 For a Single Unit

For a single unit setup, the solar panel is connected to the charge controller by linking the positive and negative terminals of the solar panel to the corresponding solar input on the charge controller. From there, the charge controller connects to the LiFePO₄ battery. The positive and negative terminals of the charge controller's battery output are connected to the battery, allowing it to charge. Once the battery is fully charged, the detection unit, which serves as the system load, is then connected to the battery to draw power and operate continuously.

3.2.4.2 For Multiple Unit

For multiple units, solar panels can be connected in either a series or parallel configuration, depending on the voltage requirements of the charge controller and the battery. Connecting panels in series increases the voltage, while connecting them in parallel increases the current output, providing flexibility in how the system is scaled. If we plan to expand to a large system, it may be necessary to use multiple charge controllers. Each group of solar panels could be connected to its own controller, ensuring efficient charging and distribution of power. To streamline coordination and ensure the entire system operates seamlessly, a master/slave setup for the charge controllers can be implemented. This approach allows for better monitoring and synchronization across the system, which is especially important in larger installations.

3.2.4.3 Additional Recommendations

Additionally, some important recommendations should be followed to maintain system safety and performance. Overcurrent protection devices such as fuses or circuit breakers should be installed in both the panel-to-controller and controller-to-battery connections to protect against potential short circuits or overcurrent situations. Proper sizing of the solar panels and battery is crucial to meet the system's energy requirements; using a system size calculator can help ensure the panel wattage and battery capacity are well-matched. Wire gauge selection is also vital to minimize voltage loss and safely handle the current. For instance, a 10 AWG wire is typically suitable for connecting the solar panels to the charge controller, while a 12 AWG wire is appropriate for connecting the battery to the system load. By ensuring the correct sizing of components and incorporating safety measures, the system will be more reliable and efficient in both single and multi-unit configurations.

3.2.5 Power Supply Part Selection

For our Power Supply Design, we have selected a combination of Renogy solar components to ensure that the system operates autonomously in remote areas with minimal maintenance. This

includes the Renogy RNG-100D Solar Panel, the Renogy Rover 40A MPPT Charge Controller, and the LiTime 100Ah 12V LiFePO4 Battery. These components work together to provide reliable, renewable power for the system, supporting long-term, off-grid operation in challenging environments, as they are all designed to be fully compatible with one another, ensuring seamless integration within our design.

The Renogy RNG-100D Solar Panel is an efficient, 100-watt monocrystalline solar panel designed for a wide range of applications. Its high energy conversion efficiency makes it ideal for powering our detection units in shady locations as well as nighttime. With its durable construction and ability to generate consistent energy even in variable sunlight conditions, the RNG-100D ensures that our system can operate continuously without relying on external power sources. The panel's lightweight and compact design also make it easy to transport and install, which is helpful for deploying the detection units across large areas.

To optimize energy collection and battery charging, we use the Renogy Rover 40A MPPT Charge Controller. This controller is designed to maximize the efficiency of the solar panel by employing Maximum Power Point Tracking (MPPT) technology. MPPT ensures that the solar panel operates at its highest possible efficiency, adapting to changing sunlight conditions and delivering more power to the battery compared to traditional PWM controllers. This feature is particularly important for our system, as it allows us to get the most out of our solar panels and maintain continuous operation even in less-than-ideal weather. The 40A capacity is sufficient to handle the power needs of our detection units, ensuring that the batteries are charged efficiently without overcharging or damaging them.

The LiTime 100Ah 12V LiFePO4 Battery is the final component of the energy system. LiFePO4 (Lithium Iron Phosphate) batteries are known for their high cycle life, safety, and efficiency, making them an excellent choice for our off-grid solar setup. With a 100Ah capacity, this battery provides enough energy storage to power the detection units during nighttime hours or cloudy days when solar generation is lower. The LiFePO4 battery is also lightweight and compact, which helps keep the overall system portable and easy to deploy in remote locations. Additionally, these batteries are more stable and have a longer lifespan compared to other lithium-ion options, reducing the need for frequent replacements and ensuring the long-term viability of the system.

Together, these components form a robust and reliable power solution for our detection nodes. The Renogy RNG-100D Solar Panel collects energy, the Renogy Rover 40A MPPT Charge Controller ensures efficient charging, and the LiTime 100Ah 12V LiFePO4 Battery stores energy to power the system when sunlight is not available. This combination provides a sustainable, low-maintenance power solution that supports the system's autonomy, allowing us to monitor aircraft in remote areas for extended periods without needing external power sources.

3.3 Communication Technologies

3.3.1. Mobile services

3.3.1.1 AT&T

For our passive aircraft detection system, reliable and cost-effective network connectivity is essential for real-time data transmission, cloud integration, and remote monitoring. One option we can consider is AT&T Unlimited Starter, priced at \$65 per month for a single line. This plan provides unlimited talk, text, and data, with access to AT&T's 5G network. However, all data is deprioritized, meaning speeds may be reduced during times of network congestion. Additionally, the plan does not include premium high-speed data or mobile hotspot usage, which may limit connectivity options in testing environments that require tethering.

A key advantage of AT&T Unlimited Starter is its nationwide 5G coverage, ensuring strong connectivity in urban and many rural areas. The plan also includes unlimited talk, text, and data in Mexico and Canada, with data speeds limited to 128 kbps—which is useful for basic communication but too slow for large-scale data uploads. While video streaming is limited to standard definition (480p), this is not a major drawback for our project, as our primary data needs involve telemetry and cloud reporting rather than high-bandwidth streaming.

Despite the lack of hotspot data, AT&T's strong coverage and reliable speeds make it a suitable option for ensuring our detection system can communicate with cloud servers and monitoring stations.

3.3.1.2 Verizon

Another option for network connectivity in our passive aircraft detection system is Verizon's Unlimited Welcome plan, which is priced at \$65 per month for a single line. Like AT&T Unlimited Starter, this plan provides unlimited talk, text, and data, but data speeds may be deprioritized when the network is congested. Unlike higher-tier Verizon plans, hotspot data is not included, which could be a limitation for remote testing or field deployments that require tethered internet access.

One of Verizon's biggest strengths is its strong nationwide 5G coverage, particularly in rural and remote areas, where our detection system may be deployed. Additionally, the plan includes unlimited talk, text, and data in Mexico and Canada, though data speeds are reduced to 2G (128 kbps) when roaming internationally. For video streaming, the plan limits quality to 480p (SD), similar to AT&T's Starter plan.

A notable advantage of Verizon is its network reliability and performance, making it a great option for ensuring stable communication between detection units and cloud-based processing systems. However, since no hotspot data is provided, we would need to rely on alternative connectivity solutions for cases where tethering is required.

3.3.1.3 T-Mobile

Since T-Mobile's Essentials Saver plan is provided by our sponsor, we will be using it to enable real-time communication, cloud data transfer, and system monitoring in our passive aircraft

detection system. This plan is the most affordable of the three at \$50 per month per line, making it a cost-effective solution for ensuring continuous data reporting from our detection units. Unlike AT&T and Verizon's basic unlimited plans, T-Mobile Essentials Saver includes 50GB of premium high-speed data, meaning we won't experience deprioritization until we exceed this limit.

One key advantage of T-Mobile Essentials Saver is its 5G access, providing faster speeds in urban and many suburban areas. Additionally, the plan includes unlimited international texting to 210+ countries and Mexico/Canada roaming, though data speeds are limited to 128 kbps while roaming internationally. However, a major limitation of this plan is that hotspot data is restricted to 3G speeds, which could be insufficient for testing scenarios requiring high-speed internet tethering.

T-Mobile's network is strongest in urban and suburban areas but may not be as reliable in rural regions compared to Verizon or AT&T. This could be a factor when deploying our system in remote locations. However, since this plan is provided by our sponsor, it significantly reduces project costs while providing a sufficient data allowance for real-time monitoring. If higher-speed hotspot access is required, we may need to seek additional data solutions or explore T-Mobile's higher-tier plans.

To gain a complete understanding of our options, we have created the comparison table below, highlighting key differences in features, performance, and suitability for our project.

Table 3.10 Mobile services comparison by Authors

Feature	AT&T Unlimited Starter	Verizon Unlimited Welcome	T-Mobile Essentials Saver
Monthly Price (Single Line)	\$65/month	\$65/month	\$50/month
5G Network Access	Yes (AT&T 5G & 5G+)	Yes (Verizon 5G Nationwide)	Yes (T-Mobile 5G)
Mobile Hotspot Data	Not included	Not included	3G speeds only
Video Streaming Quality	SD (480p)	SD (480p)	SD (480p)
International Calling & Roaming	Mexico & Canada (Talk, Text & Data at 128kbps)	Mexico & Canada (Talk, Text & Data at 2G speeds)	Mexico & Canada (Talk, Text & Data at 2G speeds)
International Texting	Yes (210+ countries)	Yes (200+ countries)	Yes (210+ countries)

3.3.1.4 Mobile Service Selection

In our passive aircraft detection system, reliable wireless connectivity is essential for real-time data transmission, remote monitoring, and cloud integration. While the T-Mobile Essentials Saver plan is a budget-friendly consumer plan, it offers unlimited data, nationwide 5G coverage, and international text capabilities, which can support certain aspects of our project's communication needs.

One key consideration is data transmission. Since our system requires sending detection results to cloud servers or remote monitoring stations, we need consistent connectivity. The Essentials Saver plan provides 50GB of premium data before deprioritization, which may be sufficient for moderate sensor data uploads and remote system access. However, potential speed reductions during network congestion and 3G-speed hotspot tethering could be limitations, especially for applications requiring low latency and high-speed data transmission.

Additionally, international capabilities are relevant if our project includes cross-border deployments or satellite-based communication backups. The plan allows texting to over 210 countries, though its Canada and Mexico data speeds (128kbps) may be too slow for real-time applications.

While this plan may not be the primary solution for our project's core communication infrastructure, it could serve as a backup data connection for field testing, remote access to detection nodes, or secondary data transmission where high-speed connectivity is not required. For real-time high-bandwidth applications, alternative solutions such as T-Mobile's enterprise IoT plans, private LTE, or satellite connectivity would be better suited.

3.3.2. Communication Methods

Reliable communication is a key part of our aircraft detection system, ensuring that sensor units can send and receive data accurately and efficiently. Our primary method of communication is Starlink SATCOM, which allows real-time data transmission from remote units to a central hub. However, we are also considering short-range communication technologies to help sensor units share data locally, provide redundancy in case of network failures, or optimize power usage. Different technologies offer different advantages—Zigbee and Z-Wave are low-power options designed for mesh networks, while Wi-Fi and Bluetooth provide faster data transfer but consume more energy. NFC, on the other hand, is best for very short-range communication but isn't practical for our needs. Each of these technologies has strengths and weaknesses when it comes to range, speed, power consumption, and reliability. By evaluating them, we can determine whether they have a useful role in our system or if our primary focus should remain on Starlink SATCOM. The goal is to ensure seamless, energy-efficient, and reliable communication between detection units while keeping the system flexible and scalable for future improvements.

3.3.2.1 Zigbee

Zigbee is a wireless communication protocol specifically designed for low-power, short-range applications such as sensor networks, automation systems, and smart home devices. It is built on the IEEE 802.15.4 standard and typically operates in the 2.4 GHz frequency band, although it can also operate on sub-GHz frequencies depending on the region and application. One of Zigbee's defining characteristics is its support for mesh networking, which allows devices within the network to communicate with each other directly or through intermediary devices. This feature increases the reliability and resilience of the network by enabling data to be rerouted around nodes that go offline or experience interference.

One of the biggest advantages of Zigbee is its extremely low power consumption, which makes it ideal for battery-powered devices that need to run for months or even years without being recharged or replaced. Zigbee modules can be put into deep sleep modes between transmissions,

consuming only microamps of current when idle. This is why Zigbee is commonly used in applications such as smart thermostats, motion sensors, and remote-controlled lighting systems. Another key benefit is scalability—Zigbee networks can support hundreds of devices, and the mesh topology ensures that communication remains stable even as the network grows. These features make Zigbee particularly attractive for projects that require a large number of interconnected nodes operating on limited power.

Despite these strengths, Zigbee also comes with some limitations that impact its usefulness in more complex or data-heavy systems—such as ours. For starters, Zigbee has a relatively **low** maximum data rate of 250 kbps. While this is sufficient for basic data logging or status updates (like a sensor reporting temperature or battery level), it is far too limited for our application, which may involve the transmission of RF signal characteristics, timestamps, GPS data, and other detailed logs from each detection node. This kind of real-time communication demands significantly more bandwidth than Zigbee can offer.

In addition to bandwidth limitations, Zigbee’s effective range is also fairly limited, with typical distances reaching about 100 meters in open space. This range can drop significantly in the presence of physical obstructions or interference from other devices operating in the 2.4 GHz band. For a project like ours—which is designed for remote outdoor deployment across large open regions—this lack of range becomes a major challenge. We would need to add extra relay nodes just to cover longer distances, which adds cost, complexity, and potential failure points to the system.

That being said, Zigbee has been explored in aviation and UAV-related applications, although primarily in small-scale or internal systems. One study published by TheIREDD (2023) looked into Zigbee’s use in aircraft hydraulic monitoring systems. In this context, Zigbee was found to be a good fit because the data being transmitted was low-bandwidth, and the power-saving features helped reduce the load on the aircraft’s electrical systems. Another study shared on ResearchGate (2023) examined Zigbee in multi-UAV coordination. It showed that Zigbee could be useful for basic communication between drones flying in close formation, though it clearly struggled when applied to high-speed data sharing or long-range control scenarios.

For our project—designing a passive aircraft detection system for remote, off-grid environments—Zigbee unfortunately does not meet the requirements needed for the core communication layer. Our system will eventually involve multiple detection units spaced over a wide geographic area, each potentially transmitting detection data in real time to a base station or cloud platform. These communications demand not only longer range but also more bandwidth than Zigbee is capable of providing.

However, that does not mean Zigbee is completely irrelevant to our project. While it won’t serve as the main communication protocol between detection units or to the base station, it could still have value in localized applications within each unit. For example, Zigbee could be used for internal communication between subsystems, or for low-power environmental monitoring modules that report temperature, humidity, or battery status to the main processor. In that way, Zigbee could serve as a supporting protocol that enables more intelligent, energy-aware operation without adding much complexity or power drain.

Additionally, if future iterations of our project include smart diagnostics or automated maintenance systems, Zigbee could potentially be used to communicate between nearby nodes during field servicing. A technician might interact with the node wirelessly using a Zigbee-compatible handheld device or tablet, accessing internal logs or configuring the system without needing a physical connection.

In conclusion, Zigbee is a proven and reliable technology in many low-power, low-data applications. Its strength lies in its simplicity, energy efficiency, and ability to form mesh networks that enhance reliability. However, its limited range and data rate prevent it from being the backbone of our aircraft detection system. That said, it could still play a role in smaller, less bandwidth-intensive tasks inside the unit. As we continue to develop and refine our system, we will keep Zigbee in mind as a secondary tool that could contribute to the internal functionality and energy savings of the overall platform.

3.3.2.2 Z-Wave

Z-Wave is a low-power wireless communication protocol designed primarily for smart home automation and Internet of Things (IoT) applications. It is commonly used to connect devices such as smart locks, motion detectors, light switches, and security systems, allowing them to operate in sync through a central hub or controller. Unlike many other short-range wireless protocols that operate in the crowded 2.4 GHz band (such as Wi-Fi and Bluetooth), Z-Wave operates in the sub-1 GHz frequency range. This gives it the advantage of avoiding much of the interference that can affect other wireless systems, making it particularly reliable in environments with many connected devices.

One of Z-Wave's most well-known features is its mesh networking capability. In a mesh network, devices do not need to communicate directly with the central hub. Instead, each device can pass data to its neighbors, creating multiple possible paths for the data to reach its destination. This means that if one device goes offline or a signal is blocked, the data can simply be routed through another path. This mesh functionality significantly improves the reliability and range of Z-Wave networks, especially in buildings where walls and furniture can obstruct signals. It also makes Z-Wave an appealing option in smart home setups, where many small devices are spread throughout a space.

Z-Wave is also valued for its energy efficiency, which is one of the main reasons it has been widely adopted for battery-powered devices. Z-Wave modules can run on very little power and remain in sleep mode most of the time, waking only when they need to send or receive data. This allows devices to operate for months or even years on a single battery, depending on usage. Another benefit is its strong interoperability. Z-Wave has a well-established standard, and most Z-Wave-certified devices from different manufacturers can communicate with one another without issue. This makes it a highly flexible choice for consumers and developers alike.

Despite all these positives, Z-Wave has some serious limitations—especially when it comes to systems like ours. The most significant of these is its limited data rate. Z-Wave can only transmit data at speeds of up to 100 kbps, which is enough for small commands like “turn on light” or “door is locked,” but completely insufficient for real-time transmission of complex RF detection data. Our aircraft detection system will need to send signal strength, time stamps, GPS

coordinates, and other real-time data to a central server. That kind of data stream requires much faster transmission rates, and Z-Wave simply can't keep up.

Another issue is Z-Wave's limited communication range. In optimal, open-air conditions, Z-Wave may reach up to around 100 meters, but in real-world scenarios—especially those involving trees, terrain, or other physical obstructions—the effective range is often much less. This becomes a major problem for our project, which involves remote deployment of multiple detection units spread over wide areas. We need a system that can handle long-range data transmission, and ideally, one that can do so reliably without relying on a dense network of repeaters. Relying on Z-Wave would force us to install far more infrastructure just to maintain network connectivity, which adds cost, complexity, and additional power needs.

While Z-Wave has found some niche uses in aviation and UAV environments, it is generally limited to non-critical, low-bandwidth monitoring tasks. For example, it has been used in some ground-based airport systems for reporting equipment status or controlling lighting and environmental systems. According to GAO Tek (2023), Z-Wave has shown potential in localized control scenarios where low power consumption and simple status updates are prioritized. However, it has not been shown to perform well in use cases that involve large data sets or time-sensitive communication. That makes it a poor fit for any system that requires real-time analysis, such as the kind our aircraft detection platform depends on.

That being said, we don't completely rule out the potential use of Z-Wave in certain internal or auxiliary roles within a detection node. For instance, it could potentially be used for internal sensor monitoring, such as checking internal temperature, battery level, or case tampering alerts. These tasks don't require high-speed data or long-distance range, and Z-Wave could be a good way to offload that kind of monitoring from the main processor. This kind of internal communication could also be useful during system setup or maintenance, particularly if we later develop a local Z-Wave app that can wirelessly interact with a detection unit at close range.

In conclusion, Z-Wave is a strong protocol for short-range, low-power communication in fixed installations like homes or office buildings. Its ability to create stable mesh networks and its low energy use are definitely strengths, and it has earned its place in the world of IoT and home automation. However, the demands of our passive aircraft detection system—particularly the need for real-time, wide-area communication with moderate to high data throughput—simply exceed what Z-Wave was built to handle. It may find limited use in local monitoring tasks within a detection node, but it is not suitable as the primary communication method between detection units or to the central base station.

3.3.2.3 Near Field Communication (NFC)

Near Field Communication (NFC) is a short-range wireless technology that allows devices to communicate when they are only a few centimeters apart. It operates at 13.56 MHz and offers low data transfer speeds, typically ranging from 106 to 424 kbps (Wikipedia, 2023). NFC is widely used in everyday consumer applications, such as contactless payments, keyless access, and data sharing between smartphones and other smart devices. Its simplicity and security make it ideal for personal transactions and short-distance communication tasks.

NFC's main advantages include its ease of use, as it works with just a simple tap, allowing for quick and secure interactions. Because of its extremely short operating range, it is less vulnerable to hacking or signal interception, making it a good fit for applications where secure, device-to-device communication is needed. It also has very low power consumption, which is helpful in battery-operated devices, especially those requiring infrequent use.

However, NFC has critical limitations that make it impractical for use in our aircraft detection system. Its extremely short range—just a few centimeters—prevents it from supporting any kind of long-distance communication. Additionally, its data rate is far too low for the type of real-time signal processing and communication required for aircraft detection. These limitations mean that NFC cannot support the bandwidth or range needed for unit-to-unit data sharing or cloud synchronization in our system.

In the aviation industry, NFC has been used to improve the passenger experience rather than for detection or data exchange between systems. Some airlines utilize NFC-enabled boarding passes that allow passengers to check in by tapping their phones at airport security gates (Airport Technology, 2023). Airports also use NFC for mobile ticketing, enabling travelers to purchase and store tickets on their smartphones (ResearchGate, 2023). Additionally, NFC can assist with real-time notifications such as gate changes or delay alerts, helping streamline the travel experience (QR Lab, 2023).

In conclusion, while NFC is excellent for short-range, secure, low-power interactions, it is not suitable for the needs of our passive aircraft detection system. The limited communication range and low data throughput prevent it from being used for real-time RF data sharing or system-wide connectivity. As such, NFC is not a viable option for this project.

3.3.2.4 Bluetooth

Bluetooth is a short-range wireless communication technology commonly used to connect devices like headphones, smartwatches, speakers, and smartphones. It operates in the 2.4 GHz frequency range and typically allows wireless data transfer over distances of up to 10 meters. Over the years, Bluetooth has evolved significantly, with the introduction of Bluetooth Low Energy (BLE), which was specifically designed to consume less power, making it well-suited for battery-powered and wearable devices (Bluetooth, 2023).

One of Bluetooth's biggest advantages is its low power consumption, especially in BLE mode, allowing devices to remain connected without quickly draining the battery. It is also widely compatible across a broad range of consumer electronics, thanks to being a standardized protocol supported by virtually all major device manufacturers. In addition to this, Bluetooth is generally easy to use, with most devices offering quick and simple pairing procedures, making it user-friendly for consumers and developers alike.

However, Bluetooth has notable limitations that make it a poor choice for our aircraft detection system. Its limited range—generally no more than 10 meters—makes it unsuitable for long-distance or wide-area communication. This is especially problematic in our project, where detection units are likely to be spaced far apart. Furthermore, Bluetooth operates on the same 2.4 GHz band as Wi-Fi, which can cause interference and reduce reliability, particularly in

environments with many competing wireless signals. These drawbacks limit Bluetooth's usefulness in applications requiring real-time, uninterrupted data transmission across multiple detection nodes.

In aviation, Bluetooth is primarily used for enhancing passenger experience, rather than for system-critical operations like detection. For instance, United Airlines and other carriers have begun installing Bluetooth-enabled in-flight entertainment systems, allowing passengers to connect their own wireless headphones during flights (United Media Room, 2023). Additionally, some airports use Bluetooth beacons to help guide passengers through terminals with real-time navigation, baggage tracking, and flight updates (MokoBlue, 2023).

In conclusion, while Bluetooth is a convenient and energy-efficient communication tool for short-range, low-bandwidth applications, its limited range and vulnerability to interference make it a poor fit for our passive aircraft detection system. However, it could still play a supporting role in localized communication between nearby modules or user interfaces, provided the devices remain in close proximity within a controlled setting.

3.3.2.5 Wi-Fi

Wi-Fi is one of the most widely used wireless communication technologies in the world today. It has become the standard for providing internet access in homes, schools, offices, airports, and just about any place where a wireless connection is needed. Operating mainly in the 2.4 GHz and 5 GHz frequency bands, Wi-Fi offers relatively high-speed data transmission over short to medium distances. More recently, advanced versions such as Wi-Fi 6 and Wi-Fi 6E have been introduced to increase speed, reduce latency, and improve performance in crowded environments. Wi-Fi 7 is also on the horizon, promising even better speeds and network efficiency.

One of the major strengths of Wi-Fi is its fast data rate. Depending on the standard in use, Wi-Fi can support data transfer rates of several hundred megabits per second or even more. This makes it perfect for high-bandwidth applications like streaming high-definition videos, playing online games, downloading large files, and video conferencing. It's also very easy to set up and widely available, with built-in support in nearly all laptops, smartphones, tablets, smart TVs, and a wide range of IoT devices. This level of compatibility means it integrates well into existing infrastructure, which is one of the reasons why Wi-Fi is so common in both personal and commercial environments.

In addition to fast speeds, Wi-Fi's cable-free operation allows for flexible device placement. Unlike wired Ethernet, which requires physical cables and limits mobility, Wi-Fi gives users the ability to move freely while staying connected. This is especially useful in larger indoor spaces, such as offices or warehouses, where running cables might be expensive or impractical. For small-to-medium area coverage where bandwidth is more important than range, Wi-Fi is often the default solution due to its convenience and speed.

However, when looking at Wi-Fi through the lens of our senior design project—a passive aircraft detection system meant for wide-area, outdoor use—there are several drawbacks that make it an impractical choice as the main communication technology. One of the biggest issues is range.

While Wi-Fi might offer up to 100 meters of coverage in ideal open-air conditions, this range drops significantly when there are obstructions such as buildings, walls, trees, or uneven terrain. Our system is designed for deployment across wide open areas, where detection nodes may need to be hundreds of meters or even kilometers apart. Using Wi-Fi would require the installation of numerous repeaters or mesh nodes just to maintain a stable connection, which adds cost, complexity, and power requirements that aren't ideal for solar-powered, remote installations.

Another major limitation of Wi-Fi is the potential for interference. Wi-Fi operates in frequency bands that are heavily used by other devices, including Bluetooth accessories, microwave ovens, baby monitors, cordless phones, and other Wi-Fi networks. This congestion can cause signal instability, dropped connections, or reduced speeds—especially in urban or populated areas. For a system like ours, which may need to transmit sensitive RF detection data in real-time, these types of interruptions are unacceptable. Reliable communication is critical, and Wi-Fi's vulnerability to interference introduces a risk we simply can't afford.

It's also important to consider the power requirements of Wi-Fi. While modern modules are more power-efficient than older ones, Wi-Fi is still not considered a low-power communication technology, especially when compared to alternatives like LoRa, Zigbee, or even Starlink SATCOM in standby mode. For a field-deployable system powered by solar panels and batteries, every milliamp of current matters. Using a Wi-Fi module that consumes power continuously, even when not transmitting, would drain the battery faster and reduce uptime, especially during periods of limited sunlight.

Looking at real-world aviation and transportation use cases, Wi-Fi is indeed used in a number of ways—but mostly for passenger experience and convenience, not for operational or mission-critical systems. For example, many airlines offer in-flight Wi-Fi, allowing passengers to access the internet during flights. This service is often limited in bandwidth, with reduced speeds and higher latency compared to home networks. Wi-Fi is also used in airports to provide public internet access, update flight information, and help travelers navigate terminals using location-aware services. Some baggage handling systems also use Wi-Fi for tracking and routing purposes. However, all these applications are relatively low-risk and do not require the kind of guaranteed real-time communication that our system demands.

In contrast, our project involves detecting aircraft signals, processing them locally, and then transmitting data back to a base station or cloud server for further analysis. That requires consistent communication across large areas, potentially in regions with very little infrastructure. Wi-Fi simply was not designed for this use case. Its reliance on relatively short-range transmission, its interference-prone frequency bands, and its higher-than-desired power usage make it a poor fit for outdoor, solar-powered, autonomous detection units.

That said, Wi-Fi could still have limited uses in our system, though not in the main communication pathway. For instance, we could use Wi-Fi during the setup and calibration process in the field. A technician could connect to a detection unit using a mobile device or laptop over a temporary Wi-Fi hotspot broadcast by the unit, allowing configuration changes, firmware updates, or system diagnostics to be performed without needing to physically open the enclosure. This approach is used in many embedded and IoT devices that rely on wireless access for maintenance rather than constant data transmission. Wi-Fi might also be used during

development and testing phases when we're working in lab environments or doing short-range trials.

In conclusion, while Wi-Fi is a well-known, fast, and flexible wireless communication method, it falls short in several key areas that matter for our project. Its range is too short for large-scale, outdoor deployment; it is vulnerable to signal interference; and its power demands are not ideal for a solar-powered, long-life detection system. Wi-Fi is excellent for indoor, consumer-level communication and works well for non-critical tasks like browsing or streaming. But for wide-area, real-time, low-latency data transfer in remote locations, it doesn't meet the necessary requirements. As a result, Wi-Fi will not be used as the primary communication protocol for our aircraft detection system. We may still leverage it during system setup or internal testing, but it will not play a role in final field deployments.

3.3.2.6 Starlink Satellite Communication (SATCOM)

Starlink, developed by SpaceX, is a revolutionary satellite-based internet service that provides high-speed, low-latency broadband connectivity almost anywhere on Earth. Unlike traditional satellite internet services that rely on a few large geostationary satellites orbiting at altitudes around 35,000 kilometers, Starlink operates a growing constellation of thousands of low Earth orbit (LEO) satellites. These satellites orbit at much lower altitudes—approximately 550 kilometers above the surface—which significantly reduces the signal travel time, resulting in lower latency and faster, more stable internet connections.

The use of LEO satellites is a major advantage for communication systems that require real-time data transmission, as it brings satellite internet performance much closer to that of ground-based broadband. Traditional satellite internet often suffers from high latency—sometimes over 600 milliseconds—due to the long distances signals must travel to reach geostationary satellites. In contrast, Starlink regularly delivers latency in the range of 25 to 60 milliseconds, with download speeds between 25 Mbps and 220 Mbps and upload speeds around 5 to 20 Mbps. This performance enables real-time communication tasks such as video conferencing, online gaming, and most importantly for our project, real-time data transfer from field units to a central server.

One of Starlink's most appealing features is its global coverage. Because it does not depend on ground-based infrastructure, Starlink can provide internet access in extremely remote or rural locations where traditional service providers have no presence. This makes it particularly useful for field operations that require reliable internet access in areas where fiber or cellular networks are unavailable or inconsistent. For our project—developing a passive aircraft detection system that may be deployed along remote borders or in unpopulated terrain—this feature is not just helpful, it is essential.

Each of our detection nodes needs to communicate with a central processing server in real time or near-real time to ensure aircraft tracking is consistent and up to date. Because we are working with remote deployment scenarios where traditional networking solutions are not viable, we needed a communication system that is location-independent, low-latency, and capable of handling moderate data loads. Starlink checks all of those boxes. It allows us to connect each node to the internet as if it were located in a city with modern broadband infrastructure, enabling

centralized data collection, monitoring, and processing without the need for building new towers or laying network cables.

Another important factor is the scalability of Starlink. As our system grows and we add more detection units to expand the monitored area, we don't need to redesign or expand the communication network itself. Each unit connects to the same Starlink constellation and can independently relay data to the central system. This allows us to scale the project across long distances and large regions with minimal infrastructure adjustments. All that's needed is access to power—supplied by solar panels and battery systems—and a clear view of the sky.

That said, Starlink does have some limitations. Like any satellite-based service, it requires a mostly unobstructed view of the sky to function properly. Trees, hills, tall buildings, or other large physical obstacles can interfere with the signal, leading to slower speeds or temporary disconnections. This makes site selection and unit placement extremely important in our project. Each detection unit must be positioned in a way that ensures the satellite dish can maintain a clear line of sight to the sky. In forested or mountainous areas, this may require placing units on raised masts or clearing vegetation around the installation site.

Additionally, while Starlink is far more reliable than older satellite systems, it is still susceptible to environmental conditions such as heavy rain, snow, or thick cloud cover. These weather events can temporarily disrupt the signal or degrade performance. Although Starlink's phased array antennas and adaptive routing algorithms help mitigate some of these effects, they remain a factor to consider in the overall system design. To handle this, we are factoring in weather-based signal degradation into our redundancy planning and data buffering strategies. Detection units will store recent data locally if needed, and automatically resume transmissions once the connection is stable again.

Power consumption is another area where Starlink differs from some of the lower-power alternatives considered in this report, such as Zigbee or LoRa. Starlink's satellite receiver dishes and routers consume significantly more power—especially during startup and high-activity periods. For a solar-powered project like ours, this means we need to carefully size our solar panels and battery capacity to handle the energy demand of both the Starlink terminal and the detection system's internal electronics. According to various independent tests, Starlink units consume approximately 50 to 75 watts during normal operation, which is manageable but requires planning, especially for off-grid use.

Despite these minor challenges, the benefits of Starlink for our project far outweigh the drawbacks. In real-world use cases, Starlink has been successfully deployed in emergency response scenarios, military operations, and remote scientific research stations. In all of these examples, it has demonstrated the ability to maintain strong internet connectivity in places where no other internet solution is feasible. We are taking a similar approach, leveraging Starlink's reach and performance to bridge the communication gap between our remote detection units and our centralized control infrastructure.

What's also worth noting is how Starlink simplifies other parts of our system. Because it essentially brings modern internet access to each detection node, we can use widely available tools and platforms—like cloud databases, RESTful APIs, secure file transfer protocols, and

real-time dashboards—without having to custom-build a low-bandwidth or high-latency workaround. This streamlines development and debugging and helps ensure our system is modular and future-proof.

For instance, during testing, we can stream live telemetry data from detection units to a monitoring dashboard without delay. In full deployment, we can send system updates, collect diagnostics, and remotely troubleshoot or reboot units over the same connection. These features make Starlink more than just a communication link—it becomes part of the backbone of our system’s intelligence, flexibility, and maintainability.

As the Starlink constellation continues to grow, its performance is expected to improve even further. SpaceX regularly launches new satellites to fill gaps in coverage, enhance bandwidth, and reduce latency. These upgrades will directly benefit our system over time, giving us better performance without needing to change any hardware on our end. This kind of future-proof communication technology is rare, especially in the satellite space, and it aligns well with our goal of building a sustainable, long-term system that can evolve with changing needs.

In summary, Starlink is by far the most effective communication technology available for our passive aircraft detection system. It offers high-speed, low-latency connectivity that enables real-time data transmission from remote units to a central processing hub. Its global coverage, scalability, and plug-and-play nature make it ideal for a system that may be deployed in a variety of geographic and environmental conditions. While signal interruptions due to obstructions or weather are possible, they are manageable with good planning and robust software strategies. Compared to every other protocol considered—whether it's Wi-Fi, Z-Wave, or LoRa—Starlink delivers the best combination of performance, reliability, and future scalability. For these reasons, Starlink will serve as the central communication backbone of our detection network, ensuring data gets where it needs to go, when it needs to be there.

3.4 Software Technologies

3.4.1. C/C++

Role in the Project

C and C++ play a critical role in the embedded software development for our Low-Cost Passive Aircraft Detection System. These languages are used to program the microcontrollers and embedded processors that power our RF detection units. Their robust capabilities enable direct control of essential components such as RF front-ends, GPS modules, spectrum analyzers, and digital signal processors (DSPs). Within our system architecture, embedded software written in C/C++ is responsible for real-time signal acquisition, filtering, detection, time synchronization, and communication with the main analysis unit or cloud server. Tasks such as parsing RF waveform data, timestamping events, performing Fast Fourier Transforms (FFTs), and managing memory buffers require the precise and deterministic behavior that C and C++ are known for.

Relevance and Justification

- Performance and Efficiency

C and C++ are highly efficient, compiled languages that deliver fast execution times and low-level control over memory and CPU cycles—qualities essential for real-time systems.

Unlike higher-level languages such as Python or Java, C/C++ generate machine-level code that runs natively on the hardware without the need for virtual machines or interpreters. This enables faster data throughput, minimal latency, and lower power consumption, which are critical for remote RF detection systems that may rely on limited battery or solar power (Aversan, 2023). Moreover, C++ supports object-oriented programming (OOP), which helps organize large codebases into modular, reusable components, aiding in long-term maintenance and scalability.

- **Direct Hardware Interaction**

One of the standout features of C and C++ is the ability to interact directly with hardware via memory-mapped registers, I/O ports, and low-level system calls. This is crucial when configuring and operating peripherals such as analog-to-digital converters (ADCs), RF mixers, and GPS clocks. For example, timing precision in Time Difference of Arrival (TDOA) calculations relies on synchronized clocks and deterministic event capturing, which C/C++ handle reliably through bare-metal programming or integration with real-time operating systems (RTOS). Libraries such as CMSIS (Cortex Microcontroller Software Interface Standard) and libopencm3 provide low-level access that fits seamlessly into C/C++ development environments, giving developers control down to the clock cycle.

- **Industry Adoption and Long-Term Support**

C and C++ are industry standards in aerospace, defense, automotive, and embedded systems due to their proven reliability and mature toolchains. Many real-time systems—including FreeRTOS, Zephyr, VxWorks, and RTEMS—are developed in or compatible with C/C++. The availability of robust debugging tools, extensive documentation, and a vast ecosystem of community and industry support further reinforces the decision to use these languages. Moreover, critical third-party libraries for DSP, SDR (Software Defined Radio), signal filtering, and cryptographic security are predominantly written in C/C++, ensuring high compatibility and performance (Scythe-Studio, 2022).

3.4.2. Java

Role in the Project

Java plays a central role in the software architecture of our Low-Cost Passive Aircraft Detection System, specifically powering the backend infrastructure that supports data processing, system coordination, and user access. Once the sensor units detect and collect RF signal data from aircraft, this information is transmitted to the backend system, which is built using Java. Java is responsible for a wide range of backend tasks, including data aggregation from multiple detection units, secure user authentication, real-time API management for external communication, and storing processed results in the cloud or local databases. Furthermore, Java acts as the middleware that interfaces between the hardware units and the cloud infrastructure, ensuring seamless and efficient data flow throughout the system. Its integration with cloud APIs, logging mechanisms, and database systems makes it a critical technology for enabling system-wide scalability, reliability, and performance.

Relevance and Justification

- **Platform Independence**

One of the primary reasons for selecting Java is its platform independence. Java applications run on the Java Virtual Machine (JVM), which abstracts away the underlying operating system. This "write once, run anywhere" capability allows our backend software to be deployed across diverse environments—whether on-premises Linux servers, cloud-based virtual machines, or dedicated edge computing platforms—without requiring significant code modifications. This flexibility is vital for our system, as it will operate in both centralized cloud environments and potentially decentralized edge nodes. Java's support for Docker and containerized deployments further enhances its platform-agnostic nature, allowing us to use the same codebase in various configurations without compatibility issues (Coursera, 2023).

- **Multithreading and Concurrency**

Java is highly effective at handling concurrency, which is essential for a system like ours that processes data from multiple RF detection units simultaneously. Our backend must be capable of concurrently receiving incoming signals, parsing and validating those inputs, running localization algorithms, and delivering detection results to a central monitoring interface—all in real-time. Java's robust threading model and concurrency libraries (like the `java.util.concurrent` package) allow us to perform these operations in parallel without blocking the main execution threads. This ensures smooth performance even under high-load conditions and enhances the responsiveness of the system when processing large amounts of data from multiple remote sites.

- **Security and Stability**

Given that our aircraft detection system is responsible for monitoring potentially sensitive flight activity and may be deployed in areas with limited technical support, security and stability are critical. Java's memory management, enabled through its garbage collector, minimizes memory leaks and crashes that are common in lower-level languages. Furthermore, Java includes comprehensive exception-handling mechanisms, which help the system recover gracefully from unexpected errors such as data transmission faults, device communication failures, or malformed input data. Security-wise, Java offers built-in encryption libraries, role-based access control frameworks, and secure RESTful API development tools, all of which help us build a robust and secure backend environment (Moldstud, 2023). These features are especially important when integrating with cloud services like AWS or Azure, where security compliance is essential.

- **Extensibility and Ecosystem**

Another major advantage of using Java is its mature and well-supported ecosystem. Libraries like Spring Boot, Hibernate, and Apache Kafka enable rapid backend development with reliable patterns for authentication, database access, message queuing, and microservices deployment. The use of Spring Boot in particular allows us to develop REST APIs that can be consumed by mobile apps, web dashboards, or automated reporting tools. Moreover, Java integrates well with container orchestration systems like Kubernetes, allowing for horizontal scalability of backend services as more detection nodes are added during Phase 2 of the project.

3.4.3. Python

Role in the Project

Python plays a critical role in the software architecture of our Low-Cost Passive Aircraft Detection System by enabling advanced data processing, RF signal analysis, and localization algorithm development. While the embedded sensor units capture raw RF signals, it is Python that transforms this data into actionable insights such as aircraft location, altitude, speed, and

trajectory. This is accomplished through a series of signal processing pipelines, machine learning models, and mathematical operations that are implemented and tested using Python's robust scientific computing ecosystem. Furthermore, Python supports the development of automation scripts, data cleaning routines, and batch analysis tools that assist in post-processing and refining signal data collected over time. Whether used for prototyping real-time multilateration techniques or visualizing aircraft movement on geographic overlays, Python is integral to the high-level intelligence layer of our system.

Relevance and Justification

- **Rapid Development and Prototyping**

One of Python's greatest advantages is its simplicity and readability, which accelerate development cycles significantly. This allows our team to rapidly prototype signal processing and localization algorithms and test them in simulated or real-world environments. Compared to lower-level languages like C++ or more structured environments like Java, Python's concise syntax reduces the overhead involved in writing and debugging code. This agility is especially important during the iterative development of algorithms used for aircraft detection, where performance tuning and data modeling must evolve quickly based on field testing results (Coursera, 2023). With Python, our team can experiment with multiple approaches—such as signal thresholding, clustering, or regression-based localization—without incurring the delay of longer development cycles.

- **Scientific Computing and Data Processing**

Python is renowned for its extensive collection of scientific and data analytics libraries, which provide powerful tools for signal filtering, statistical modeling, and visualization. Libraries such as NumPy and SciPy allow us to perform Fourier transforms, filter noise, and process signal strength data from multiple detection units. Pandas is used for handling large datasets and managing time-series data, while Matplotlib and Seaborn provide dynamic and customizable visualizations of aircraft trajectories, detection accuracy, and signal intensity maps. Additionally, Python supports machine learning libraries like scikit-learn, TensorFlow, and PyTorch, which are valuable for building classifiers to distinguish between aircraft and environmental interference. These tools make Python a natural fit for the computational tasks that lie at the heart of our passive detection strategy (SnapLogic, 2023).

- **Integration with Other Languages**

While Python offers powerful high-level abstractions, it also excels in integrating with low-level languages like C and C++ using tools such as Cython, ctypes, or the Python/C API. This hybrid programming approach allows us to offload real-time, performance-intensive signal processing tasks to compiled C++ libraries while retaining Python for high-level coordination and visualization. For example, a core RF signal decoding function might be written in C++ for speed, while Python manages the aggregation of decoded packets, applies localization algorithms, and displays aircraft paths on a graphical interface. This cross-language integration maximizes the strengths of each language and ensures that our system performs efficiently while remaining easy to maintain and extend.

Conclusion

In summary, Python plays a pivotal role in transforming raw RF signal data into useful detection results in our aircraft monitoring system. Its rapid development capabilities, extensive scientific libraries, and flexible integration with C/C++ make it the ideal choice for developing signal analysis workflows and localization models. When combined with the embedded control provided by C/C++ and the secure, scalable backend support of Java, Python completes a powerful triad of technologies that work together to deliver a robust and intelligent aircraft detection solution. This multi-language strategy enables our system to balance real-time performance with analytical depth, ensuring reliable and actionable detection outcomes in a cost-effective and scalable manner.

3.4.4. Development Environment: Languages and Repositories

For this project, we have chosen C/C++, Java, and Python as our primary programming languages. Each of these languages serves a specific purpose, optimized for different components of our system. C/C++ is used for embedded programming on the sensor units, Java is utilized for backend server operations and system management, and Python is primarily used for data processing, analysis, and algorithm implementation. By leveraging the strengths of each language, our system achieves high performance, real-time processing, efficient networking, and scalability.

3.4.5 Language Selection

For our passive aircraft detection system, we need a programming language that can efficiently handle real-time signal processing, hardware interfacing, cloud connectivity, and automation while ensuring ease of development and scalability. After evaluating multiple options, we have chosen Python as the best programming language for our project due to its versatility, extensive library support, and strong compatibility with Raspberry Pi.

Python is particularly well-suited for real-time data processing as it provides powerful libraries such as NumPy, SciPy, and scikit-dsp-comm for RF signal analysis, filtering, and data processing. Since our system relies on sensor data and RF signals to detect aircraft, Python's ability to handle large datasets efficiently makes it an ideal choice. Additionally, Python seamlessly interfaces with Raspberry Pi's GPIO, I2C, SPI, and UART communication protocols, allowing us to connect and control sensors, RF modules, and other hardware components with ease.

Another major advantage of Python is its built-in networking support, which enables seamless cloud connectivity and remote monitoring. With Python, we can develop APIs, automate data uploads, and establish communication between our detection units and cloud servers, ensuring real-time data transmission and analysis. Furthermore, if we decide to enhance our system with AI-based detection in the future, Python's compatibility with machine learning libraries such as TensorFlow, OpenCV, and Scikit-Learn makes it a future-proof choice.

Python also simplifies system automation and error handling, allowing us to schedule detection tasks, manage logs, and implement recovery mechanisms in case of system failures. Additionally, Python is officially supported by Raspberry Pi, meaning there is extensive community support, abundant documentation, and numerous open-source resources that can accelerate development and troubleshooting.

While C/C++ is better for low-latency signal processing, Python's flexibility, rapid development capabilities, and strong ecosystem make it the best overall choice for our project. If performance optimization is required, we can integrate C extensions with Python to achieve the necessary computational efficiency while maintaining Python's simplicity and ease of use. By choosing Python, we ensure that our passive aircraft detection system remains efficient, scalable, and adaptable for future enhancements.

3.4.6 Data Transfer Mechanism

The data transfer mechanism ensures that information is communicated efficiently between different parts of the system, including detection units, cloud storage, and the user interface. Since the system operates in remote locations, it requires reliable, low-bandwidth communication protocols for data transmission.

Communication Protocols Used

Table 3.11 Data Transfer Protocols

Protocol	Use Case	Advantages
MQTT	Sending real-time detection data from units to the cloud.	Low bandwidth, ideal for IoT systems.
HTTP/HTTPS API	Secure data exchange between cloud services and UI.	High security and widely supported.
WebSocket	Live data updates for dashboard monitoring.	Reduces latency and ensures live data streaming.
UART, SPI, I ² C	Communication between embedded components.	Efficient for hardware-level data transfer.
TCP/IP & UDP	Large-scale data transmission over networks.	High-speed, stable, and reliable.

3.4.7 Data Transmission Process

RF Signal Detection and Pre-Processing

The first stage in the data transmission process begins with the aircraft detection units, which are strategically deployed in remote locations to monitor RF signals continuously. These detection units are equipped with RF receivers and signal processing components that scan predefined frequency bands to capture possible aircraft communication signals. Once a signal is detected, it undergoes pre-processing, which includes filtering out noise, enhancing signal clarity, and extracting relevant features such as signal strength, frequency, and modulation type. The pre-processing step is crucial in ensuring that only valid and high-quality signals are considered for further analysis, reducing the chances of false detections.

To prevent loss of critical data during transmission failures, the system employs a local data storage mechanism at each detection unit. This means that all detected signals are temporarily stored in local memory or a database before being transmitted to the cloud. The local storage ensures that even if the network connection is temporarily unavailable, the system retains all captured detection events. Once the network is restored, the stored data is transmitted sequentially to ensure that no detection logs are lost. This approach enhances the reliability of the system and allows it to function effectively even in harsh or network-constrained environments.

Cloud Transmission via MQTT and HTTPS APIs

Once the RF signal data is pre-processed and temporarily stored, it is transmitted to a centralized cloud server for further processing and analysis. The system employs two primary communication protocols for this process:

MQTT (Message Queuing Telemetry Transport) – This lightweight messaging protocol is used for real-time data transfer between the detection units and the cloud. MQTT is specifically designed for low-bandwidth applications, making it ideal for remote deployments where network availability may be limited. The system establishes a persistent connection between the detection unit and the cloud server, ensuring that data is transmitted efficiently with minimal overhead.

HTTPS APIs (Hypertext Transfer Protocol Secure) – For secure and structured data transmission, the system also utilizes RESTful APIs over HTTPS. This ensures that all detection data is encrypted and transmitted securely to prevent unauthorized access or tampering. The HTTPS API is primarily used for batch uploads of detection logs, historical data synchronization, and retrieving stored information for further processing.

Real-Time Data Retrieval and UI Updates Using WebSockets

Once the detection data reaches the cloud, it becomes available for retrieval by the User Interface (UI). To ensure real-time monitoring, the system uses WebSocket technology for continuous two-way communication between the cloud and the UI. Unlike traditional HTTP requests, which require frequent polling to retrieve updates, WebSockets enable the system to push data directly to the UI as soon as new detection events are received. This significantly reduces latency and provides instantaneous updates to users.

When an aircraft is detected, the UI immediately displays the detection event, including key details such as:

- Aircraft ID (if available)
- Signal strength and frequency
- Geolocation data (latitude, longitude, altitude)
- Detection timestamp

This ensures that operators have up-to-the-minute awareness of detected aircraft, allowing them to make informed decisions. Additionally, the UI provides options for filtering, analyzing historical records, and exporting data for further study.

Optimization Techniques for Efficient Data Transmission

Since the system operates in environments where network bandwidth may be constrained, efficiency optimizations are implemented to ensure smooth data transmission while reducing resource consumption.

Data Compression Techniques – Before transmission, the system compresses detection data to reduce the size of transmitted packets. This helps minimize bandwidth usage, allowing the

system to send more data over the same network capacity. Common techniques include gzip compression, binary encoding, and lightweight data formats such as JSON.

Error Detection and Checksum Validation – To prevent data corruption during transmission, the system employs checksum validation techniques. This involves appending an integrity check to each data packet before transmission. When the data is received on the cloud server, the checksum is verified to confirm that the data has not been altered or lost in transit. If an inconsistency is detected, the system automatically requests retransmission of the affected data packets.

Automatic Retry and Failover Mechanisms – In cases where network interruptions occur during data transmission, the system includes automatic retry mechanisms to ensure that data is eventually delivered. If a detection unit fails to transmit data due to a temporary network failure, it will store the unsent data locally and attempt to resend it at regular intervals. If the primary cloud server is unreachable for an extended period, the system is designed to switch to an alternative backup server to maintain data continuity.

3.4.8 Data Structure and Storage

To manage and store detection data effectively, the system uses a structured database schema that allows efficient retrieval, filtering, and analysis. The data structure is optimized for real-time processing, ensuring that the system can handle large volumes of incoming signals without performance degradation.

Table 3.12 Storage Solutions

Storage Type	Use Case	Advantages
JSON	Storing real-time detection data in a structured format.	Lightweight, easy to parse and transfer.
SQL Database	Long-term storage of aircraft detection records.	Supports complex queries and filtering.
NoSQL Database	Storing rapidly changing detection data	High-speed access and scalable storage.
CSV/Flat Files	Storing raw detection logs for offline access.	Simple, human-readable format.

Each detection event contains the following key attributes:

- **Timestamp** – The exact time the signal was detected.
- **Signal Strength** – The power level of the detected RF signal.
- **Frequency** – The frequency at which the signal was captured.
- **Aircraft ID** – If identified, the unique ID of the aircraft.
- **Location** – Includes latitude, longitude, and altitude of the detected aircraft.

- **Validation Status** – Determines whether the detection is confirmed or a false positive.

3.4.9 Software Architecture and System Workflow

The software architecture follows a modular design, allowing different system components to work independently while seamlessly interacting through APIs and data pipelines.

Table 3.13 Software Architecture

Software Module	Function
RF Signal Processor	Captures, filters, and processes RF signals from detection units
Detection Algorithm	Validates and identifies aircraft based on detected signals.
Data Logger	Stores processed data locally and in cloud databases.
Cloud Communicator	Transmits data to cloud storage and external servers.
User Interface Handler	Retrieves and displays detection data for user monitoring.

The software system operates as follows:

- The RF Signal Processor detects and filters incoming signals.
- The Detection Algorithm validates aircraft presence based on predefined criteria.
- Processed data is stored locally and transmitted to cloud storage via MQTT or HTTP APIs.
- The UI retrieves and displays real-time detection data for monitoring and analysis.

To ensure system stability, the software architecture follows fault tolerance techniques, such as error handling, automated recovery, and redundancy mechanisms. These measures allow the system to continue functioning even in the event of network interruptions or hardware malfunctions.

Chapter 4 Standards and Design Constraints

4.1 Software

4.1.1 Software Standards

To ensure the reliability, security, and efficiency of our passive aircraft detection system, we must adhere to industry software standards that define best practices for software development, data security, and system interoperability. These standards help us maintain software quality, prevent security vulnerabilities, and ensure long-term maintainability. Two key software

standards that are most relevant to our project are IEEE 12207 for software development lifecycle and ISO/IEC 27001 for information security management.

4.1.1.1 IEEE 12207 – Software Life Cycle Processes

The IEEE 12207 standard provides a structured framework for software development and maintenance, ensuring that all aspects of the software lifecycle are well-defined, repeatable, and scalable. This standard is essential for our passive aircraft detection system, as our software must undergo continuous updates, testing, and integration with cloud services to ensure long-term performance, reliability, and security. Given that our system involves real-time RF signal processing, cloud-based communication, and automated aircraft detection alerts, adhering to a structured software development methodology is crucial to maintaining stability and efficiency.

One of the key benefits of IEEE 12207 is that it establishes a systematic approach to software development, beginning with requirements analysis. This phase involves identifying both functional and non-functional software requirements, ensuring that the system meets all necessary performance and security needs. Functional requirements include the ability to process RF signals in real time, communicate with cloud-based monitoring platforms, and generate automated alerts for detected aircraft. Meanwhile, non-functional requirements focus on factors such as software reliability, efficiency, and compliance with cybersecurity best practices. By defining these requirements early in the development cycle, we can ensure that our system is designed to function optimally under various deployment conditions.

Once the requirements are established, the next phase is software design and development, where the system's architecture is structured to support modularity and scalability. To ensure efficient functionality, different software components—including signal processing, data logging, networking, and cloud communication—will be independently tested and integrated. A modular software structure allows for easier maintenance and the ability to introduce future enhancements without disrupting the entire system. Additionally, by incorporating object-oriented programming principles and API-based design, we can enhance the system's flexibility and compatibility with other software components and external services.

After the design and development phase, testing and validation play a critical role in ensuring that the system operates reliably under real-world conditions. Unit tests will verify the functionality of individual software modules, while integration tests will ensure that all components work seamlessly together. Additionally, real-world deployment tests will be conducted to simulate operational environments and assess system performance in different scenarios. Since our detection system relies on wireless communication and cloud-based data transmission, testing will also evaluate network stability, latency, and overall responsiveness to ensure that the system meets performance expectations.

Once the software passes testing, the deployment and maintenance phase ensures that the system can be continuously updated and improved. Software updates will be managed through continuous integration and continuous deployment (CI/CD) pipelines, allowing us to release feature enhancements, security patches, and performance optimizations efficiently. Version control mechanisms will be in place to ensure that system administrators can roll back updates in case of errors. Additionally, a long-term maintenance strategy will be implemented, where

software logs and system metrics will be analyzed to identify performance bottlenecks and improve system efficiency over time.

Another critical aspect of IEEE 12207 is the emphasis on documentation and traceability, which ensures that all software components are well-documented, making future maintenance and upgrades more manageable. Proper documentation includes detailed software design specifications, user manuals, debugging procedures, and system architecture diagrams. This level of documentation provides transparency and allows future developers or system administrators to understand, modify, and expand the system without introducing errors or inefficiencies.

By following the IEEE 12207 standard, our software development process will remain structured, scalable, and optimized for long-term reliability. This approach will help us reduce software development risks, improve collaboration among team members, and ensure that the system remains maintainable and adaptable as new requirements arise. Given the complexity of our aircraft detection system, adhering to this internationally recognized standard will contribute significantly to ensuring the project's success and sustainability.

4.1.1.2 ISO/IEC 27001 – Information Security Management

Since our passive aircraft detection system relies on real-time wireless data transmission, ensuring information security and data integrity is one of our top priorities. The ISO/IEC 27001 standard is an internationally recognized framework for information security management, providing guidelines to protect sensitive data, prevent cybersecurity threats, and maintain system integrity. This standard is critical for our project because our system must transmit and store detection data over wireless networks, cloud servers, and satellite-based communication channels, which makes it vulnerable to data breaches, unauthorized access, and cyber threats.

One of the most important aspects of ISO/IEC 27001 is data encryption, which ensures that all transmitted aircraft detection data is protected from unauthorized interception. To achieve this, we will implement Transport Layer Security (TLS) and Secure Sockets Layer (SSL) protocols, ensuring that all communications between our detection system and cloud-based analytics platforms remain encrypted. Additionally, for sensitive stored data, Advanced Encryption Standard (AES-256) encryption will be used to provide a high level of protection against potential breaches. By encrypting both transmitted and stored data, we can prevent data leaks and unauthorized access to sensitive detection logs.

Another critical component of ISO/IEC 27001 is access control and authentication. To ensure that only authorized personnel can access the system's cloud storage and remote monitoring platform, we will implement multi-factor authentication (MFA) as an additional security layer. This means that users will need to verify their identity through multiple authentication steps before gaining access. Furthermore, we will use role-based access control (RBAC) to limit the level of access granted to different users based on their responsibilities. This prevents unauthorized users from modifying system configurations or accessing restricted data, enhancing overall system security.

To maintain a strong security posture, regular threat assessment and risk management must be conducted. Our team will implement security audits, penetration testing, and vulnerability assessments to identify potential weaknesses in our software and network infrastructure. By

continuously monitoring the system for security risks, we can proactively address potential threats before they become critical vulnerabilities. Additionally, incident response protocols will be established to handle cybersecurity incidents efficiently, ensuring that any breaches or attempted intrusions are quickly detected, mitigated, and documented.

Another essential security measure under ISO/IEC 27001 is logging and auditing, which ensures that all system transactions, user activities, and data access events are recorded and stored securely. These logs will help track any unauthorized access attempts and allow system administrators to analyze patterns of suspicious activity. Additionally, regular audits will be conducted to ensure that security controls remain effective over time. By maintaining detailed logs and performing periodic security reviews, we can enhance accountability and traceability, ensuring that any potential security incidents are investigated and resolved efficiently.

In addition to securing our system, compliance with ISO/IEC 27001 also ensures that our project aligns with global data protection regulations. We will ensure that our security policies adhere to standards such as the General Data Protection Regulation (GDPR) and the National Institute of Standards and Technology (NIST) Cybersecurity Framework, reinforcing our commitment to data privacy and regulatory compliance. Additionally, any cloud service providers we use—such as AWS, Google Cloud, or Azure—must also comply with ISO 27001 standards to ensure that our stored data remains protected under industry best practices.

By implementing ISO/IEC 27001, we establish a comprehensive security framework that safeguards our system from cyber threats while ensuring secure data transmission and storage. This standard enables us to protect sensitive aircraft detection data, prevent system vulnerabilities, and maintain user trust. Security is a fundamental requirement for our project, and adhering to ISO/IEC 27001 will ensure that our aircraft detection system remains resilient, compliant, and capable of withstanding modern cybersecurity challenges.

4.2 Hardware

Developing a network of passive aircraft detection units requires careful planning and adherence to hardware standards to ensure that the system operates efficiently, reliably, and within legal regulations. Our system's deployment in remote and potentially harsh environments, combined with its reliance on passive RF detection and satellite communication, creates unique challenges that must be carefully addressed in the hardware design. The detection units must be self-sustaining, operate for long durations without maintenance, and transmit data securely and efficiently to a central processing hub.

One of the most critical aspects of hardware design is ensuring compliance with industry regulations, particularly those governing RF emissions, electronic safety, and wireless communication protocols. Failure to meet these regulations could result in interference with other communication systems, reduced system performance, or legal complications. In addition, given that our system is deployed in remote locations, hardware reliability is a major concern. Components must be rugged, weatherproof, and resistant to extreme environmental conditions, including high temperatures, humidity, and potential physical impact.

Another key hardware challenge is power management. Since our detection units will be solar-powered, energy efficiency is crucial for maintaining continuous operation, even in low

sunlight conditions. The system must incorporate low-power embedded processors, efficient voltage regulation, and optimized power consumption strategies to ensure maximum uptime. Additionally, the system's computational capacity must be carefully optimized to balance processing speed and power efficiency, ensuring that signal detection and data transmission occur without excessive delays.

Furthermore, our system's reliance on satellite communication (Starlink SATCOM) introduces additional hardware constraints, including bandwidth limitations, latency concerns, and the need for high-gain antennas to maintain a stable connection. The communication modules must be designed to handle real-time data transmission efficiently, compressing data where possible to minimize network congestion. At the same time, RF hardware selection and antenna placement must be carefully planned to maximize signal reception and reduce potential interference.

This section explores the hardware standards and design constraints that govern our system's development, ensuring that our detection units are legally compliant, energy-efficient, durable, and capable of reliable long-range data transmission. By addressing these challenges, we can create a robust and scalable passive aircraft detection system that meets both technical and regulatory requirements while maintaining long-term reliability in the field.

4.2.1 Hardware Standards

Ensuring that our passive aircraft detection system adheres to the appropriate hardware standards is essential for both regulatory compliance and system reliability. These standards cover various aspects of our design, including RF emissions, wireless communication, electronic safety, and environmental durability. Compliance with these industry standards not only guarantees legal operation but also helps to optimize performance, ensure reliability in the field, and enhance system longevity. Given that our detection units are designed to operate in remote areas with limited maintenance, hardware selection must be based on standards that prioritize power efficiency, robust construction, and interference mitigation.

One of the most critical regulatory requirements for our system is FCC Part 15, which governs unlicensed radio frequency (RF) devices in the United States. According to this regulation, our detection units must not emit harmful interference and must be able to function properly in the presence of other RF signals. Since our system passively detects RF emissions rather than transmitting signals, compliance with FCC Part 15 is less restrictive than it would be for an active transmitter. However, we must still ensure that our hardware does not unintentionally radiate emissions that could interfere with other communication systems. This requires incorporating RF shielding techniques, noise filtering components, and proper grounding methods into our design to minimize unintended emissions and meet legal RF compliance requirements (Federal Communications Commission, 2023).

Another essential hardware standard that we must adhere to is IEEE 802.15.4, which defines the operational guidelines for low-power wireless communication networks. This standard is particularly relevant to our project since our system requires energy-efficient communication between detection units and the central processing hub. IEEE 802.15.4 ensures that our system's wireless modules are optimized for low power consumption, which is especially important for solar-powered remote deployments. Additionally, this standard supports reliable, short-range

communication between devices, enabling low-latency data exchange while minimizing energy usage. Operating within Industrial, Scientific, and Medical (ISM) radio bands, as specified by the International Telecommunication Union (ITU), also helps our system avoid the need for costly licensing fees while ensuring compliance with global RF communication regulations (IEEE, 2022).

In addition to communication and RF standards, hardware safety regulations such as UL 60950-1 play a vital role in our system's design. This standard outlines requirements for electronic safety, including fire resistance, electrical hazard prevention, and mechanical durability. Since our detection units are intended to function autonomously in outdoor environments, they must be rugged, weather-resistant, and capable of withstanding prolonged exposure to extreme conditions. To meet these requirements, we ensure that all critical components, including power management circuits, microcontrollers, and communication modules, are certified for UL 60950-1 compliance. Furthermore, the enclosures housing the electronics must be IP65 or higher,

protecting the system from dust, water ingress, and environmental damage (Underwriters Laboratories, 2022).

Beyond electrical safety, hardware reliability under environmental stress is another crucial consideration. Given that our detection units will be deployed in various terrains, from border regions to remote surveillance sites, all hardware must meet military-grade environmental durability standards. Components must be resistant to temperature fluctuations, humidity, and mechanical shock to prevent failures. Standards such as NEMA 4X and MIL-STD-810G outline best practices for designing electronics that can endure harsh conditions, ensuring that our detection system operates reliably for extended periods without frequent maintenance or hardware failures (National Institute of Standards and Technology, 2023).

By ensuring compliance with FCC Part 15, IEEE 802.15.4, UL 60950-1, and environmental durability standards, we can design a system that is both legally compliant and functionally robust. These hardware standards directly influence our component selection, system architecture, and overall deployment strategy, ensuring that our passive aircraft detection system meets the necessary technical, regulatory, and operational requirements for long-term reliability.

4.2.2 Hardware Design Constraints

Designing a passive aircraft detection system for remote and autonomous operation presents multiple hardware constraints that must be carefully managed. These constraints impact the power efficiency, processing capabilities, environmental durability, and network performance of our system. Since the detection units will be deployed in isolated locations with minimal maintenance, every hardware component must be optimized for long-term, reliable operation while minimizing energy consumption and maximizing signal detection accuracy. Addressing these design constraints is crucial for ensuring that our system operates efficiently under real-world conditions and can sustain continuous aircraft monitoring without failure.

One of the most significant hardware limitations in our system is power efficiency. Since our detection units rely on solar energy, they must consume as little power as possible while maintaining real-time signal detection and data transmission. Unlike traditional radar systems

that use active RF emissions, our system passively listens for RF signals, meaning that power must be carefully distributed between signal processing, wireless communication, and onboard computation. To extend battery life, we are implementing low-power microcontrollers, energy-efficient software-defined radios (SDRs), and power management strategies like duty-cycling and sleep modes. Dynamic power scaling will also be used to ensure that components only operate at full power when necessary, significantly reducing energy consumption (Texas Instruments, 2023).

Another constraint is computational efficiency. The detection units must process incoming RF signals in real time, classifying and filtering the data before sending it to the main processing hub. Since embedded processors have limited processing power, they must efficiently handle complex digital signal processing (DSP) operations without causing bottlenecks in data transmission. Hardware-accelerated DSP units or FPGAs (Field-Programmable Gate Arrays) may be incorporated to offload computational tasks, reducing strain on the main processor and increasing processing speed. Additionally, since raw RF data is extremely large, we must implement optimized filtering and compression techniques to extract only the most relevant signal information before transmission, minimizing the amount of data sent over the network (Analog Devices, 2023).

Network bandwidth and latency constraints must also be considered. Since detection units rely on Starlink SATCOM for real-time communication, there are limitations in both bandwidth availability and network latency. Unlike fiber-optic or terrestrial networks, satellite communication introduces higher latency, meaning that data must be transmitted efficiently to avoid congestion and delays. To address this, our system will use edge computing techniques, where preliminary data processing is performed locally on each detection unit before transmitting essential information. This approach significantly reduces network load, allowing for faster updates and lower latency in detecting aircraft movements (SpaceX, 2023).

Environmental durability is another key design constraint. Since detection units will be installed in outdoor locations, they must be built to withstand extreme weather conditions, temperature fluctuations, and potential physical impact. Components need to be rated for high humidity, dust exposure, and temperature extremes, requiring industrial-grade enclosures with IP65 or higher ratings to protect against environmental damage. Additionally, hardware must be resistant to vibrations, high winds, and potential wildlife interference, ensuring long-term system stability. Materials such as corrosion-resistant aluminum, reinforced polymers, and weather-sealed connectors will be used to extend the lifespan of the units while minimizing maintenance requirements (National Institute of Standards and Technology, 2023).

Antenna selection also presents challenges. The system requires antennas that can receive weak RF signals from long distances while maintaining a compact and durable form factor. The challenge is balancing antenna gain, directionality, and environmental resistance while ensuring that the antenna design does not interfere with other system components. Antennas must also be protected from moisture buildup, signal degradation due to obstructions, and damage from extreme weather. Proper positioning and mounting techniques must be considered to maximize signal reception and avoid interference (IEEE, 2023).

By addressing these hardware design constraints, we can ensure that our system remains efficient, durable, and capable of long-term operation in remote environments. Through low-power electronics, computational optimizations, durable construction, and network efficiency improvements, our passive aircraft detection system will be reliable and scalable, allowing for continuous monitoring and accurate data transmission without unnecessary downtime or failures.

4.2.3 Non-Technical Constraints

Engineering projects are often evaluated based on technical design, component selection, and system performance. However, in reality, many of the most critical factors that influence whether a project succeeds or fails are non-technical in nature. These include time, environmental conditions, financial limitations, manpower, expertise, and physical deployment concerns. In our project, which involves developing a passive aircraft detection system for use in remote areas, non-technical constraints have had a major impact on nearly every phase of development—from planning and design to testing and delivery. Understanding these constraints and proactively addressing them is just as important as selecting the right processor or programming language. This section outlines the most significant non-technical constraints affecting our project and describes how we have adapted our approach to manage them.

Time Constraints

Time is one of the most significant and challenging non-technical limitations that we face as an academic engineering team. Unlike industry projects, which may span several months or years and allow for continuous revisions and support, our project must be completed within the rigid time frame of a university semester. This includes multiple deliverables such as the project proposal, midterm report, hardware and software demonstrations, final report, and end-of-semester presentation. These deadlines are fixed and cannot be moved, regardless of unforeseen issues or development setbacks.

In a real-world scenario, an engineering team encountering delays due to shipping, debugging, or component failure might be able to push back delivery or request more funding. In contrast, we must deliver results by a specific date or risk losing points, failing benchmarks, or missing the opportunity to field test entirely. This has a direct effect on our decision-making process. We must prioritize functionality over perfection, minimize iteration cycles, and ensure that each phase of the project leaves us enough time to test and validate the system before the next deadline. There is no time buffer for trial-and-error once implementation begins.

Furthermore, time constraints limit the scope of what we can realistically accomplish within a single semester. While we would ideally like to build a robust system that includes advanced features such as machine learning-based signal classification or predictive tracking algorithms, we must instead focus on the essential elements that will make the system work reliably. Time limitations also affect our ability to collaborate with external experts, seek out advanced training, or conduct more detailed simulations. With multiple team members balancing other classes, exams, and personal responsibilities, scheduling work sessions can also become a challenge, further compressing the hours we can dedicate to this project each week.

Environmental Constraints

Environmental constraints are another major factor in the design of our passive aircraft detection system. Unlike projects that are designed for indoor use or controlled environments, our system is intended to operate in harsh, unpredictable, and isolated outdoor conditions. This includes exposure to extreme heat during the day, cold temperatures at night, high humidity, rain, strong winds, and the presence of dust, insects, and potentially even wildlife interference. All of these factors can degrade system performance, damage hardware, or cause complete failure if not accounted for in the design.

As a result, every component in our system must be selected and configured with durability in mind. This includes using sealed enclosures that meet IP65 or higher water- and dust-resistance standards, corrosion-resistant connectors, UV-stabilized materials, and temperature-tolerant electronics. Our solar panels must be rugged enough to withstand weather and impact from debris, while our batteries must be housed in compartments that protect against water ingress and overheating. Even small details—such as how cables are routed, or where ventilation openings are placed—can make a difference in whether the system survives real-world deployment.

In addition to hardware challenges, environmental constraints influence system performance from a signal processing and communication standpoint. For example, heavy rain or dense foliage can affect signal reception, while uneven terrain can introduce delays or distortions in data transmission. Solar energy generation can be inconsistent in cloudy or shaded areas, which means that our system must include power management strategies like duty cycling, deep sleep modes, and energy-efficient processing.

Another important consideration is that environmental testing is difficult to simulate accurately in a university lab setting. While we can test for water resistance using spray bottles or run temperature simulations using software, these are not always good substitutes for real-world field testing. Our limited ability to validate our system under the actual environmental conditions it will face makes it even more important that we overengineer for resilience.

Budget Constraints

Budget limitations are an unavoidable reality of student-led engineering projects. Although our sponsor has generously provided funding for parts and tools, the amount is finite and must cover all expenses from start to finish. Every dollar spent on one part of the system means one less dollar available for testing, backup components, or optional features. This creates a continuous trade-off between cost and performance that influences every major design decision.

For example, while we may have considered higher-end microcontrollers or RF front-end modules with better sensitivity and faster processing, their cost would have exceeded what we can afford. Instead, we rely on cost-effective alternatives, even if they offer fewer features or lower performance. The same goes for our communication system: while cellular or mesh networks might offer a viable alternative to satellite communication, they come with recurring data costs or additional infrastructure that would stretch our budget. Starlink SATCOM, while not cheap, offers a single upfront cost and global coverage, which aligns with both our technical and financial constraints.

Budget constraints also affect our ability to iterate and improve. Ideally, we would produce multiple versions of each PCB to test different layouts or shielding strategies. In reality, each fabrication run adds cost and delays, so we are forced to get it right the first time. This often leads to conservative design choices, where we prioritize reliability and compatibility over experimentation.

Another challenge is accounting for hidden or unexpected costs. Shipping fees, tax, broken components, tools, and test equipment all consume portions of the budget that aren't always visible in the planning phase. For this reason, we must maintain a running ledger of all expenditures and include a financial buffer in case of emergency. These practices ensure that we stay on track without compromising critical functionality.

Manpower and Expertise Constraints

Unlike professional engineering firms that include specialized staff for every major discipline, our student team must handle all aspects of the project with limited personnel and varying skill levels. While this offers a great opportunity for learning and teamwork, it also creates bottlenecks when we encounter topics or technologies that no one on the team has worked with before. For instance, not all team members are experienced in embedded programming, signal processing, or RF system design, so we often need to learn these skills while simultaneously trying to implement them.

This constraint has a direct impact on our development timeline and the depth of the system features we can implement. We must allocate time for training, experimentation, and knowledge sharing among team members, which further compresses our already limited schedule. Moreover, with each member juggling multiple responsibilities—both academic and personal—the amount of time that can be dedicated to the project each week is limited. We cannot assume 40 hours per week of availability like in a job setting.

Another issue is project management. Because we are all relatively new to large-scale technical projects, we are also learning how to communicate effectively, divide tasks, manage documentation, and track progress. Without a dedicated project manager, these responsibilities must be shared, which can sometimes lead to confusion or misalignment. To mitigate this, we hold regular meetings, document our work consistently, and use collaboration tools like GitHub and shared drives to keep everyone on the same page.

Deployment and Accessibility Constraints

Finally, deployment and accessibility constraints are especially important in our project due to the remote and isolated nature of our target environments. The detection units must be easy to transport, assemble, and activate with minimal tools or technical knowledge. Once deployed, they may not be reachable for weeks or even months, so the system must be designed to operate autonomously with self-diagnostics and fail-safes built in.

This imposes strict constraints on hardware integration and software reliability. We must ensure that power systems can function continuously, that enclosures can withstand field conditions, and that communication links remain stable. There must also be a system in place for remote

monitoring and updates, allowing us to push configuration changes or receive alerts if a unit malfunctions.

Accessibility also refers to the ease with which the system can be operated by non-technical personnel. While we are building the units ourselves, future users may not have engineering backgrounds, so the deployment process must be intuitive and well-documented. Simple LED indicators, labeled ports, and plug-and-play connections can reduce the risk of setup errors. Similarly, the dashboard interface used to monitor the units should be designed with usability in mind, minimizing clutter and presenting data in a clear, meaningful way.

Chapter 5. Comparison of ChatGPT with Similar Platforms

As artificial intelligence continues to evolve, AI-driven platforms like ChatGPT, Microsoft Copilot, Google AI, and DeepL have gained popularity for their ability to assist users in research, learning, and project development. These platforms provide instant responses to user queries, helping students, professionals, and researchers gather information, generate ideas, and improve workflow efficiency. In the context of Senior Design, where students must balance technical research, software and hardware development, and project documentation, AI platforms offer valuable assistance in understanding complex concepts, debugging code, and structuring reports. However, while these platforms provide numerous benefits, they also have limitations that must be considered. This chapter compares ChatGPT, Google Bard, and DeepL, analyzing their strengths, weaknesses, and impact on our learning experience during Senior Design.

5.1 Case study 1: ChatGPT vs Microsoft Copilot

Prompt: “What are good aspects when using Raspberry pi model 4?”

The response presents a well-rounded analysis of the Raspberry Pi 4, covering essential aspects such as processing power, memory, OS support, connectivity, GPIO access, and scalability—all directly relevant to our aircraft detection system. It is context-aware, linking features like edge computing, real-time processing, and cloud integration (e.g., Starlink) to our project's goals. The technical details are clear yet accessible, making the content suitable for formal documentation. It also provides actionable implementation paths, such as using real-time Linux or Docker for enhanced performance.

However, the response lacks mention of potential drawbacks, such as the Pi 4’s higher power consumption, thermal throttling, and limited real-time capabilities without kernel modification. It also doesn’t compare alternative boards like ESP32 or Jetson Nano, nor does it address security or power efficiency for remote deployment. Including these limitations would improve the balance and make the evaluation more complete.

When prompting the same question with Copilot :

Copilot’s response is well-structured and beginner-friendly, offering a quick overview of why Raspberry Pi 4 is a solid option for embedded signal processing projects. However, it lacks critical analysis and technical depth necessary for detailed engineering decision-making. For a Senior Design report, it would need to be expanded with system-specific justifications, limitations, and comparisons to be fully useful.

In conclusion, both ChatGPT and Copilot provide helpful insights when evaluating the Raspberry Pi 4 for use in a passive aircraft detection system, but they serve different purposes in terms of depth and usability. ChatGPT's response offers a more detailed, technically thorough analysis—covering aspects such as processing power, OS compatibility, GPIO interfacing, real-time performance, and cloud integration—while tying these features specifically to the project's needs. It also hints at advanced implementation strategies like using Docker or real-time Linux, making it better suited for academic reporting or engineering decision-making.

On the other hand, Copilot's response is more concise and user-friendly, making it a quick reference for developers or beginners. It effectively highlights the Raspberry Pi 4's general advantages such as affordability, connectivity, and open-source support but lacks technical depth and omits important limitations like power consumption, real-time constraints, or thermal management.

Ultimately, ChatGPT excels at comprehensive evaluation and technical planning, whereas Copilot provides a strong high-level summary. For a detailed engineering project like yours, ChatGPT's response is more appropriate as a foundation for formal documentation, while Copilot's can serve as a useful starting point or quick checklist.

5.2 Case study 2: ChatGPT vs Google Gemini

Note: (Both AIs were prepped and informed of the components in our system and the background of the project before the prompt was made)

Prompt: “Tell me about the voltage and current requirements of our system, and how to connect our power supply unit to fill those needs”

The response from ChatGPT is very broad and informative, giving good insight into specs of each product and general recommendations. However, it is not always 100% accurate, and can require some background knowledge to verify that what it's telling you is exact. For example, it cites a 12V connection and a fuse for connecting our Spectrum Analyzer, but we can quickly verify from the SignalHound website that the power input on the BB60D is a USB3.0 power draw straight from the Raspberry Pi (or whichever computer to which it is connected). Thus, we can see that it is not always a perfectly accurate source, but can be super helpful when researching to help get us off the ground. Best practice is likely to take the info we receive and then go and verify the facts from that.

When asking Google's Gemini AI, it is a much more vague response, directing me to datasheets and specifications of each component. One consideration it did take is the relation of output watts and the systems Ah value for a 24 hour runtime, but overall it gives me much less info and details to work with.

ChatGPT excelled in technical reasoning and system-level understanding, helping me integrate parts like the Renogy solar components into a cohesive design. It remembered the context of my setup, allowing for deeper, more tailored insights—especially when analyzing trade-offs or interpreting specs from datasheets. The conversational format made it easy to refine ideas and ask follow-up questions without starting from scratch.

Google Gemini, on the other hand, was more useful for real-time information, including datasheet access, availability, and pricing. It was especially helpful when checking for newer model releases. However, it lacked the depth of system-level understanding that ChatGPT provided, and often required me to restate details about the project. Overall, ChatGPT was better suited for design-oriented tasks and technical evaluation, while Gemini worked best as a search-driven tool for quick data gathering. Using both in tandem allowed me to cover both breadth and depth in my component research. Thus, despite ChatGPTs occasionally misprints, I find it is a much better starting point than what Google Gemini gave.

5.3 Case study 3: ChatGPT vs Grok

For this part of the project, I used both ChatGPT and Grok AI to compare how well each one could help me with a technical question we needed to answer for our aircraft detection system. I asked them both for antenna recommendations and how those antennas would work with our setup. Right away, I noticed some big differences in the way the two AIs responded—not just in the information they gave, but in how easy it was to understand and use their answers. ChatGPT gave me a very clear, well-organized explanation. It recommended using a Log-Periodic Dipole Array (LPDA) antenna and explained why that type was a good match for our project. It talked about the frequency range, signal direction, durability, and even gave me a simple step-by-step explanation for how the antenna could be set up. The tone was straightforward, easy to follow, and made it super clear how the information could be applied to our real-world system. As someone who's still learning a lot of this stuff, I really appreciated how user-friendly it was. I didn't have to spend extra time researching terms or trying to figure out what the response meant—it just worked for what I needed.

Grok's response was definitely more technical and in-depth, which at first seemed impressive, but after reading it a few times, I realized it was a little overwhelming. It went deep into concepts like TDOA (time difference of arrival), signal triangulation, and placement logic. While this kind of detail might be useful for someone with more experience in RF systems or advanced signal processing, I found it harder to pull out the key points I needed. Grok also didn't give me a clear antenna recommendation right away—instead, it focused more on the general approach and theory behind setting up an antenna network. That's valuable information, but it didn't help me move forward as quickly. I felt like I'd have to summarize or rewrite Grok's response just to use it in our report, whereas ChatGPT's answer was basically copy-and-paste ready after a bit of editing.

Overall, I think both AIs have their strengths. Grok is good for detailed, technical reasoning and could be really useful for backing up a decision or digging deeper into a topic. But when it comes to speed, clarity, and practical use, ChatGPT worked better for me. It felt more like a helpful teammate that understood the level I was at and gave me the information in a way that I could immediately use. For an undergraduate project like ours, where we're trying to balance learning and execution, that made a big difference. I'd definitely keep using ChatGPT as my main tool and maybe use Grok on the side for cross-referencing or if I ever need to dive deeper into something really technical later on.

Chapter 6. Hardware Design

6.1 Power Supply System

The system is designed for full autonomy using the EcoFlow RIVER 2 Solar Generator (PV110W), an integrated solar power solution ideal for continuous operation in remote areas. This all-in-one system combines a 256Wh LiFePO4 (LFP) battery, known for its long lifespan and safety, with a 110W portable solar panel. The solar panel efficiently charges the power station, achieving a full recharge in approximately 2.9 hours under optimal conditions. The RIVER 2 features multiple output ports, including AC, DC, and USB, providing regulated power to subsystems such as the Raspberry Pi, Signal Hound BB60D, and other electronics. Its Battery Management System (BMS) offers protection against over-voltage, overloading, over-temperature, short circuits, low-temperature, low voltage, and overcurrent, ensuring the safety of connected devices. This compact and lightweight solution ensures reliable operation under various environmental conditions, making it suitable for long-term deployment in off-grid locations.

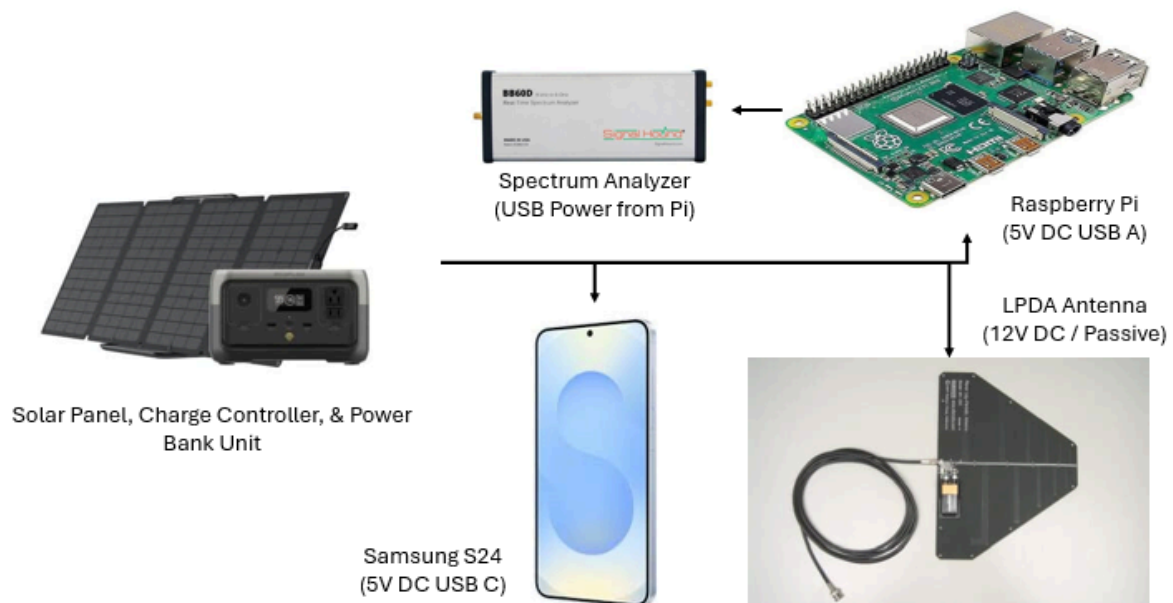


Figure 6.1 Power Subsystem Wiring Diagram

Each component should be properly grounded to prevent electrical noise and ensure stable operation.

- A USB-A connection will power the Raspberry Pi.
- A USB-C power adapter (5V 3A) is needed for the Samsung S24, with proper circuit protection.
- A USB3.0 direct connection from the Raspberry Pi is used for the Signal Hound BB60D.

6.2 RF Detection Subsystem

The RF detection system consists of a Planar Log-Periodic Antenna (LPDA), which is optimized for broadband signal reception. The antenna is connected to the Signal Hound BB60D Spectrum Analyzer, a real-time spectrum analyzer capable of capturing RF signals from aircraft transmissions. The BB60D is interfaced with a Raspberry Pi, which serves as the primary processing unit. The Raspberry Pi runs Digital Signal Processing (DSP) algorithms to filter, classify, and log detected signals. These processed signals are prepared for transmission to a remote server for further analysis and visualization.

6.2.1 Antenna Schematic (Active/Passive)

- The Planar Log-Periodic Antenna (LPDA) is connected to the Signal Hound BB60D Spectrum Analyzer using a coaxial cable (SMA or N-type connector).
- A low-noise amplifier (LNA) may be needed for weak signals. If used, the LNA must be placed close to the antenna to minimize cable losses.
- A bandpass filter can be included to eliminate unwanted RF noise.

Active vs. Passive Setup:

- Passive Antenna Setup → Direct coaxial connection to the spectrum analyzer.
- Active Antenna Setup → Requires bias-tee power injection for the LNA.

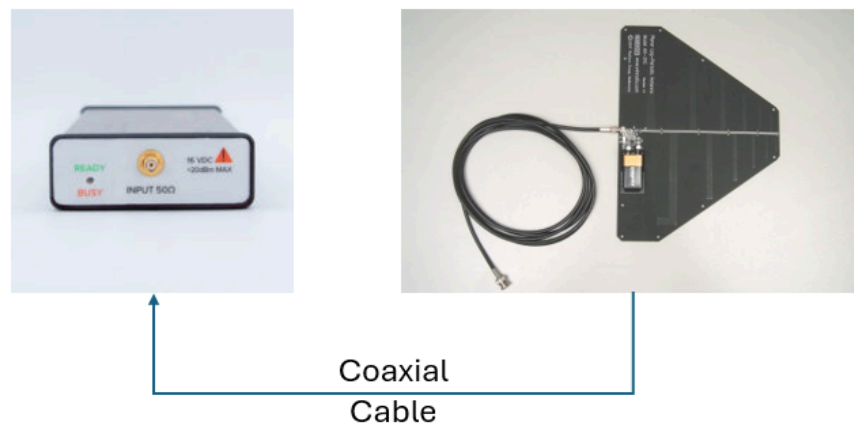


Figure 6.2 Passive Antenna Setup

6.2.2 Spectrum Analyzer Connections

The Signal Hound BB60D requires both data and power connections:

- Power: 5V DC (from Raspberry Pi or external).
- RF Input: SMA/N-Type coaxial cable from the antenna.
- Data Connection: USB 3.0 to Raspberry Pi for signal processing.
- Grounding: A proper RF ground plane should be established to reduce noise.

To reduce interference, the USB cable should be shielded, and power cables should be routed separately from RF connections.

6.3 Data Processing and Communications System

Once the Raspberry Pi processes the aircraft signals, the data is forwarded to an Android Cellular Device (Samsung S24), which serves as an intermediary for wireless communication. The device connects to a Base Station via 4G/5G or Starlink SATCOM, ensuring that real-time aircraft detection data is securely transmitted to a centralized monitoring system. This setup enables remote users to access the data from anywhere, providing a flexible and scalable monitoring solution. The system ensures minimal latency and secure end-to-end encryption for data transmission.

6.3.1 Raspberry Pi

The Raspberry Pi serves as the main computational unit, running DSP algorithms for aircraft signal classification.

The Signal Hound BB60D connects to the Raspberry Pi via USB 3.0 for high-speed data transfer. If additional peripherals (external SSD, sensors) are needed, a powered USB hub should be used to prevent excessive current draw.

6.3.1.1 Power Schematic

A 5V 3A regulated supply (from the DC-DC converter) powers the Raspberry Pi through the GPIO power pins or USB-C port. A fused connection ensures safety from power surges. To prevent corruption during power loss, a capacitor-based power backup or graceful shutdown script could be implemented.

6.3.2 Samsung S24

For real-time data transmission, the Samsung S24 provides 4G/5G cellular connectivity to the base station.

Power Wiring:

- The Samsung S24 is charged via a 5V USB-C power adapter, connected to the battery through a DC-DC regulator.
- A fused USB-C power cable is recommended to prevent overcurrent issues.

Data Connection:

- The Raspberry Pi communicates with the Samsung S24 via USB tethering or Wi-Fi hotspot, enabling live data transmission to the base station.
- A USB-C to USB-A cable can be used for wired data transfer, reducing latency compared to Wi-Fi.

To optimize power consumption, the Samsung S24 should be set to low-power mode when data transmission is not required.

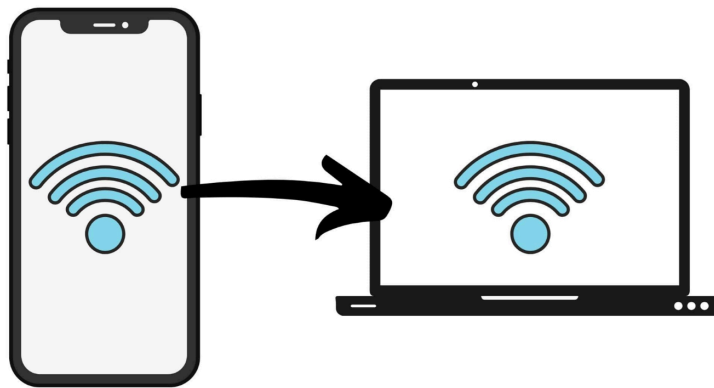


Figure 6.3 Cell Phone to Laptop Connection

Chapter 7. Software Design

7.1 Use Case Diagram

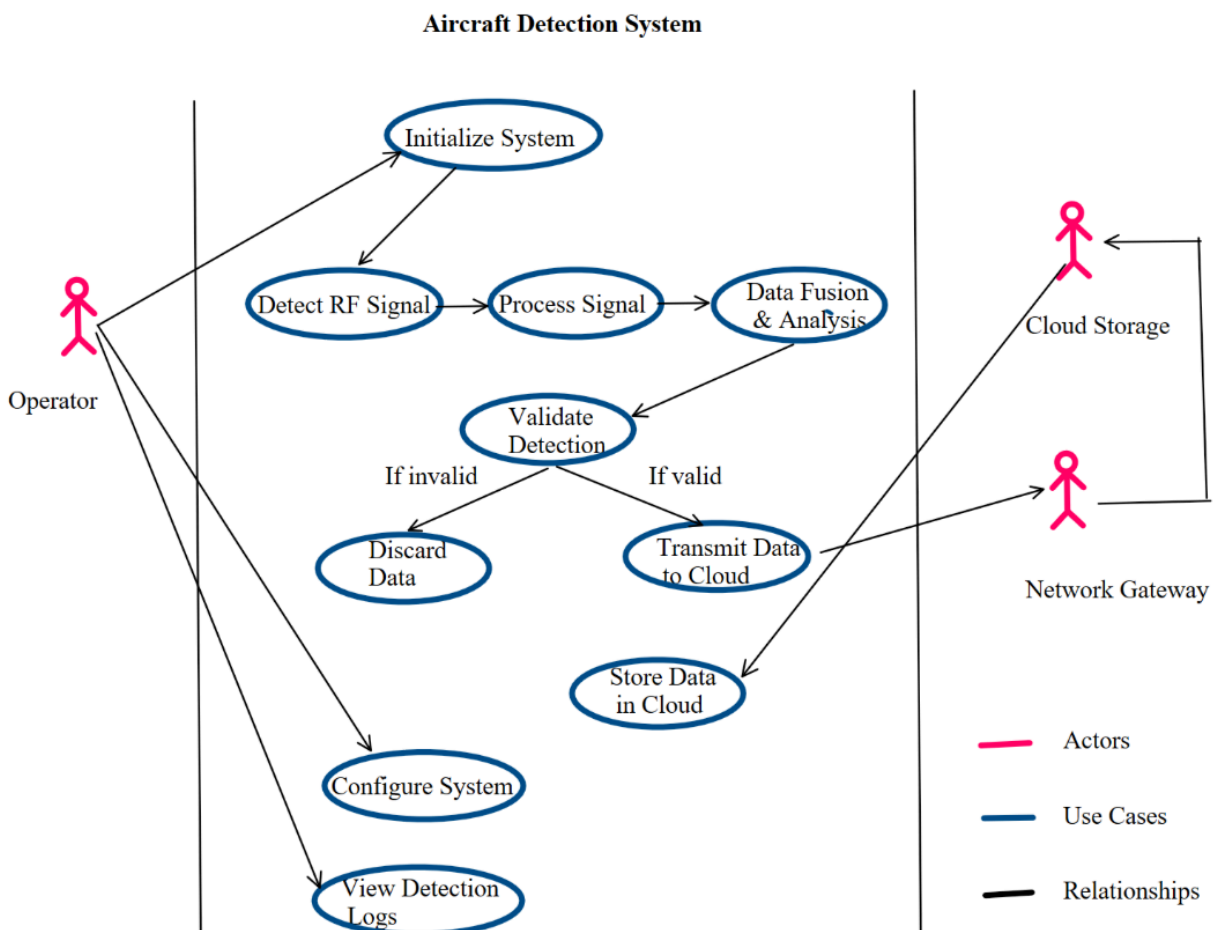
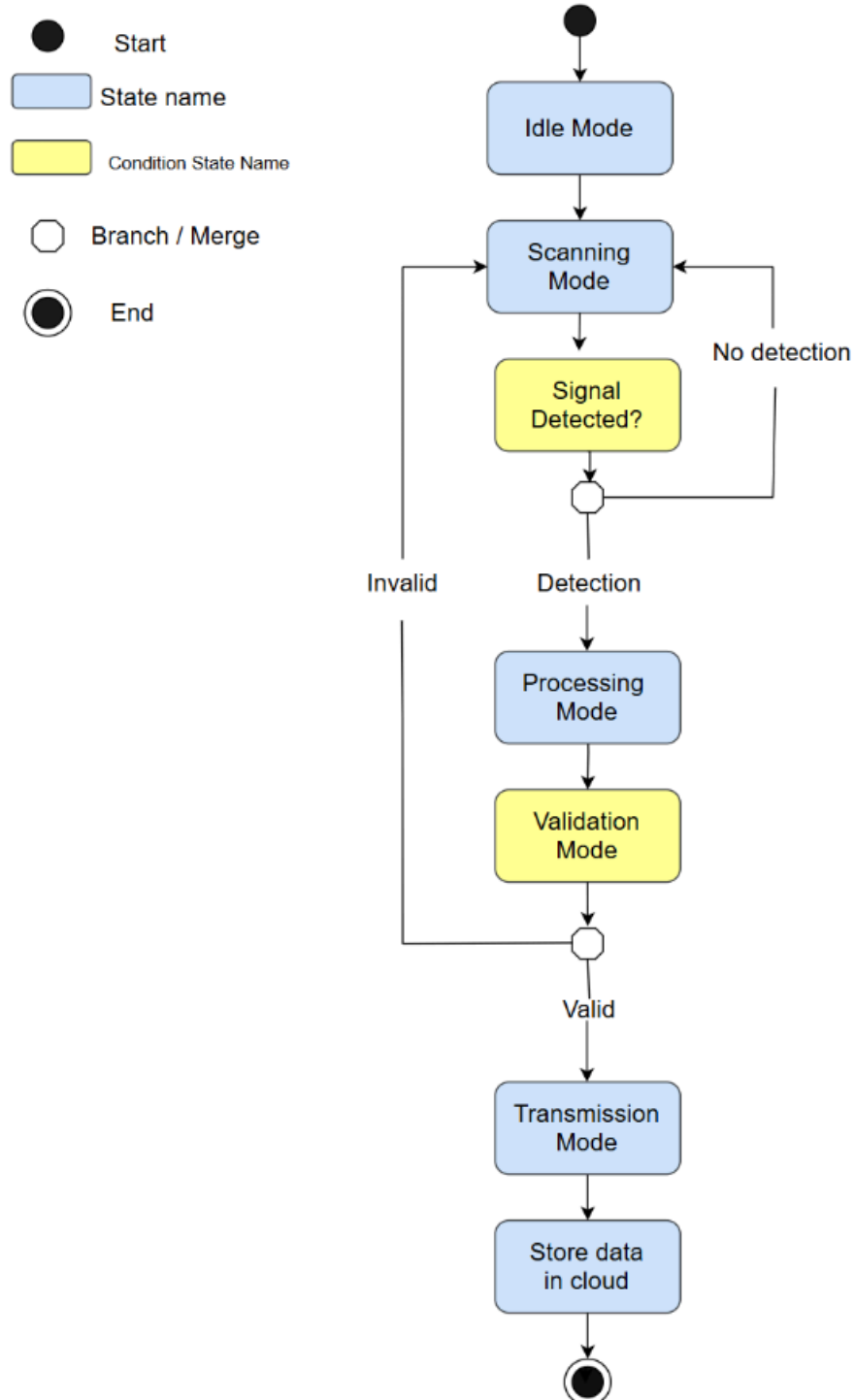


Figure 7.1 Software Use Case Diagram by Authors**7.2 State Diagram****Figure 7.2** Software State Diagrams by Authors

7.3. User Interface (UI) Design

The User Interface (UI) serves as the primary access point for users to interact with the aircraft detection system. It provides essential information about system status, detected aircraft, real-time signal monitoring, and system configuration options. The UI must be intuitive, user-friendly, and efficient to support real-time monitoring while ensuring ease of navigation.

The UI consists of multiple sections, each designed for specific functionalities:

Table 7.1 UI Breakdown

UI Component	Description	Implementation
Dashboard	Displays overall system status, aircraft detections, and alerts.	Web-based (React.js, HTML, JavaScript)
Live Detection Panel	Shows real-time RF signal processing and aircraft information	WebSocket integration for live updates
Data Log Section	Stores historical records of detected aircraft and system performance logs.	SQL Database + API Retrieval
Settings Panel	Allows users to adjust system parameters, including frequency selection and network connectivity.	UI Forms (HTML, Python Tkinter)

The Dashboard is the primary interface where users can see real-time detections and alerts. The Live Detection Panel continuously updates aircraft signal information to ensure that all detection data is visible in real time. The Data Log Section provides access to past detection records, enabling users to analyze aircraft movement trends. Additionally, the Settings Panel allows users to modify system parameters, including signal sensitivity, frequency ranges, and cloud synchronization settings.

The UI is built using React.js and JavaScript for web-based applications and Python Tkinter or PyQt for local desktop applications. The system also utilizes WebSocket technology to push live data updates, ensuring that users receive real-time alerts without needing to refresh the dashboard manually.

7.4 Entity-Relationship Diagram (ERD)

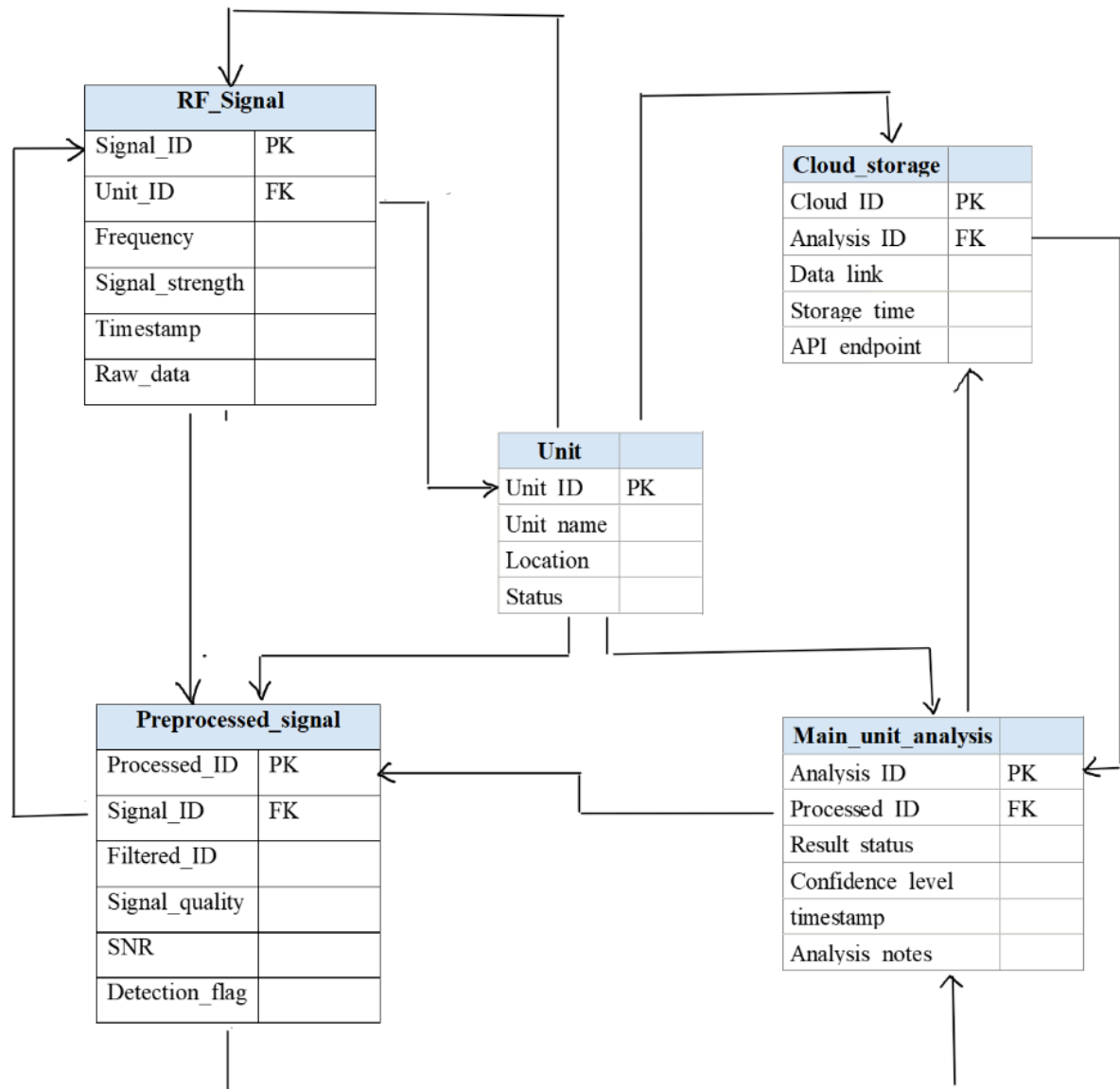


Figure 7.3 ERD Diagram

7.5 Activity Diagram

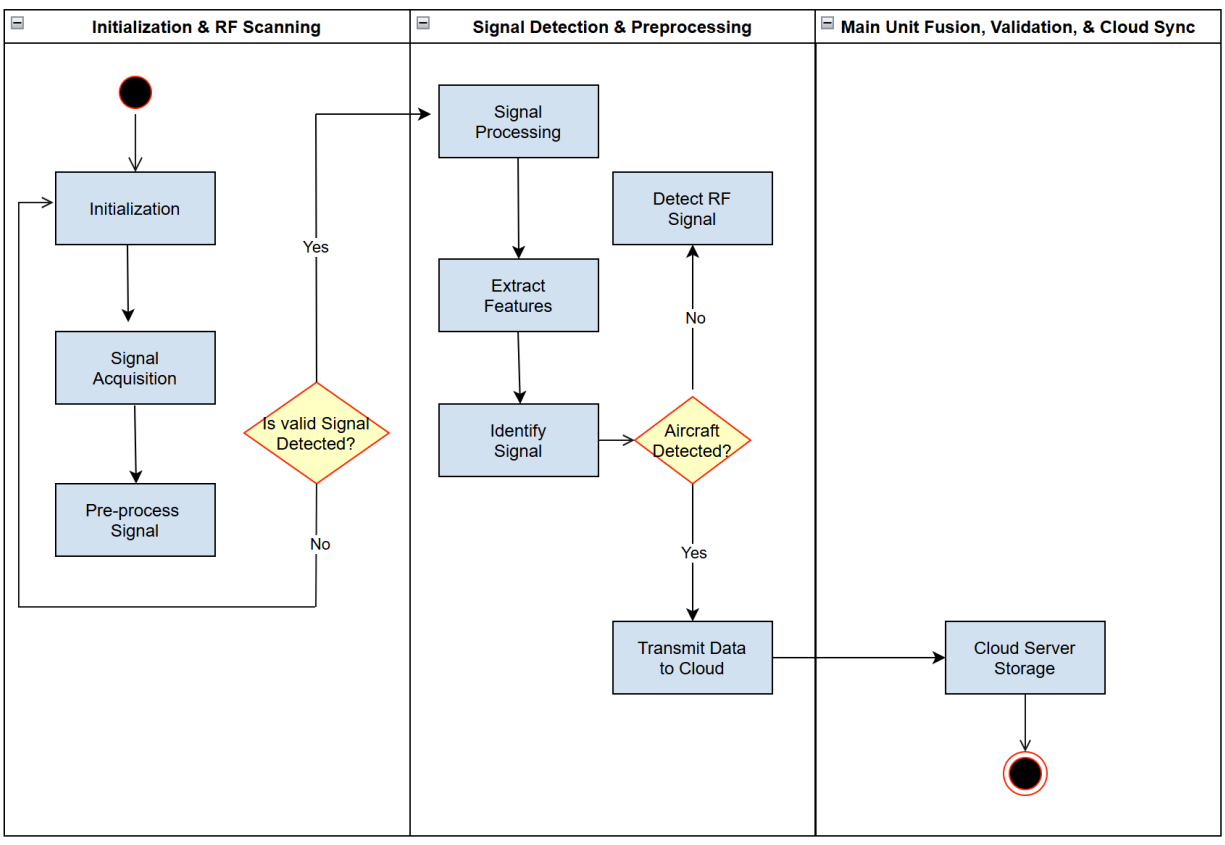


Figure 7.5: Activity Diagram

7.6 Localization diagram

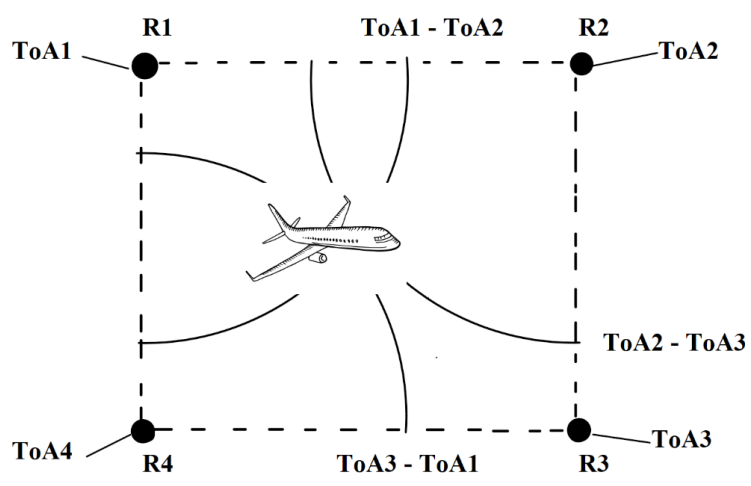


Figure 7.6.1: Localization diagram

- R_1, R_2, R_3, R_4 : These are four receiver nodes (also called sensors or units) placed at known fixed locations.
- $ToA_1, ToA_2, ToA_3, ToA_4$: Time of Arrival of the signal at each receiver.
- TDoA (Time Difference of Arrival) arrows (e.g., $ToA_1 - ToA_2$): Show the difference in time that the signal takes to arrive at different receivers.

Math of Localization (TDoA)

Let:

- T_1, T_2, T_3 = arrival times of the signal at each detection node
- $\Delta T_{12} = T_1 - T_2$ = time difference of arrival between nodes 1 and 2
- s = position of the **signal source** (e.g., the aircraft)
- r_i = position of receiver node i
- c = speed of light $\approx 3 \times 10^8$ m/s
- t_0 = unknown transmission time of the signal

Distance Model

$$T_i = \frac{|s - r_i|}{c} + t_0$$

Where:

- $|s - r_i|$ is the Euclidean distance between the signal source and receiver i
- The absolute time of signal transmission t_0 is unknown, but **cancels out** when computing time differences

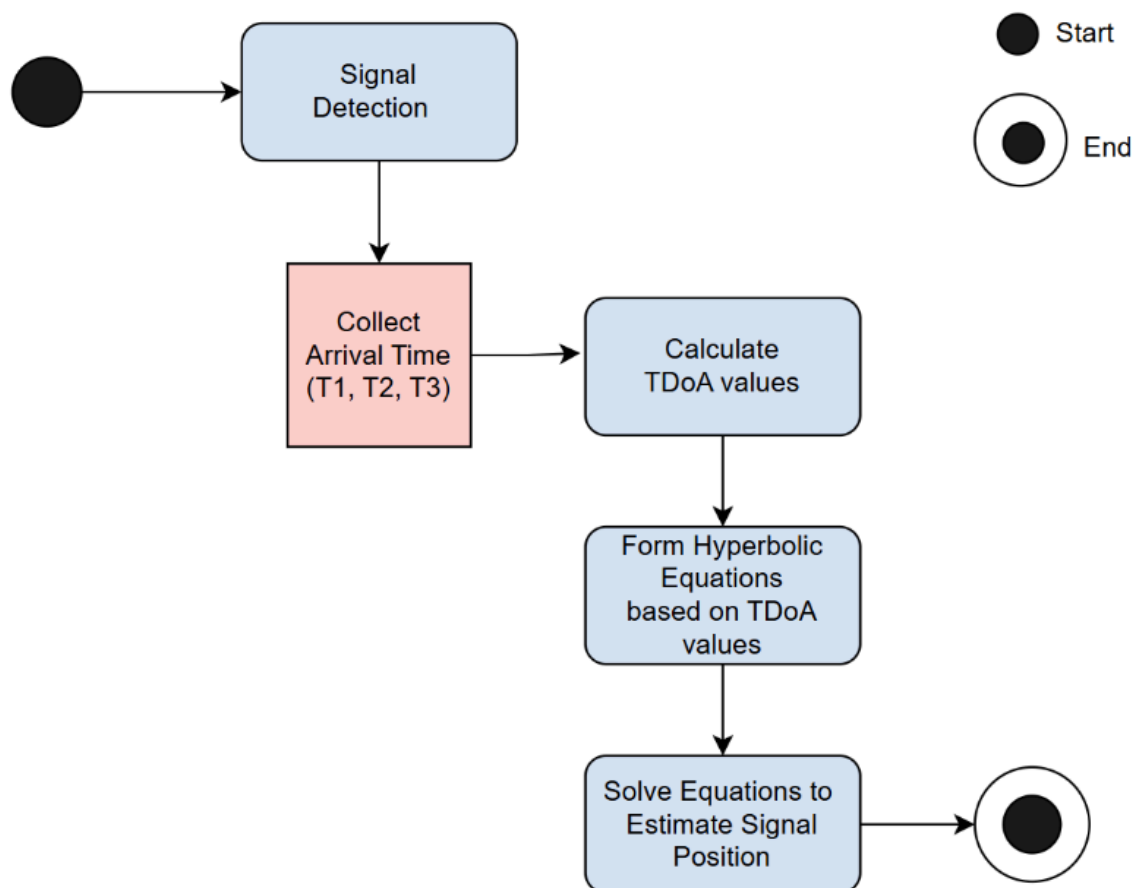


Figure 7.6.2: Localization flowchart

Chapter 8: Prototyping and Testing

8.1 Hardware Testing

Since our sponsor waived the need for a custom PCB, our hardware testing process revolved around building and evaluating a modular prototype using individual components. This approach allowed us to work with standard, off-the-shelf parts and focus on testing performance under conditions that simulate real deployment. Our goal was to verify that essential hardware components—including the microphone, amplifier, power source, and processing unit—would function correctly together without a printed circuit board.

We started by testing a Knowles SPU1410LR5H-QB microphone. This electret condenser microphone was selected for its small size, omnidirectional pickup pattern, and suitability for embedded applications. The microphone was connected to a TLV9051 op-amp from Texas Instruments, chosen for its low-noise performance and rail-to-rail output, which is useful in battery-powered systems. Our initial breadboard tests were conducted indoors using a signal generator, speakers, and ambient noise sources like conversation and background hum to simulate varying sound environments. The microphone successfully picked up low-level signals,

and the op-amp provided sufficient gain to bring the signal into the readable range of an oscilloscope and a Raspberry Pi's analog input (through an ADC).

We also tested the power consumption of the microphone and op-amp combination, as energy efficiency is essential in a solar-powered, remote deployment. The circuit drew less than 10 mA under normal operation, which aligned with our expectations and confirmed that it would be sustainable under solar-battery power. However, we encountered noise issues from both electromagnetic interference and power supply ripple. To address this, we experimented with decoupling capacitors across the op-amp's power rails, shielding on exposed wires, and physical separation of the power leads from signal paths. These small adjustments made a noticeable difference and improved the clarity of the captured signals.

We repeated the testing in an outdoor environment to check how the microphone and op-amp responded to wind, temperature, and ambient noise. Results were consistent, although wind gusts and sudden sound reflections from nearby walls caused occasional spikes in the signal. This highlighted the importance of proper enclosure design and microphone placement, which would later be addressed in our integration and housing plans.

Although our setup was built without a PCB, the modular hardware tests allowed us to validate performance, troubleshoot noise issues, and make informed decisions about power, amplification, and signal handling. These early experiments laid the foundation for more complex system-level integration and testing.

8.2 Software Testing

While hardware development was underway, our team was also heavily focused on writing and testing the software that controls data acquisition, processing, and communication. The system is being built around a Raspberry Pi 4, which serves as the core processing unit due to its combination of GPIO flexibility, Linux environment, and support for Python-based development.

The first step was writing Python scripts that allow the Raspberry Pi to read analog signals from the op-amp's output using an external ADC. Since the Raspberry Pi does not have a built-in ADC, we used an MCP3008 chip for analog-to-digital conversion. This chip communicates over SPI and allowed us to sample signals at adjustable rates. Our initial tests focused on detecting voltage fluctuations that would correspond to detected aircraft signals. The Pi successfully captured the data and logged it locally in a CSV format for later analysis.

To better visualize the signal data, we developed a Python program using Matplotlib and NumPy to create live graphs. This gave us a clearer picture of how signal spikes, background noise, and filtering methods affected the data. We also implemented basic thresholding and moving average filters to remove short-duration noise spikes and stabilize the signal.

The next phase involved testing serial communication between the Raspberry Pi and a laptop or Android phone. We configured a UART serial interface running at 9600 baud, and tested it under continuous transmission conditions for several hours. The communication remained stable, and no data was lost during the transfer, even when the system was logging data continuously. This will be critical for later stages of the project when we transmit data from the unit to a base station or cloud service.

We also experimented with low-power modes, including reducing CPU frequency and disabling unnecessary services, to measure how much energy could be saved during idle periods. While the savings were modest, it provided insight into how we could optimize the software for energy efficiency during long deployments. Our codebase was modular from the start, with separate files for data capture, filtering, and transmission logic, which makes it easier to test, debug, and scale later on.

These early software tests have been vital in shaping our signal handling and communication architecture. We confirmed that our software can reliably acquire and process analog signals, filter and display the data, and transmit it to an external system. More advanced features, such as GPS synchronization and packet batching, are planned for the next development phase.

8.3 Integration Testing

Once we were confident in the basic operation of our hardware and software separately, we moved on to integration testing. This phase aimed to evaluate how all components—microphone, op-amp, Raspberry Pi, power source, and data logging scripts—would function together as a single system. Integration testing is one of the most important steps in the development process because it reveals how real-world factors like timing, noise, and power stability affect the complete unit.

Our first full system test was set up on a test bench, where we connected the microphone and op-amp circuit to the Raspberry Pi through an MCP3008 ADC. The Pi was powered using a 12V LiFePO4 battery connected through a 5V step-down converter. This setup closely mimicked the conditions of a remote deployment, including reliance on battery power and off-grid operation.

We began by logging signal data continuously for a period of several hours. During this test, we simulated aircraft-like events using a speaker to play back recorded ADS-B signals and general noise to replicate environmental sound. The Raspberry Pi successfully logged the events, and the filtering scripts were able to distinguish between baseline noise and higher-amplitude spikes, confirming that our gain settings and thresholds were appropriate.

The next step was to test the power system under sunlight using a 100W solar panel and an MPPT solar charge controller. This allowed us to simulate how the system would recharge in the field and helped us identify limitations in power draw and charging rates. We monitored the current flow into the battery and load to estimate daily energy requirements. Over the course of a full day, the system maintained stable voltage levels and continued operation without issue, even as clouds occasionally passed overhead.

We also tested the Raspberry Pi's response to sudden shutdowns and restarts, to mimic possible power drops during real deployments. While the system rebooted properly in most cases, we plan to add a watchdog timer and automated reboot script to ensure long-term uptime.

This round of integration testing taught us a lot about how our system would perform under real-world conditions. It confirmed that the microphone and amplifier could reliably feed signal data into the Raspberry Pi, that the data could be captured and processed, and that the power system could support extended runtime. The insights gained from this testing will directly inform

the next phase of development, which will include satellite data transmission and GPS-based timestamping.

8.4 Enclosure and Environmental Housing

One of the most important components of our system, especially since we are not using a printed circuit board (PCB), is the physical enclosure that houses all of the electronic parts. Our detection units are designed to be deployed in remote outdoor areas for long periods of time, so the enclosure is critical to keeping everything protected. It doesn't just hold the hardware together—it shields it from harsh environmental conditions like rain, dust, wind, sunlight, and even animals. Without a reliable enclosure, the system would be vulnerable to failures caused by weather exposure, moisture intrusion, or physical impact.

The goal is for our enclosure to meet at least an IP65 rating, which ensures protection against dust and low-pressure water jets. This would allow the unit to survive conditions such as rain, mud, and windblown debris without letting in moisture or dirt. We're currently considering enclosure materials like polycarbonate and fiberglass-reinforced ABS plastic because they are lightweight, UV-resistant, and durable. Aluminum is also an option in cases where extra strength or RF shielding is needed, but it's heavier and more expensive, so it may be reserved for specific deployments.

Inside the enclosure, we're planning the layout to keep everything secure and well-organized. Since there is no PCB to mount the components on, each piece of hardware—like the Raspberry Pi, amplifier circuit, solar controller, and battery—will be mounted individually using brackets or foam padding. This setup helps prevent parts from moving around, even during transport or vibration, and it keeps wiring manageable so we can make repairs or upgrades in the future if needed.

Cable management is another big part of our enclosure design. All cables will pass through sealed cable glands to prevent leaks and to reduce the chance of water getting into the case during rain. Strain reliefs are added to the cables so that movement doesn't loosen or damage the connections. We're also planning to use shielded wires with ferrite beads to reduce electrical noise from the environment or from the other components inside the case.

Thermal control is something we had to think about, especially since the Raspberry Pi and other devices can generate heat over time. Because we don't want to use fans—since they can fail and pull dust into the case—we're going with passive cooling methods. This includes painting the outside of the case with a reflective coating to reduce solar heating, using waterproof vents with breathable membranes to let hot air escape, and spacing the components inside the case to allow for better airflow. These simple changes can make a big difference in keeping the system from overheating during long-term outdoor use.

Mounting the enclosure itself is another challenge. The solar panel that powers the unit needs to be securely attached at the right angle—usually between 30 and 45 degrees depending on where we deploy it—to get maximum sunlight throughout the year. The antenna also needs to be mounted high enough to get a clear signal, but still be protected from the weather. We're

planning to mount both the solar panel and antenna to the enclosure using brackets and sealed ports, so everything stays compact and weatherproof.

We plan to run several tests to make sure the enclosure holds up. These include spraying the case with water to check for leaks, leaving it out in direct sunlight to see how hot it gets, and dropping or shaking the unit to make sure the components stay in place. We'll also test how it handles dust and humidity, since those are both likely in the real environments where the units will be deployed.

In the end, the enclosure is much more than just a container. It's one of the most important parts of the system because it keeps everything working. A strong, weatherproof case allows us to put our detection units out in the field for weeks or months without having to worry about them failing. Since we don't have a single PCB to tie everything together, the case acts like the backbone of the whole unit. It's what makes the system durable, portable, and reliable in real-world conditions.

Chapter 9: Test Plan

This chapter outlines the testing methodology for validating the functionality and reliability of the computing subsystem used in the system. A primary objective is to ensure that software and data processing pipelines developed for the Raspberry Pi can be effectively prototyped and verified on an ASUS NUC running Linux, before final deployment. This approach provides a more powerful and accessible development platform during the initial phases of software development, allowing for efficient testing and debugging.

9.1 Raspberry Pi as the Target Hardware Platform

The Raspberry Pi, specifically the Raspberry Pi 4, serves as the final embedded computing platform in the aircraft detection nodes. Its low power consumption, small form factor, and full Linux support make it ideal for deployment in remote, solar-powered environments. All system software including RF signal processing scripts, data logging, and SATCOM communication must function correctly on this platform.

9.2 ASUS NUC as a Prototyping Platform

To streamline development, an ASUS NUC mini PC will be used as the primary prototyping platform. The NUC, equipped with a full Linux operating system, provides higher computational performance and easier access to development tools. This environment allows for rapid software iteration and comprehensive logging during early development. Once software is verified on the NUC, it will be migrated to the Raspberry Pi for hardware compatibility and performance validation.

Testing on the ASUS NUC includes verification of the following components:

- Signal processing and filtering of raw RF data from the BB60D.
- Data formatting and timestamping routines.

- Communication scripts for transferring data via Starlink SATCOM emulator.
- System control logic (e.g., sleep mode, error handling, logging).

9.3 Software Migration and Compatibility Testing

Once stable on the NUC, the software will be migrated to the Raspberry Pi. This migration will include package compatibility verification, system performance benchmarking, and end-to-end functionality testing. Power consumption and thermal behavior will also be monitored to ensure suitability for field deployment. Python scripts and Bash-based automation tools will be tested under the Raspberry Pi's constrained hardware environment.

9.4 Additional Testing Strategies

Several supplementary testing strategies will be implemented to ensure robustness:

- Headless Boot Testing: Ensure that the Raspberry Pi can boot and operate autonomously without manual intervention.
- RF Signal Injection: Simulated aircraft signals will be fed into the system to verify correct classification and logging.
- Environmental Simulation: Temperature and humidity stress testing will be performed to simulate real-world deployment conditions.
- Network Loss Testing: SATCOM dropouts and reconnection behavior will be evaluated.
- Solar Power Simulation: Operation under varying voltage conditions will be tested to replicate solar panel performance during cloudy or low-light conditions.

9.5 Detailed Development and Testing Plan

To facilitate early software development and ensure compatibility with the Raspberry Pi's Linux-based environment, a dual-boot configuration will be set up on the ASUS NUC. The hard drive will be partitioned to support two operating systems: Windows (for general-purpose use) and Ubuntu Linux (for development and testing). Ubuntu provides a comparable environment to the Raspberry Pi OS, allowing us to accurately simulate the runtime environment.

To configure and utilize the dual-boot system on the ASUS NUC, we will begin by backing up any existing data and shrinking the current Windows partition using built-in disk management tools. This creates space for the Ubuntu Linux installation, which will be carried out using a bootable USB drive containing the latest Ubuntu LTS distribution. Once installed, Ubuntu will serve as the primary environment for testing due to its similarity to the Raspberry Pi OS.

Within the Ubuntu environment, we will install all essential software packages, including Python 3 and the necessary libraries such as NumPy, SciPy, and PySerial. Additionally, we will install RF signal analysis tools, including Signal Hound's SDK or compatible open-source wrappers to interface with the BB60D spectrum analyzer. After setting up the development environment, the

project repository will be cloned and initial smoke tests will be executed to verify core functionalities such as RF signal reception, script execution, and data logging.

To simulate conditions expected in the final deployment, system services and scheduled tasks will be configured using system and cron. These will ensure that the software runs automatically on startup and at regular intervals, mimicking the autonomous behavior of the Raspberry Pi. Hardware compatibility testing will also be performed to confirm reliable interaction with external devices such as the BB60D and USB-connected Wi-Fi modules under the Linux OS. Finally, we will validate the SATCOM communication scripts either through emulation or direct use of the Starlink terminal, ensuring that the system can handle both data transmission and connectivity interruptions gracefully.

By confirming all software runs properly on the Ubuntu environment of the ASUS NUC, we will be able to confidently port the system to Raspberry Pi OS with minimal changes. This approach helps identify and resolve compatibility issues early, improving the stability and reliability of the final deployed system.

Chapter 10. Administrative Content

10.1 Project Budget and Financing

Our budget for the project is funded by the team and a sponsor. The sponsor will not be sending funds but rather has already picked out parts that we must use and bought them. Through conversation with the sponsor it is unlikely that they will fund anything other than the components they are already buying and thus the team will be handling those costs.

Table 10.1 Budget

Component	Name	Price	Quantity
Spectrum Analyzer	Signal Hound BB60D Real-Time Spectrum Analyzer	\$4835.00	5
Wideband Antenna	Planar Log-Periodic Antenna AX-37A	\$459.95	10
Starlink Terminal	Starlink Mini Terminal	\$599.00	5
Starlink Connection	Roam Unlimited (2 months)	\$330.00	1
Phone	Samsung Galaxy S24	\$799.99	5
Cell Service	T-Mobile Essential Saver Plan (2 months, 5 lines)	\$300.00	1
Laptop PC	HP Laptop 17	\$549.99	1

MCU	Raspberry Pi 5	\$120	5
Total		\$37,804.43	

10.2 Bill of Materials

Attached below is the BOM of all components the sponsor will be providing us with.

Figure 10.1 BOM

10.3 Work Distribution

Passive Aircraft Detection System Equipment List

1x Signal Hound BB60D spectrum analyzer https://signalhound.com/products/bb60d-6-ghz-real-time-spectrum-analyzer/	4690.00
1x Starlink Mini Terminal https://www.starlink.com/order?processorToken=f2aaa461-a084-4b03-9706-7ffb29fa16cb	450.00
1x Starlink Roam Unlimited service (2mo.) https://www.starlink.com/order?processorToken=f2aaa461-a084-4b03-9706-7ffb29fa16cb	330.00
2x Planar Log-periodic antenna https://aventasine.com/product/planar-log-periodic-antenna-8/	920.00
1x Android Cellular phone handset https://us.motorola.com/smartphones-moto-g-5g-gen-3/p?skuld=1071	150.00
1x T-Mobile service (2 mo.) (Essential Saver Plan) https://www.t-mobile.com/cell-phone-plans	75.00
1x Laptop PC (Core i7) https://www.hp.com/us-en/shop/pdp/hp-laptop-17-cn4047nr?jumpid=ma_weekly-deals_product-tile_laptops_30_a05fxua_hp-laptop-17%2C-window	600.00
1x Intel NUC (Core i7) https://www.newegg.com/intel-nuc-13-pro-arena-canyon/p/2SW-000B-004P3	750.00
1x Portable power supply unit https://www.tractorsupply.com/tsc/product/westinghouse-igen160s-portable-power-station-	130.00
TOTAL ESTIMATED COST: \$ 8095.00	

Table 10.2 Table of Work Distributions

Member	Assembly & Manufacturing	Detection Algorithm	Localization Algorithm	PSU Design
Kim	Secondary • Secondary Team Lead • Assign Roles	Secondary • Verify Detection Algorithm	Primary • Design Localization Algorithm	
Jurgis		Primary • Coding & Framework of Detection Alg	Secondary • Verify and Test Localization Algorithm	
Evan	Primary • Team Lead • Ensure Functional Device			Primary • Design & Assembly of PSU • Connect all Component to Needed Power

10.4 Schedule and Milestones

10.4.1 Senior Design 1

Table 10.3 SD1 Schedule

Senior Design 1	
Week	Description and Dates
1-2	Formulate Ideas and Construct Groups
3	Research/Write Divide and Conquer Document and Form Committee(1/24/25)
4	D&C Meeting with SD Coordinators(1/29/25), Revise D&C(2/7/25), Start 60 Page Report (3/24/25)
5-6	Research/Order Components and Research Software, 15 Page Check-in

7-8	Build/Test Designs, Midterm Optics Showcase(2/25/25), 30 Page Check-In
9-10	More Testing and Optimizing Designs, 45 Page Check-In
11-12	Finish 60 Page Draft(3/24/23), Feedback Meeting, Begin 120 Page Report(4/22/25)
13	Begin Constructing Prototype, 75 Page Check-In
14	Finish Construction of Prototype and Begin Testing, 90 Page Check-In
15	Complete Testing of Prototype, 105 Page Check-In, Final Optics Showcase(4/15/25)
16	Produce Complete Prototype, Finish 120 Page Report(4/22/25)

10.4.2 Senior Design 2

Table 10.4 SD2 Schedule

Senior Design 2	
Week	Description and Dates
1	Edit 120 Page Report as Needed
2-3	Start Connecting Devices to a Network of Devices and start on Solar Power Supply
4-5	Research Interconnecting Devices, Continue Making Original Prototype Self-Sustained
6	Finish Converting Prototype to be Self Sufficient
7-8	Test Self Sufficient System, Build Additional Prototypes for Final Report
9-10	Assess and Fix Potential Errors, Finish up Interconnection Software
11-12	Begin Full System Testing, Assess Problems and Begin on Solutions
13-15	Just Keep Testing, Just Keep Testing, Just Keep Testing Testing Testing
16	Final Presentation for the Committee

Chapter 11: Conclusion

As we close out the first phase of our senior design project, it's clear just how far we've come from where we started. What began as a general idea—creating a passive aircraft detection system that could work in remote areas—has grown into a real, well-thought-out design supported by hours of research, testing, team discussions, and problem-solving. Throughout the semester, we've worked to turn this idea into a working system that can actually solve a real-world problem. It hasn't always been easy, but the progress we've made gives us confidence that we're on the right track as we move into Senior Design 2.

The original goal of our project was to design a system that could detect aircraft flying through areas without radar coverage. These areas—especially those along borders or in low-infrastructure regions—don't have the ability to monitor airspace effectively, which creates major security risks. Our system aims to fill that gap by using passive RF detection. That means instead of sending out signals like traditional radar, we just listen for signals that aircraft naturally emit. This approach is not only more discreet, but also significantly cheaper and more energy-efficient. It's a great solution for places that need coverage but don't have the resources for expensive, power-hungry radar systems.

From the start, we were also focused on how to make our system scalable. We knew it wasn't just about building one detection unit that worked. The real challenge was making several of them work together. That meant figuring out how to synchronize them, how to share data between units, and how to build software that could process inputs from multiple points to estimate an aircraft's position. We spent a lot of time researching how to do this using methods like time difference of arrival (TDoA), which lets us figure out where an aircraft is based on when each unit detects its signal. It's exciting because it transforms our system from just detecting something is in the air to knowing where it is and where it's going.

As we dug deeper into the design, we had to make some big decisions about what parts and tools we would use. We ended up selecting the Raspberry Pi 4 as our main processor. It gave us the flexibility and computing power we needed while still being low-cost and energy-efficient—two really important factors for a field-deployed system. We paired that with other critical components, like the Signal Hound BB60D for RF spectrum analysis and a Log-Periodic Dipole Array (LPDA) antenna, which we chose for its ability to pick up a wide range of frequencies with strong directional gain. All of this was powered by a solar-battery setup so that each unit could work in remote locations without needing to be plugged in.

One thing we're especially proud of is how much we were able to test and validate, even without building a custom PCB. Since the sponsor didn't require us to fabricate a board, we worked with modular setups on breadboards. We tested the microphone and amplifier circuits, hooked them up to the Raspberry Pi, and monitored signal strength using both software and simple visual

tools. This allowed us to catch issues early, like signal noise and power instability, and make adjustments before integrating more complex components.

We also learned a lot from building and testing the software. We wrote scripts that allowed us to collect data, process it, filter out noise, and even visualize signals in real time. We tested serial communication between the Pi and other devices and ran stress tests to see how well the system would hold up under continuous operation. These tests helped us think more deeply about how the final system will function in the field, and they gave us the foundation we need for full system integration in the next phase.

Another huge part of this semester's work was figuring out how to protect the system from the elements. Since the units will be deployed outdoors, we needed to design a case that could handle rain, heat, wind, dust, and even wildlife. We spent a lot of time looking at different enclosure materials and design features—like waterproof cable glands, breathable membranes for passive cooling, and shock-mounted components to absorb vibrations. It might seem like a small thing, but the enclosure is what will ultimately keep the system running when no one is around to fix it. With no PCB holding everything together, the enclosure became even more important. It's the physical support system and the first line of defense against weather and wear.

Looking ahead to Senior Design 2, there's still a lot to do, but we're in a good place to keep building. One of our main goals will be to scale the system and test it as a network. That means setting up multiple units, syncing them using GPS, and seeing how well they can work together to detect and locate aircraft in real time. We also plan to build out our base station, where all the detection data will be sent, processed, and displayed on a user-friendly dashboard. This will give us a clear view of how the system is working and whether it's ready for more complex deployment scenarios.

We're also planning to spend time improving system efficiency. We'll keep working on power-saving features, like sleep modes for the Pi, smarter data filtering, and better error handling. We may even look into machine learning for signal classification down the line, depending on how much time we have. There's also room for refining our enclosure with field feedback, stress testing, and potential improvements in layout and heat management.

Beyond the technical side, this project has been an incredible learning experience for all of us. It's challenged us to work as a team, manage our time, and stay organized even when things didn't go according to plan. We've had to learn new tools, figure out how to break down a big idea into smaller, testable steps, and communicate our progress in a way that made sense not just to us but to our sponsor and professors. The fact that this project could have real-world impact made it even more meaningful. Knowing that the system we're building could help secure airspace in underserved regions kept us focused and motivated, even during the tougher parts of the semester.

In the end, this first phase of the project gave us everything we hoped it would. We explored the core concepts, built a working prototype, and proved that the system is viable—not just on paper, but in real-world tests. We identified the key challenges ahead and have a clear roadmap for what needs to be done in Senior Design 2. There's still a lot of work to do, but now that the foundation is solid, we're confident we can build the full system and see it through to completion.

As we move forward, we're excited not just about finishing the project, but about the opportunity to make something that works in the real world. Something that can be deployed, maintained, and used to help solve a problem that really matters. That's what engineering is all about, and we're proud to be part of a project that reflects that.

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APPENDIX B

5.1. ChatGPT vs Copilot

Prompt: “What are good aspects when using Raspberry pi model 4?”

ChatGPT’s response:

“ 1. High Processing Power: The Raspberry Pi 4 is equipped with a quad-core ARM Cortex-A72 processor (1.5 GHz), which provides the necessary computational power for real-time RF signal processing, noise filtering, and multi-threaded data handling. This makes it capable of running complex signal analysis algorithms and supporting AI-based data fusion at the edge.

2. Adequate Memory Options: Available with 2GB, 4GB, or 8GB of LPDDR4 RAM, the Pi 4 offers flexibility depending on your software demands. This is particularly important for buffering sensor data, supporting multi-process applications, or running lightweight machine learning models for aircraft classification.

3. Full Operating System Support: It can run a full Linux OS (e.g., Raspberry Pi OS), which allows you to:

Use high-level programming languages like Python, C++, and JavaScript

Leverage Linux-based tools and libraries (e.g., TensorFlow Lite, OpenCV, Paho MQTT)

Easily develop and test software in a familiar environment

This reduces development time and increases compatibility with cloud APIs, security libraries, and networking tools.

4. Rich Connectivity: Raspberry Pi 4 comes with:

Dual-band Wi-Fi (2.4GHz and 5GHz)

Gigabit Ethernet for stable wired connections

Bluetooth 5.0 for short-range wireless communication

USB 3.0 ports for fast data transfer and external sensor support

These features ensure reliable communication between distributed sensor nodes and your central system or cloud server, even in real-time.

5. **GPIO & Peripheral Interfaces:** The 40-pin GPIO header supports I²C, SPI, and UART, which are critical for interfacing with sensors (e.g., RF modules, GPS, ADCs, etc.). This enables seamless integration with your aircraft detection hardware.
6. **Scalability and Modularity:** With support for Docker, MQTT brokers, WebSockets, and cloud SDKs, the Raspberry Pi 4 allows you to scale your project easily—from a single prototype to a multi-node detection system with centralized or distributed processing.
7. **Cost-Effective and Widely Supported:** Despite its features, the Raspberry Pi 4 remains affordable and has an extensive online community. You'll find ample support, libraries, and tutorials—helping you troubleshoot and optimize your design efficiently.
8. **Support for Real-Time Enhancements:** While not a hard real-time system by default, the Pi 4 can run real-time patched Linux kernels (PREEMPT_RT) to reduce latency for more time-sensitive applications. This is ideal for real-time signal acquisition and preprocessing before cloud transmission.” (OpenAI, 2025).

Copilot response:

“The Raspberry Pi Model 4 is a versatile and cost-effective choice for building a passive aircraft detection system. Here are some of its advantages:

1. **Affordability:** The Raspberry Pi 4 is relatively inexpensive, making it accessible for hobbyists and researchers working on budget-friendly projects.
2. **Processing Power:** With its quad-core processor and up to 8GB of RAM, the Raspberry Pi 4 can handle computational tasks like signal processing and machine learning for aircraft detection.
3. **Connectivity:** It offers multiple USB ports, Gigabit Ethernet, and dual-band Wi-Fi, which are essential for connecting peripherals like software-defined radios (SDRs) and antennas.
4. **Compact Size:** Its small form factor allows for easy integration into portable or space-constrained setups.
5. **Open-Source Ecosystem:** The Raspberry Pi supports a wide range of open-source software, including tools for signal analysis and machine learning, which can be used to process aircraft signals.
6. **Community Support:** A large community of Raspberry Pi enthusiasts and developers provides extensive resources, tutorials, and troubleshooting help.
7. **Energy Efficiency:** The Raspberry Pi 4 consumes less power compared to traditional computers, making it suitable for continuous operation in remote or off-grid locations.” (Copilot, 2025)

2. What factors should I consider when selecting a Raspberry Pi for real-time signal processing?

“When choosing a Raspberry Pi model for real-time signal processing, you should consider:

Processing power: Higher clock speed and more cores allow faster computations (e.g., Raspberry Pi 4 Model B with Cortex-A72, 1.5GHz).

Memory: More RAM helps in handling large signal datasets and AI-based processing (Pi 4 offers up to 8GB).

Connectivity: USB 3.0, Gigabit Ethernet, and Wi-Fi 5 ensure fast data transfer between sensor modules and cloud systems.

Power consumption: A lower-power model like Raspberry Pi Zero 2 W is useful if the system is battery-operated.

I/O and expandability: If you need external signal processing hardware (e.g., ADC/DAC modules, DSP coprocessors), PCIe support in Compute Module 4 (CM4) is beneficial.”

3. Is the Raspberry Pi 4 Model B the best choice for real-time signal processing?

“Yes, Raspberry Pi 4 Model B is the best general-purpose choice due to:

Quad-core Cortex-A72 (1.5 GHz) offering fast processing.

Up to 8GB RAM, ensuring smooth execution of real-time data filtering and AI models.

Gigabit Ethernet and USB 3.0, useful for high-speed data transmission.

Dual micro-HDMI support, allowing real-time visualization of processed signals.

However, it consumes more power and may require active cooling for intensive tasks.”

4. When should I use a Raspberry Pi Compute Module 4 (CM4) instead?

“The Raspberry Pi Compute Module 4 is a better choice if:

You need hardware customization (e.g., industrial-grade real-time applications).

You require PCIe support to interface with high-speed DSPs or AI accelerators.

You want to embed the board into a compact system, as CM4 allows integration with custom carrier boards.

However, CM4 requires additional external components, making it less beginner-friendly than a standard Pi 4 Model B.”

5. Can Raspberry Pi Zero 2 W be used for real-time signal processing?

“Yes, but with limitations. The Raspberry Pi Zero 2 W has:

A quad-core Cortex-A53 processor (1 GHz), which is weaker than the Pi 4.

512MB RAM, limiting its ability to handle large data sets or AI-based processing.

Built-in Wi-Fi and Bluetooth, useful for lightweight wireless applications.

It is suitable for low-power applications, like basic RF signal detection or small-scale IoT systems, but not ideal for heavy real-time processing.”

6. Do I need additional hardware for real-time signal processing on Raspberry Pi?

“Yes, depending on your signal type, you may need:

Analog-to-Digital Converters (ADC) like MCP3008 or ADS1115 for analog signals.

Digital-to-Analog Converters (DAC) such as MCP4725 for signal output.

External DSP processors if you need faster real-time computations than what the Raspberry Pi CPU can handle.

Cooling solutions (fans or heatsinks), especially if performing intensive FFT analysis or AI inference on Raspberry Pi 4.”

7. Can Raspberry Pi handle AI-based real-time signal processing?

“Yes, Raspberry Pi 4 and CM4 can run lightweight AI models for signal processing, such as:

TensorFlow Lite for machine learning-based signal classification.

Edge Impulse for real-time AI-powered anomaly detection in signals.

OpenCV for image/audio-based real-time analysis.

However, for complex AI-based real-time signal processing, a dedicated edge AI processor (like Google Coral or NVIDIA Jetson Nano) may be needed.”

8. How does power consumption affect real-time processing on Raspberry Pi?

“Real-time processing increases CPU and memory usage, leading to:

Higher power consumption (Pi 4 consumes ~3W at idle but up to 7W under load).

Increased heat generation, requiring active cooling for stable performance.

Shorter battery life, if running on a battery-powered system.

For energy efficiency, consider Raspberry Pi Zero 2 W or optimize code for lower CPU usage.”

9. Can Raspberry Pi run a real-time operating system (RTOS) for better performance?

“Yes, Raspberry Pi can run RTOS-based systems like:

FreeRTOS for microcontroller-like real-time scheduling.

Preempt-RT patched Linux for low-latency real-time applications.

Xenomai for high-performance real-time Linux applications.

For hard real-time constraints, a dedicated MCU or FPGA-based system may be more suitable”.

10. What software can be used for real-time signal processing on Raspberry Pi?

“Some useful software tools include:

Python with SciPy/NumPy for real-time data filtering and FFT processing.

GNU Radio for real-time RF signal processing applications.

MATLAB & Simulink for real-time algorithm prototyping.

SoX or Audacity for real-time audio processing.

For best results, optimized C++ implementations with multi-threading are recommended”.
(OpenAI, 2025).

5.2 Case Study - ChatGPT

Prompt: “Tell me about the voltage and current requirements of our system, and how to connect our power supply unit to fill those needs”

ChatGPT’s response:

“Voltage and Current Requirements of the System & Power Supply Connections

1. Overview of Power Requirements

*Your system consists of multiple electronic components, each with specific voltage and current requirements. Since the system is deployed in a remote location, it is **solar-powered**, relying on a **12V LiFePO4 battery** and an **MPPT charge controller** to regulate power distribution.*

Below is a breakdown of the voltage and current requirements for each major subsystem:

<i>Component</i>	<i>Voltage Requirement</i>	<i>Current Requirement</i>
<i>Raspberry Pi (Data Processing Unit)</i>	<i>5V DC</i>	<i>~2.5-3A</i>
<i>Signal Hound BB60D (Spectrum Analyzer)</i>	<i>12V DC</i>	<i>~2A</i>
<i>Samsung S24 (Data Transmission)</i>	<i>5V DC (USB-C)</i>	<i>~2A</i>
<i>Low-Noise Amplifier (if used)</i>	<i>5V DC / Bias-Tee</i>	<i>~100-200mA</i>
<i>Voltage Regulators & Misc. Sensors</i>	<i>Varies (5V/3.3V)</i>	<i>~500mA - 1A</i>

LED Indicators & Monitoring Circuit	3.3V - 5V DC	~100mA
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2. Power Source & Connection Overview

The primary **power source** is a **12V LiFePO4 battery** charged via a **solar panel** and **MPPT charge controller**. Since not all components operate at **12V**, different **voltage regulators** are used to step down power accordingly.

- **12V Bus:** Powers the **Signal Hound BB60D** directly.
- **5V Bus:** Powers the **Raspberry Pi**, **Samsung S24**, and other peripherals.
- **3.3V Bus (if needed):** Powers LED indicators, sensors, and logic circuits.

3. Connecting the Power Supply to Meet System Needs

Step 1: Solar Panel to MPPT Charge Controller

1. Connect the **solar panel output** to the **PV input** of the MPPT charge controller.
2. Ensure proper **polarity (positive to positive, negative to negative)** to avoid damage.
3. The MPPT controller will optimize the charging process for the **12V LiFePO4 battery**.

Step 2: Battery Connection

1. Connect the **MPPT charge controller output** to the **12V LiFePO4 battery terminals**.
2. Use **fuse protection** (e.g., **10A fuse**) to prevent short circuits.
3. The battery stores power and provides a stable **12V DC output**.

Step 3: Voltage Regulation for Each Component

Since most components require voltages other than **12V**, **voltage regulators** are used:

12V to 5V Conversion (For Raspberry Pi, Samsung S24, LNA, etc.)

- Use a **DC-DC step-down buck converter** (e.g., **LM2596** or **MP1584**) to convert **12V to 5V** efficiently.
- Ensure the regulator can handle at least **3A** to support the Raspberry Pi and Samsung S24.
- Connect the **5V output** to a **USB-C adapter** to charge the Samsung S24 and power the Raspberry Pi.
- If using an LNA, ensure the **5V output is clean** (minimal noise) to avoid RF interference.

Direct 12V Connection (For Signal Hound BB60D)

- *The Signal Hound BB60D requires a stable 12V DC supply.*
- *Use a 12V fuse (~3A) in series to prevent overcurrent issues.*
- *Ensure proper **grounding** to minimize electrical noise.*

4. Power Distribution & Safety Considerations

To ensure stable power delivery, follow these best practices:

✓ *Use proper wire gauges:*

- *Solar Panel to Charge Controller: 10-12 AWG*
- *Battery to Load: 12 AWG*
- *Voltage Regulators to Components: 16-18 AWG*

✓ *Use fuses and circuit breakers at key points:*

- *10A fuse between the battery and the charge controller*
- *5A fuse on the 5V bus*
- *3A fuse on the 12V line to the Signal Hound BB60D*

✓ *Minimize power losses by keeping cable runs short and using efficient regulators.*

✓ *Implement an LED power indicator system to monitor voltage levels and detect failures.*

5. Summary of Power Connections

<i>Component</i>	<i>Connected To</i>	<i>Voltage Source</i>
<i>Solar Panel</i>	<i>MPPT Charge Controller (PV Input)</i>	<i>Varies (~18V)</i>
<i>MPPT Charge Controller</i>	<i>12V LiFePO4 Battery</i>	<i>12V DC</i>
<i>Raspberry Pi</i>	<i>12V Battery → 5V Buck Converter</i>	<i>5V DC</i>
<i>Signal Hound BB60D</i>	<i>Directly to 12V Battery (Fused)</i>	<i>12V DC</i>
<i>Samsung S24 (USB-C)</i>	<i>12V Battery → 5V USB-C Adapter</i>	<i>5V DC</i>
<i>Low-Noise Amplifier (LNA)</i>	<i>5V Regulator (if used) / Bias-Tee</i>	<i>5V DC</i>

LED Indicators	3.3V/5V Regulator	3.3V - 5V DC
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By carefully managing voltage regulation and power distribution, your system will remain efficient, safe, and reliable for continuous operation in remote environments. 🚀

5.3 ChatGPT vs Grok

Chatgpt

Prompt: What kind of antenna is best to use?

Response:

The best type of antenna for your Low-Cost Passive Aircraft Detection System is a Log-Periodic Dipole Array (LPDA) antenna. Specifically, your group is already using the Planar Log-Periodic Antenna 8 from Aventas Inc., which is an excellent choice for this project. This antenna covers a wide frequency range—from 500 MHz to 8 GHz—which is ideal for picking up various types of aircraft signals such as ADS-B, VHF, UHF, and GPS. Since you're using a passive RF detection approach, having a wideband antenna ensures that you can detect signals from both cooperative and non-cooperative aircraft.

The LPDA is also highly directional, which allows for more precise detection and improves the system's ability to localize where the signal is coming from. This becomes especially useful when multiple nodes are deployed and you're using Time Difference of Arrival (TDOA) methods to triangulate aircraft positions.

Some key reasons why the LPDA is the best fit for your system:

- It provides wide frequency coverage, which is critical for detecting a range of RF signals emitted by different aircraft systems.

- It offers high directional gain, improving detection accuracy and range.

- It is scalable and modular, making it suitable for multi-node deployments like yours.

- It is weatherproof and built for outdoor, remote environments, ensuring long-term reliability.

- It strikes a good balance between performance and cost, making it a practical choice for a low-cost system.

Other antenna types, such as Yagi-Uda or dipole antennas, either lack the necessary bandwidth or offer less gain and precision. Phased array antennas are more advanced and offer electronic beam steering, but they are expensive and overly complex for your current budget and goals. Monopole and microstrip patch antennas are compact and cheap but do not provide the gain or frequency coverage needed for effective aircraft detection.

Overall, the LPDA stands out as the most suitable antenna for your project due to its performance, versatility, and durability in remote deployments.

My Response:

Why is this better than the other ones that would be recommended?

ChatGPT Response:

Why the LPDA is Better Than Other Options:

Wide Frequency Coverage

Most aircraft emit RF signals across a broad range of frequencies—VHF, UHF, ADS-B (around 1090 MHz), GPS, and more.

LPDA antennas are designed to cover a very wide frequency range (500 MHz to 8 GHz in your case), making them ideal for catching a variety of signals without needing to switch antennas.

Other antennas, like Yagi-Uda or microstrip patch, tend to work best in narrower frequency bands, which limits their usefulness if you're trying to detect multiple types of signals.

High Directional Gain

LPDA antennas are directional, meaning they focus on receiving signals from a specific area.

This increases detection range and signal quality—important when you're trying to pick up weak aircraft signals.

While dipole and monopole antennas are omnidirectional (receive from all directions), they have lower gain and are more likely to pick up background noise, making it harder to distinguish aircraft signals.

Triangulation and Localization

Your Phase II system involves multiple nodes working together to localize aircraft using Time Difference of Arrival (TDOA).

A directional antenna like an LPDA improves the precision of the time and direction of signal arrival, which is critical for accurate triangulation.

Antennas that are omnidirectional (like dipole or monopole) don't offer the same precision, which would hurt localization accuracy.

Environmental Durability

LPDA antennas (especially the Planar model you're using) are rugged and weatherproof, designed for long-term use outdoors.

Other advanced options, like phased array antennas, may offer better performance on paper but require complex electronics and are expensive, sensitive, and not ideal for harsh, remote deployments.

Cost-Effectiveness

LPDA antennas provide excellent performance without excessive cost.

Phased arrays or high-end commercial systems like Raytheon's Silent Sentry are not only costly but also complex to maintain.

LPDA gives you high gain and bandwidth while keeping the project affordable and practical.

Bottom Line:

The LPDA antenna is the most balanced solution for your system. It combines:

Wideband detection,

Directional precision,

Environmental durability,

And affordability.

Other antennas might be cheaper (like dipoles), more compact (like patches), or more advanced (like phased arrays), but none of them check all the boxes for a reliable, scalable, and low-cost passive aircraft detection system the way LPDA does.

My Response:

Could you quickly explain the installation process?

ChatGPT Response:**LPDA Antenna Installation Process (Quick Steps)****Choose the Location**

Pick a high, clear area with line-of-sight to the sky.

Avoid trees, buildings, or RF noise sources (e.g., power lines or radio towers).

Mount the Antenna

Use a metal or fiberglass mast to mount the antenna—typically on a pole or tripod.

Point the antenna in the general direction of air traffic you're interested in monitoring.

Make sure the antenna is securely fastened and weatherproofed.

Connect the Coaxial Cable

Use a low-loss coaxial cable (like LMR-400) to connect the antenna to the spectrum analyzer (Signal Hound BB60D).

If the connectors differ (e.g., N-type on the antenna, SMA on the analyzer), use the proper adapter.

(Optional) Add Signal Conditioning

For better performance, you can insert a low-noise amplifier (LNA) near the antenna to boost weak signals.

You can also use a bandpass filter to reduce out-of-band noise if you're focusing on specific aircraft signals (like ADS-B).

Connect to the Analyzer and Processor

Plug the coax cable into the Signal Hound BB60D.

The BB60D connects via USB to the Raspberry Pi or your local processor.

Power Everything On

Ensure your power system (battery and/or solar panel) is functioning.

Turn on the Raspberry Pi and run the software to start scanning RF signals.

Check Alignment and Signal Strength

Use your signal visualization software (like Signal Hound's Spike or SpectraVue) to fine-tune the antenna alignment.

Adjust as needed for maximum signal strength.

Grok:**Prompt: What kind of antenna is best to use?****Response:**

Given your project's focus on a low-cost passive aircraft detection system using multiple units arranged in an array, the choice of antenna is critical to balancing cost, performance, and practicality. Your system aims to detect aircraft signals (likely ADS-B at 1090 MHz or other RF emissions) passively, using Commercial Off-The-Shelf (COTS) components, and scale up by deploying multiple nodes to work together for triangulation and enhanced coverage. Based on your "Divide and Conquer" document and the problem statement, here's a recommendation for the best antenna type, tailored to your needs:

Recommended Antenna: Planar Log-Periodic Antenna (LPDA)

Your document already lists the Planar Log-Periodic Antenna AX-37A in the budget (priced at \$459.95 each, with 10 units planned), and it aligns well with your project's goals. Here's why it's the best choice for your low-cost, multi-unit array system:

Why a Log-Periodic Antenna?

Broadband Coverage:

LPDAs are wideband antennas, capable of receiving signals across a large frequency range (e.g., 300-3000 MHz for the AX-37A, per your specs). This ensures your system can detect ADS-B signals at 1090 MHz and potentially other aircraft RF emissions without needing multiple specialized antennas, keeping costs down.

Cost-Effectiveness:

At \$459.95 per unit, the AX-37A is a COTS component that offers good performance for the price. While not the cheapest option upfront, its broadband capability eliminates the need for multiple narrowband antennas, reducing overall system complexity and cost when scaling to an array of 10+ units.

Directional Gain:

LPDAs provide moderate gain (≥ 6 dBi per your specs), which improves signal reception over omnidirectional antennas like dipoles. This directionality is useful for an array setup, as you can orient each unit to cover specific sectors, enhancing detection accuracy when triangulating aircraft positions across multiple nodes.

Scalability for Array Deployment:

In a multi-unit array, LPDAs can be strategically placed and angled to overlap coverage zones, allowing your system to use time-difference-of-arrival (TDOA) or signal strength differences to localize aircraft. Their predictable radiation pattern supports this networked approach without requiring expensive phased-array tech.

Durability and Simplicity:

LPDAs are rugged and weather-resistant, fitting your requirement for deployment in harsh, remote environments. Their planar design (as opposed to bulky Yagi antennas) simplifies mounting and integration with your solar-powered nodes.

Comparison to Alternatives

Here's how the LPDA stacks up against other low-cost options you might consider:

Dipole Antenna:

Pros: Very cheap (often under \$50), simple to build or buy, omnidirectional.

Cons: Low gain (typically 2-3 dBi), less sensitivity to weak signals, and no directionality, making it harder to localize aircraft in an array. You'd need more nodes to achieve the same coverage.

Verdict: Too basic for your multi-unit triangulation goals.

Yagi-Uda Antenna:

Pros: Higher gain (8-12 dBi), directional, decent range for 1090 MHz if tuned properly.

Cons: Narrowband (requires specific tuning to ADS-B or other frequencies), bulkier than LPDA, and slightly more expensive per unit (around \$100-\$200 for COTS versions). Harder to adapt to varying aircraft signals.

Verdict: Good for single-frequency detection but less versatile and cost-effective than LPDA for your broadband needs.

Omnidirectional Collinear Antenna:

Pros: Affordable (\$50-\$150), 360-degree coverage, easy to deploy.

Cons: Lower gain (3-6 dBi), less precise for array-based localization since it picks up signals from all directions equally, increasing noise and false positives.

Verdict: Useful for initial detection but suboptimal for your multi-node precision goals.

Patch Antenna:

Pros: Compact, low-cost (\$20-\$100), decent gain (5-8 dBi).

Cons: Narrowband and highly directional, limiting its use to specific frequencies and requiring precise alignment, which complicates array setup in remote areas.

Verdict: Too specialized and alignment-sensitive for your scalable, low-maintenance array.

Why LPDA Wins for Your Project

Cost vs. Performance: At \$459.95 per unit, the AX-37A is pricier than a basic dipole or patch, but its broadband range and gain reduce the number of antennas and nodes needed, keeping the total system cost under your \$8,000 prototype budget when paired with other COTS parts like the Raspberry Pi and Signal Hound BB60D.

Array Synergy: Multiple LPDAs can work together effectively in your Phase 2 multi-unit network. Their directional nature allows you to cover a border area by spacing nodes 2-10 km apart (per your specs), using TDOA to pinpoint aircraft locations with your GPS-synchronized Raspberry Pis.

Low-Cost Maintenance: The LPDA's durability and lack of moving parts align with your plug-and-play, solar-powered design, minimizing upkeep in remote locations.

Practical Considerations for Your Array

Placement: Space nodes 4-10 km apart (your specs suggest 2-10 km for localization density, with a 4 km node range). Orient each LPDA to maximize coverage overlap, adjusting angles based on terrain and expected flight paths.

Integration: Connect the LPDA to the Signal Hound BB60D via a coaxial cable (SMA or N-type, as noted in your hardware design). Add a low-noise amplifier (LNA) if signals are weak, powered via a bias-tee from your 5V bus (per your power schematic).

Cost Scaling: With 10 units budgeted at \$4,599.50 total, you're within bounds for a multi-node prototype. If costs need trimming, consider fewer nodes initially (e.g., 5 units at \$2,299.75) and expand later.

Final Recommendation

Stick with the Planar Log-Periodic Antenna AX-37A as your primary antenna. It's the best low-cost, COTS option that supports your multi-unit array strategy, offering broadband detection, sufficient gain, and durability for remote deployment. It's already in your sponsor's BOM and budget, so it leverages existing resources while meeting your technical goals for passive RF detection and scalability. For your report, emphasize how its wideband capability and directional gain enable cost-effective coverage and precise localization when paired with your networked nodes.

Let me know if you'd like help refining this further for your report or calculating array placement specifics!

My Response:

So the planar log periodic antenna AX 37A is best you would say?

Grok Response:

Yes, I'd say the Planar Log-Periodic Antenna AX-37A is the best choice for your low-cost passive aircraft detection system, given your project's specific goals and constraints. Here's a concise breakdown of why it stands out:

Matches Your Requirements: It covers a wide frequency range (300-3000 MHz per your specs), including the critical 1090 MHz ADS-B signals, making it versatile for detecting various aircraft RF emissions without needing multiple antenna types.

Cost-Effective for Scale: At \$459.95 each, it's a COTS component that fits within your \$8,000 prototype budget (10 units total \$4,599.50), especially since your sponsor is already providing it. Its broadband capability reduces the need for additional hardware, keeping costs down as you scale to an array.

Array-Friendly: With a gain of ≥ 6 dBi and directional pattern, it's ideal for your multi-unit setup. Multiple AX-37As can be arranged to overlap coverage zones, enabling triangulation (via TDOA or signal strength) across your 2-10 km localization density, as outlined in your specs.

Practical for Remote Use: Its weatherproof, planar design suits your solar-powered, low-maintenance nodes in harsh environments, aligning with your 10-year durability goal.

Sponsor Alignment: It's already in your Bill of Materials (BOM) and purchased by your sponsor, so it leverages existing resources without extra funding from your team.

Compared to alternatives like dipoles (too low gain), Yagis (narrowband, bulkier), or omnidirectional antennas (less precise for localization), the AX-37A strikes the right balance of performance, affordability, and scalability for your Phase 2 multi-node network. It's not the absolute cheapest per unit, but its versatility and array synergy make it the most cost-effective overall for your system's success.

So, yes, I'd confidently recommend sticking with the AX-37A as the best antenna for your project. It's a solid foundation for your report and practical implementation. Want me to draft a paragraph for your report justifying this choice, or help with anything else related to it?

My Response:

Could you quickly explain how installation would work?

Grok Response:

Here's a quick explanation of how installation would work for the Planar Log-Periodic Antenna AX-37A in your low-cost passive aircraft detection system, focusing on setting up multiple units in an array:

Installation Process for the AX-37A in Your System

Site Selection:

Choose locations for each node based on your coverage goals (e.g., 2-10 km spacing per your specs, with a 4 km detection radius per node). Position them along a border or remote area to maximize overlap for triangulation. Consider terrain—elevated spots like hills improve line-of-sight to aircraft.

Mounting the Antenna:

Attach the AX-37A to a sturdy mast or pole (e.g., a 1-2 meter metal pole) using its mounting hardware. Its planar design is lightweight (likely under 25 kg total unit weight, per your specs), so a simple clamp or bracket works.

Orient the antenna directionally toward the expected flight path. Since it's a log-periodic antenna, it has a focused radiation pattern—angle it to cover a specific sector (e.g., 60-90° beamwidth) that overlaps with neighboring nodes.

Connecting to the Node:

Run a coaxial cable (SMA or N-type, as specified in your hardware design) from the AX-37A to the Signal Hound BB60D spectrum analyzer. Keep the cable short (e.g., 1-3 meters) to minimize signal loss.

If using a low-noise amplifier (LNA), install it near the antenna with a bias-tee powered from the 5V bus (via your Raspberry Pi or power supply), as noted in your RF detection subsystem.

Power and Hardware Setup:

Secure the node's other components (Raspberry Pi, BB60D, Samsung S24, solar panel, battery) in a weatherproof enclosure (IP65-rated, per your durability specs). Mount the solar panel above the enclosure, angled for optimal sunlight.

Connect the 12V LiFePO4 battery to the MPPT charge controller, then distribute power: 12V directly to the BB60D (via USB 3.0 from the Raspberry Pi, correcting your doc's 12V note), and 5V (via a buck converter) to the Raspberry Pi and Samsung S24.

Network Integration:

Link the Raspberry Pi to the Samsung S24 via USB tethering or Wi-Fi for Starlink SATCOM access. Ensure the Starlink Mini Terminal (or cellular service) is operational, with its antenna clear of obstructions for satellite uplink.

Testing and Calibration:

Power on the node and verify the AX-37A detects RF signals (e.g., ADS-B at 1090 MHz) through the BB60D and Raspberry Pi software. Use a known aircraft (like a commercial flight on FlightRadar24) to calibrate orientation and sensitivity.

Repeat for each node, ensuring GPS synchronization (via Raspberry Pi) for accurate TDOA across the array.

Array Coordination

Install 5-10 nodes (per your budget) in a line or grid pattern, spaced 4-10 km apart. Each AX-37A's directional coverage complements its neighbors, enabling the system to fuse data (via your software) and pinpoint aircraft locations in real-time.

Key Notes

Time: Your "plug-and-play" goal aims for setup in under an hour per node—achievable with pre-assembled enclosures and connectors.

Cost: Uses existing sponsor-provided AX-37As, minimizing additional expenses.

Scalability: Add nodes as needed, adjusting placement based on field test results.

This installation leverages the AX-37A's strengths—directional gain and broadband range—to create an effective, low-cost array. Let me know if you need a more detailed step-by-step or a diagram sketch for your report!

7.4 ERD Overview

1. Unit

Purpose: Represents the physical RF detection unit (e.g., sensors or nodes).

Attributes:

Unit_ID (PK): Primary key uniquely identifying each unit.

Unit_name: Human-readable name for identification.

Location: Geographic placement of the unit.

Status: Indicates operational status (e.g., "Active", "Offline").

Relationships:

One-to-many with RF_Signal → A single unit can detect many signals.

2. RF_Signal

Purpose: Stores raw RF data captured by each unit.

Attributes:

Signal_ID (PK): Unique ID for each signal event.

Unit_ID (FK): Foreign key linking to Unit.

Frequency: Signal frequency in MHz/GHz.

Signal_strength: Signal amplitude (dBm).

Timestamp: When the signal was captured.

Raw_data: Binary or structured format of raw signal.

Relationships:

Many-to-one with Unit.

One-to-one or one-to-many with Preprocessed_signal.

3. Preprocessed_signal

Purpose: Intermediate stage that processes raw signal data (filtering, enhancement).

Attributes:

Processed_ID (PK): Unique ID for the processed signal.

Signal_ID (FK): Links to the raw signal.

Filtered_ID: Optional field (e.g., filter profile used).

Signal_quality: Qualitative measure or score.

SNR: Signal-to-noise ratio.

Detection_flag: Boolean or integer indicating detection success (e.g., 1 = valid).

Relationships:

Many-to-one with RF_Signal.

One-to-one with Main_unit_analysis.

4. Main_unit_analysis

Purpose: Final interpretation and validation of the preprocessed signal.

Attributes:

Analysis_ID (PK): Unique analysis record.

Processed_ID (FK): Link to the preprocessed signal.

Result_status: Outcome (e.g., "Valid", "Noise", "Aircraft Detected").

Confidence_level: Percent or score (e.g., 0.95).

Timestamp: When the analysis occurred.

Analysis_notes: Any supporting comments or AI annotations.

Relationships:

One-to-one with Preprocessed_signal.

One-to-one or one-to-many with Cloud_storage.

5. Cloud_storage

Purpose: Logs final data storage to cloud for remote access, archiving, or API use.

Attributes:

Cloud_ID (PK): Unique ID for each cloud upload.

Analysis_ID (FK): Link to the final analysis that was uploaded.

Data_link: URL or identifier for stored data location.

Storage_time: Timestamp of upload.

API_endpoint: REST or MQTT endpoint used for access.

Relationships:

Many-to-one with Main_unit_analysis.