Dalgona

RF based Antenna Tracking System

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Executive Summary

The RF-based Antenna Tracking System (RFATS) is a cutting-edge solution designed to provide accurate, real-time tracking of mobile RF transmitters without the need for GPS or location data. As the demand for reliable wireless communication grows in environments where GPS signals are unreliable or subject to interference and jamming, RFATS addresses this critical need by offering a robust, interference-resistant tracking mechanism. This system is particularly suited for applications such as remote area communication, UAV tracking, and secure military operations, where maintaining continuous signal lock with a moving transmitter is essential.

The core of the RFATS design leverages Software Defined Radio (SDR) technology to enable flexible and adaptive RF communication. Custom-designed waveforms are integrated to optimize performance even when signals are weak or disrupted by jamming. The system features a lightweight, two-axis rotating receiver that dynamically adjusts in both azimuth and elevation to track the target, ensuring continuous alignment within a 5-degree error margin. The tracking system demonstrates exceptional responsiveness, locking onto the target within three seconds, and is capable of handling angular velocities of at least 15 degrees per second. These capabilities are further enhanced by advanced signal processing algorithms developed in MATLAB, ensuring smooth operation even in noisy or adversarial environments.

A key aspect of the project is the development of mitigation techniques to counteract interference, reflected signals, and spoofing attempts, preventing false tracking, and ensuring the stability of the system. The compact and modular design of the RFATS allows for ease of deployment and scalability, making it adaptable to various operational scenarios. The project will culminate in the delivery of a fully functional prototype, comprehensive signal processing software, and rigorous testing to validate performance across diverse conditions.

The development process will span approximately nine months, covering system design, algorithm development, mechanical assembly, and testing phases. The estimated project cost, excluding SDR hardware provided by TUALCOM, is approximately $300, accounting for antenna components, motors, and software development. RFATS represents a reliable and cost-effective tracking solution, poised to enhance secure communication capabilities in GPS-denied environments and challenging operational settings.

Introduction

Motivation of the project

Reliable long-range wireless communication is essential for applications in civil, military, and industrial sectors. As unmanned systems, remote sensing devices, and secure communication networks continue to evolve, the need for accurate antenna tracking systems that can operate without GPS or external location data has become increasingly critical. Existing tracking systems often fail in environments with interference, jamming, or unpredictable target movement, limiting their effectiveness in search and rescue missions, military operations, and remote communication.

This project aims to develop an RF-based antenna tracking system capable of autonomously locking onto and following a mobile target, even in the absence of GPS. By addressing the challenges posed by signal degradation and jamming, the system will enhance communication reliability in demanding environments. The integration of Software Defined Radio (SDR) technology further supports the development of a flexible, adaptable solution that meets the growing need for cost-effective and scalable tracking systems.

Through this project, we seek to contribute to the advancement of wireless communication technologies, ensuring greater operational resilience and expanding the reach of secure, long-distance communication systems.

Literature/Market Survey (State of the Art)

Antenna tracking systems are vital for long-range wireless communication in sectors like UAV operations, remote sensing, and satellite communications. Existing solutions rely heavily on GPS-based tracking which have notable limitations. GPS-based systems are vulnerable in GPS-denied environments or areas affected by jamming.

Mechanically rotated antenna systems offer a lower-cost alternative but often lack the precision and adaptability required for tracking mobile targets under interference and multipath conditions. This creates a demand for systems that can autonomously track RF signals without external location data, ensuring reliable communication in dynamic environments.

The rise of Software Defined Radio (SDR) technology has enabled more flexible and responsive tracking systems. SDR's ability to adapt waveforms and process signals in real-time improves performance under jamming and low-signal conditions. Research has shown that predictive tracking algorithms and advanced noise mitigation techniques integrated with SDR can sustain tracking even during brief signal losses. These advancements highlight SDR's potential for creating cost-effective, high-performance antenna tracking solutions that operate in challenging environments.

Despite these developments, there remains a need for affordable, compact, and modular tracking systems that balance mechanical precision with signal processing adaptability. The proposed RF-based antenna tracking system (RFATS) addresses this gap by combining SDR technology with custom signal algorithms and lightweight mechanical design. This project aims to deliver a scalable, autonomous solution for industries where secure and uninterrupted communication is essential.

Current status of your project work

A prototype of the motor submodule was developed, capable of rotating along two axes using two servo motors. This prototype successfully passed all tests related to azimuth and elevation rotation, demonstrating smooth and precise movement within the required operational parameters. The servo motors enabled effective angular adjustments, confirming the motor submodule's reliability for tracking in both horizontal and vertical planes.

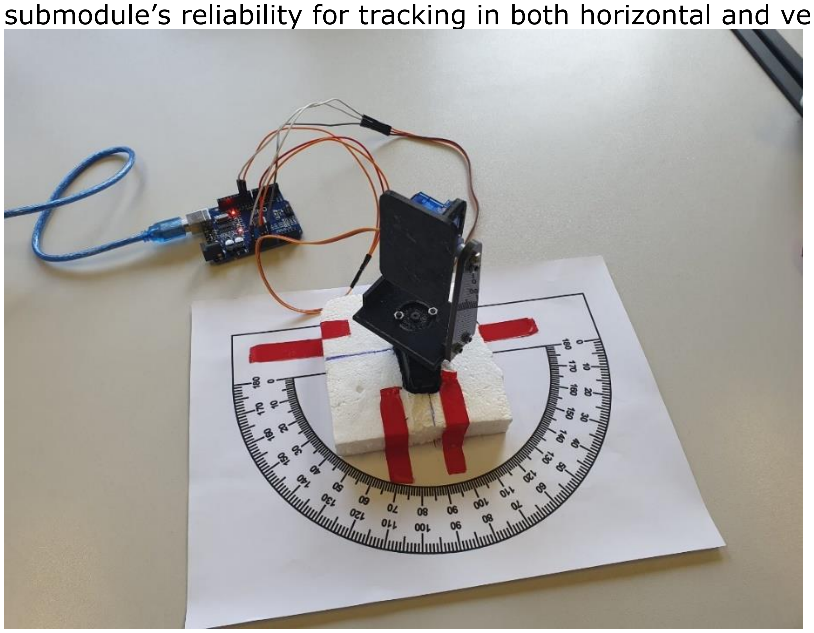

Figure 1. Current status of the motor module

In the antenna module, another prototype was constructed, incorporating two Vivaldi antennas designed to receive signals from the target. Signal processing is handled by an SDR Pluto, which interprets the incoming data. The system utilizes the **phase comparison monopulse method** to determine the exact angle of the target at short distances. For longer distances, the same method provides a rough directional estimate, ensuring consistent tracking even as signal strength diminishes.

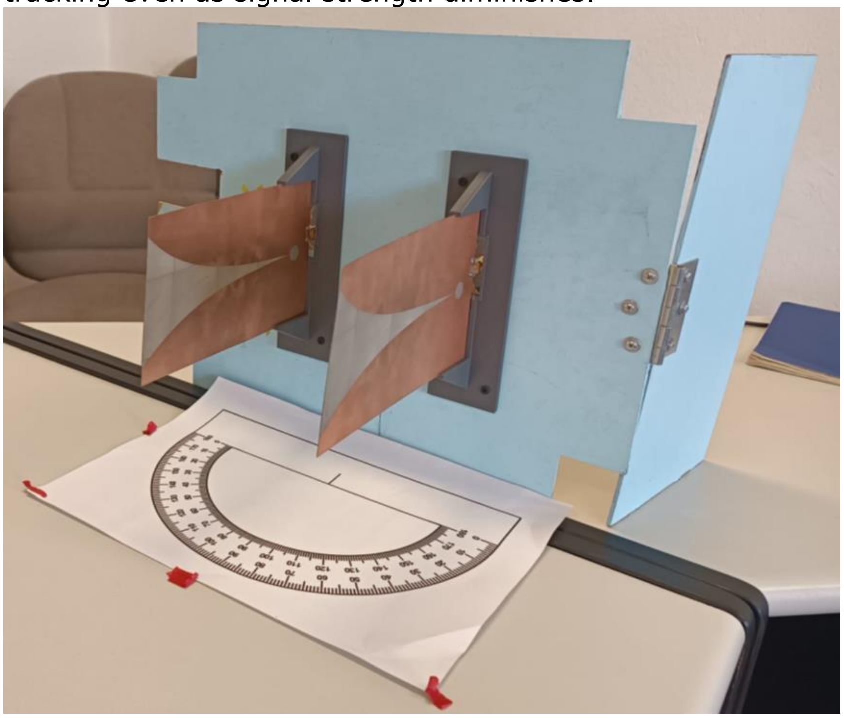

Figure 2. Current status of antenna module

Scope and organization (of the report)

This report outlines the development of an RF-based antenna tracking system designed to enable real-time tracking of a moving target without relying on GPS or external location data. The project's scope includes the design and implementation of a robust tracking mechanism that leverages Software Defined Radio (SDR) technology, custom waveform generation, and advanced signal processing algorithms to enhance tracking accuracy and resilience against interference. The antenna system operates along two axes—azimuth and elevation—ensuring accurate target alignment within a 5-degree margin, even in environments subject to signal jamming and noise. The proposed system addresses critical communication challenges in remote areas, UAV tracking, and military applications by maintaining stable connections under adverse conditions.

The organization of this report follows a structured approach to comprehensively cover each phase of the project. It begins with an executive summary that encapsulates the key aspects of the project, including objectives, methods, and anticipated outcomes. The introduction section provides background information, highlighting the project's motivation, societal impact, and current progress. A clear problem statement outlines the technical challenges driving the project, while the requirement analysis delves into customer needs, functional and performance requirements, and project constraints.

The solution procedure section elaborates on the step-by-step approach to developing the system, detailing subsystem designs, algorithms, and hardware integration. This is followed by planning and scheduling, which includes task allocation, a risk analysis framework, and a breakdown of deliverables. Test procedures and performance evaluation metrics are discussed in detail to ensure the system meets design specifications and operational goals. Finally, the report concludes with a summary of findings and potential areas for future improvement, supported by appendices containing diagrams, objective trees, and test results that provide further insight into the design process.

Problem Statement

Developing a robust RF-based antenna tracking system presents several complex engineering challenges, particularly in environments where interference, jamming, and the absence of GPS or other location data limit conventional tracking methods. One of the primary difficulties lies in ensuring that the system can accurately detect and track weak RF signals while maintaining sub-5-degree angular accuracy. This becomes increasingly problematic in environments with high levels of noise. Traditional tracking systems often fail under such conditions, as they depend heavily on continuous location input. Consequently, achieving consistent and accurate tracking without relying on external positional data requires the development of advanced signal processing algorithms capable of distinguishing the target signal from interference and environmental noise.

A significant portion of the challenge stems from the mechanical design of the antenna system. The antenna must physically rotate along both azimuth and elevation axes to maintain alignment with the target, which introduces concerns motor precision, response time, and stability. Smooth and accurate movement is essential to prevent overshoot or jerking, all of which can affect tracking performance. The system must also avoid false movements caused by environmental factors such as wind or abrupt signal loss. This necessitates the design of a highly responsive motor control system capable of rapid adjustments while minimizing power consumption and mechanical wear.

Environmental resilience is another critical aspect of the design. The system must operate reliably in conditions involving intentional jamming or heavy interference, where adversaries may attempt to disrupt communication. The antenna tracker must be capable of rejecting false tracking cues and locking onto signals with power levels as low as -80 dBm, even under narrowband jamming conditions. To address this, the system must integrate noise reduction techniques and predictive algorithms that allow the antenna to maintain its lock on the target even when the signal is temporarily lost.

Integration with Software Defined Radio (SDR) technology introduces additional engineering hurdles. The flexibility of SDR allows for customizable waveforms and real-time signal adaptation, but it also imposes computational constraints that must be carefully managed. The signal processing algorithms must operate efficiently within the limited processing power of the SDR, ensuring that tracking performance is maintained without exceeding system resources. Furthermore, the design of SDR-compatible waveforms must account for varying RF conditions to optimize detection accuracy while preserving the system’s rapid response capabilities.

Finally, the project faces constraints related to power consumption, size, and weight. The antenna tracking system must be compact and portable, facilitating deployment in diverse environments. Achieving this requires careful selection of lightweight materials and efficient component design, ensuring that the system can meet performance requirements without becoming cumbersome or power intensive. Balancing these factors is essential to developing a practical, scalable solution capable of addressing the needs of both civil and military applications.

Objectives and Requirements

Our main objective is developing a reliable antenna tracking system that mechanically rotates along azimuth and elevation axes to maintain communication. Tracking precision, response time, jamming resistance and user-friendly design are our subobjectives.

Tracking precision: The system must maintain an angular pointing accuracy with a root-mean-square (RMS) error below 5 degrees. Achieving this performance demands a closed loop tracking architecture that integrates precise rotational actuators (e.g., stepper motors or servo motors) with feedback from real-time signal strength or phase measurements. Moreover, the system should employ advanced filtering and signal processing (e.g., Kalman filters or adaptive algorithms) to reject false readings and minimize tracking jitters or overshoot.

Response time: The antenna platform must acquire and lock onto the target within 3 seconds after initialization or loss of signal. This criterion necessitates a carefully designed startup or reacquisition procedure that leverages fast scan speed control patterns or predictive estimators. Software-defined radio (SDR) modules, controlled via MATLAB, will perform instantaneous signal detection and directional estimation, triggering the mechanical drive system to converge rapidly on the correct azimuth and elevation. Efficient and optimized DSP algorithms are essential to cope with these constraints while still meeting performance targets.

Jamming resistance: To ensure reliable operation in hostile RF environments, the system must continue tracking when subjected to single-source noise jamming with up to 100 kHz bandwidth and -80 dBm power in the operational frequency band. This requirement involves incorporating robust waveform design, such as spread-spectrum or interference-resistant modulation, and mitigation techniques that minimize false lock events. Adaptive notch filters, interference cancellation algorithms, and dynamic thresholding can be combined to preserve tracking performance during jamming events.

User-friendly design: The final system should exhibit a compact, lightweight form factor that simplifies integration onto various platforms. Modular construction of the antenna array, RF front-end, and drive assemblies must facilitate straightforward installation and maintenance.

Functional/Physical Requirements

Smooth Tracking Mechanism: Must rotate the receiver panel accurately and smoothly, avoiding shudder or erratic movements.

Tracking Performance: Mechanical rotation must achieve at least 15 degrees per second in azimuth to track moderately fast-moving targets.

Software Integration: The entire solution should be controlled via intuitive software interfaces (e.g., MATLAB GUIs) that offer clear configuration parameters and diagnostic feedback. Moreover, algorithms should be compatible with Raspberry Pi 5 and Arduino UNO.

Compactness: The entire assembly—encompassing the antenna array, drive motors, and signal processing electronics—should remain within manageable weight and dimensions to ensure ease of rotation movement.

Performance Requirements

- Angular error < 5 degrees (RMS).
- Tracking time < 3 seconds.
- Tracking speed > 15 degrees per second in azimuth.
- Ability to reject false signals caused by jamming.
- Operation under jamming with -80 dBm power within the specified frequency band.
- Ability to estimate the continuous track of the target for up to 3 seconds if the signal is lost.

Constraints

Frequency Band: The system must keep fixed center frequency with no frequency hopping, which makes the communications and modulation difficult.
Jamming Conditions: The system must tolerate jamming conditions as described.
Power Requirements: Overall power consumption should be minimized for use in portable power sources such as batteries and power banks.
Size and Weight: All components must be compact for easy integration, which is addressed carefully in the following sections
Budget: All requirements should comply with budget constraints, which are about 300$.
Logistics and Supply Chain: Due to intricate and specific components needed, the logistics and required supply time should be addressed.

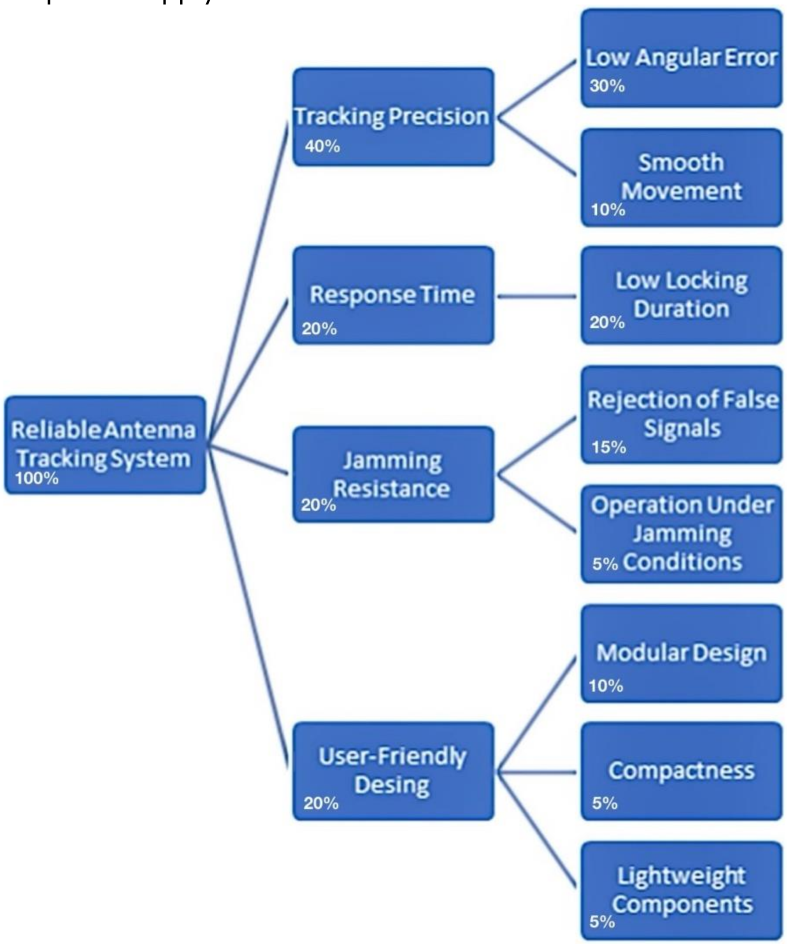

Figure 3. Weighted Objective Tree

Table 1. Weighted Objective table

Objective	**Weight (%)**	**Sub-Objectives**	**Sub-Objectives Weight (%)**
Tracking Precision	40	Low Angular Error	30
		Smooth Movement	10
Response Time	20	Low Locking Duration	20

Jamming Resistance	20	Rejection of False Signals	15
		Operation Under Jamming Conditions	5
User-Friendly Design	20	Modular Design	10
		Compactness	5
		Lightweight Components	5

System Design

The overall structure of RF-Based Antenna Tracker consists of 5 main subsystems. These are receiving antenna modules, transmitting antenna module, motor module, power module, and processing module. The objective is to create a reliable antenna tracking system that can operate without location information for wireless communication applications. In overall, the system will mechanically turn the receiver antennas in both elevation and azimuth directions to direct the tracker toward a transmitting target unit.

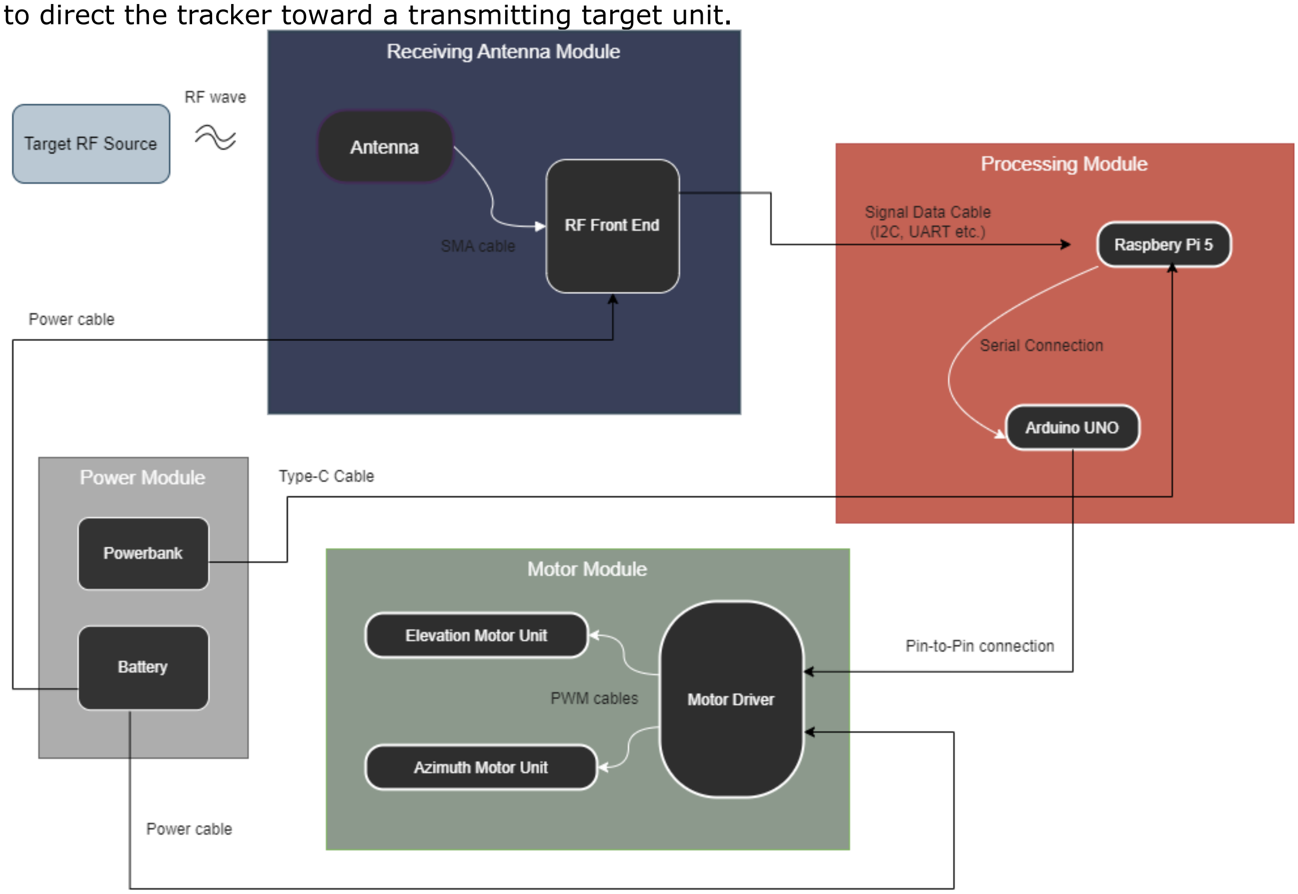

Figure 4 Block Schematic of the System

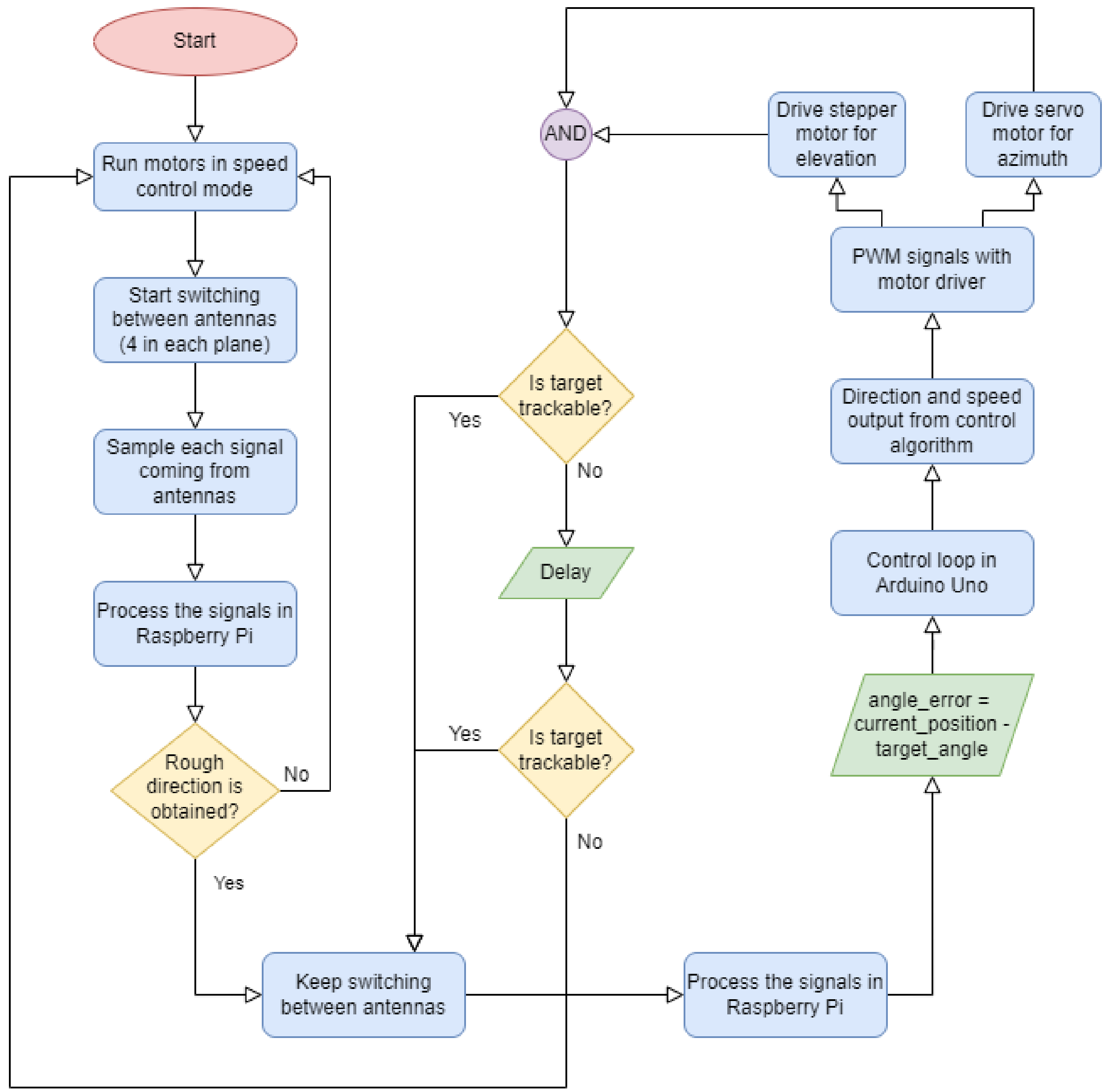

Figure 5. Working Principle in Flowchart Diagram

The transmitting target antenna module consists of an omni-directional antenna and a software defined radio to create the target signal. The receiving antenna module consists of receiving antenna array and relevant RF Front end structure including various RF components, such as mixers, local oscillators, switches, phase shifters, software defined radios etc. This module is used to receive the signal coming from target RF source. After receiving ang preprocessing the signal, the signal will be processed with various signal processing and control algorithms at the processing unit with Raspberry Pi 5 and Arduino UNO to obtain a reliable angle error to feed the Motor module. Motor module consists of azimuth and elevation motor units with corresponding motor driver to drive both units. This module will be fed by the processing module to achieve the desired angles in both elevation and azimuth. After the feeding process, the tracker will lock to the target and the process continues. The power module, on the other hand, will supply the other modules with their required rated power. It consists of a power bank and a battery. While the former supplies the Raspberry Pi 5, the latter will supply the other components. The 3D overall structure is shown in Figures below.

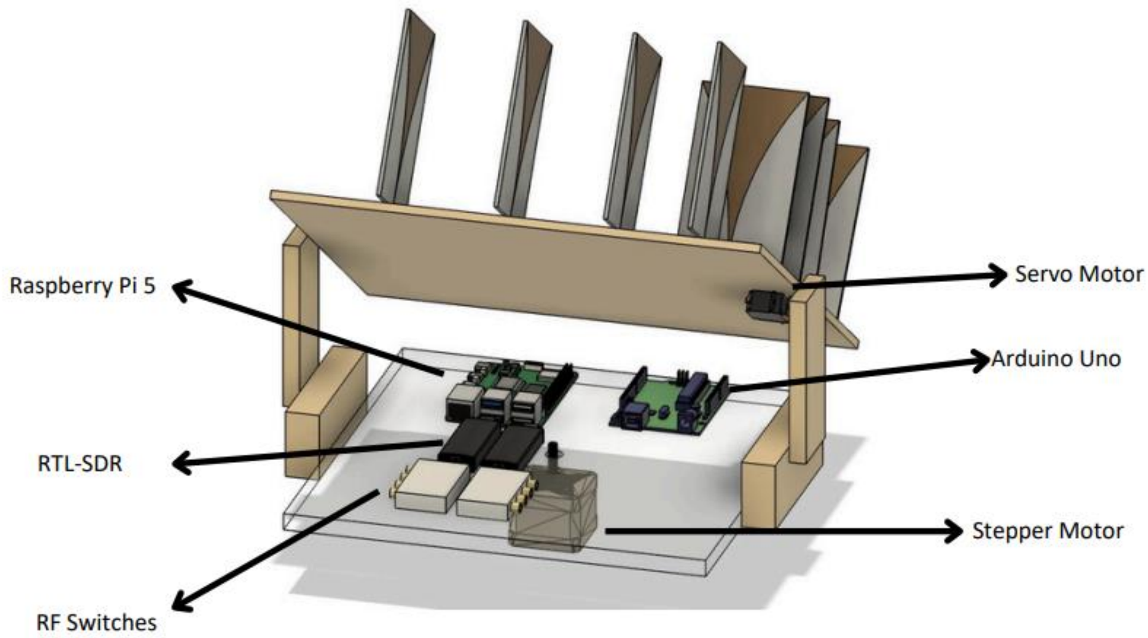

Figure 6. 3D Model of Project

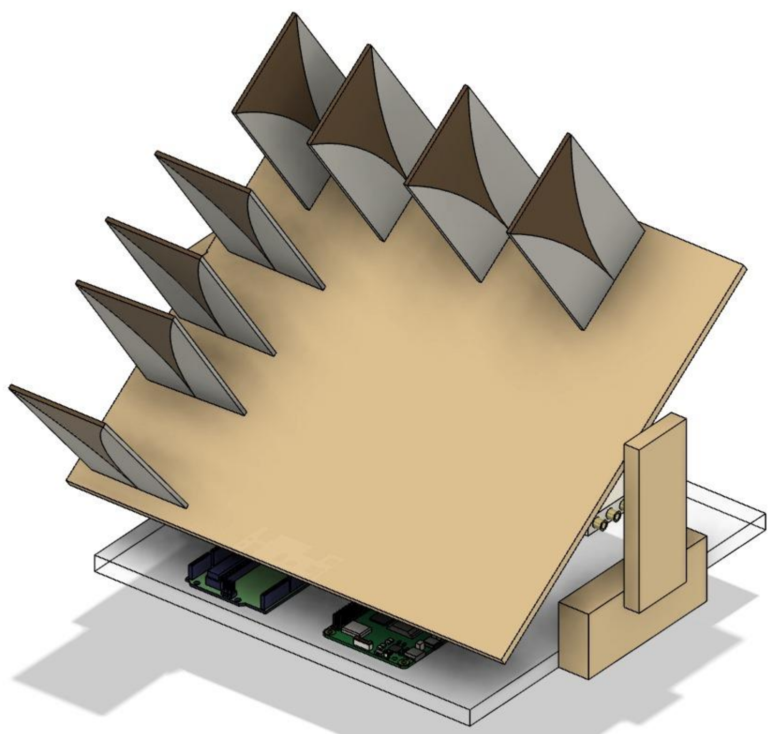

Figure 7. Receiver antenna array

Table 2. Weight of the components

Component	Weight
ADALM-PLUTO SDR	114g
RTL-SDR	59.5g
Receiver Antenna	~5g
Servo Motor	55g
Step Motor	280g
3D Printed Components	~65g
Raspberry Pi 5	30g
RF Switch	~200g

The aggregate weight of our module test demonstration setup was approximately 299 g. However, this test setup utilized a minimal number of antennas, and the motors were not finalized. Additionally, the demonstration did not require a carrier mechanical structure, panels, or similar components.
For the final design, the inclusion of additional antennas will necessitate a larger panel size, which will in turn increase the weight of the 3D-printed components. Based on the component weights listed in Table X and considering the mechanical frame to be used, our team expect the final aggregate weight of the main solution described in this report to be approximately **~785g**. This calculation excludes the weight of the carrier structures, as it does not belong to our final solution. Moreover, due to neglected cabling weight, there is an expected error at the weight of the finalized product. Furthermore, the number of antennas or the receiving unit may change based on the alternative solutions to be proposed. This calculation has been done for the main solution in a very general, approximate fashion.
There is a carrier panel and box, where we mount the external components as they are expected to be moved. This frame can be considered as the entire system except the step motor. Therefore, the size of this frame approximately yields the dimensions for our system as every other component and structure is installed within this frame. The dimensions for the design are provided in the table below. A clearer understanding of the configuration can be gained by referring to the Figure 6 and 7, which contains the technical drawing. The figure offers a detailed visual representation of the system, aiding in the interpretation of the design elements and their spatial relationships.

Table 3. Dimensions of the design

Width	~25cm
Height	~25cm
Length	~22.45cm

The main components that consume the significant power are Raspberry Pi 5, and motors. RF Frontend consist of mostly passive components, and the only active component – receiver unit – is drawing current from Raspberry Pi, which can be neglected for total consumption.

Table 4. Maximum power consumption

Component	Maximum Power Consumption
Step Motor	~24W

Servo Motor	~5W
Raspberry Pi	~7.5W

Table 4 defines the maximum power consumption of the components that consume the most power. However, the design will never use the maximum rated values for power consumption. Therefore, by estimating an average torque for motors, considering the ratings of our battery units we can estimate a power consumption.

Table 5. Average power consumption

Component	Average Power Consumption
Step Motor	~6W
Servo Motor	~1.25W
Raspberry Pi	~5W

In table 5, the one can observe the average power consumption of previously mentioned components. The average power consumption is calculated as **~12.25W**. Datasheets [1],[2] of the components were utilized for this calculation.

Transmitting Antenna Module

The transmitting antenna module consists of an ADALM-PLUTO SDR and an omnidirectional antenna. This module serves as a mobile RF source, transmitting a signal with a fixed center frequency to function as the target unit for the overall system. A primary design challenge for this module is designing the transmitted waveform to meet system-level requirements.
The transmitted signal has been chosen as a single-tone sinusoidal waveform, which simplifies observation in the frequency domain at the receiver end. The operating frequency was carefully selected, taking into account environmental factors[4], system requirements, and hardware capabilities. Additionally, the receiver antenna pattern was considered for the design of the waveform to ensure a reliable connection between the transmitter and receiver.

Table 6. System-level requirements table for transmitting antenna module

System-level requirements
Main requirement for this module is to transmit a signal with respect to system constrains, which can be detected by the receiving unit from a reasonable distance while maintaining a sufficient noise-immunity characteristic.

Potential Challenges and Alternative Concepts

To address potential issues such as noise, interference, and jamming, our team is evaluating the use of modulated waveforms as transmitted signal for future iterations. Another key consideration is the impact of path loss, which has been largely overlooked so far. To enhance the reliability of signal transmission, incorporating a power amplifier to boost signal strength is being explored as a potential improvement to the current solution.
Another one of the further enhancements would be using Linear Frequency-Modulation to modulate our transmitted signal. By transmitting a Linear FM[8] signal, the time delay between the received signals at the receiver antennas can be determined by detecting the frequency shift of the signal. Since frequency detection is inherently more robust to noise and clock synchronization issues compared to phase analysis, this approach would eliminate the need for clock coherence between the devices. The calculated time delay could then be used to

accurately determine the angle of arrival, providing a more resilient and efficient solution for the system. Such a waveform was not prone to easier debugging therefore not preferred for initial design and testing process.

Table 7. Challenge and Solution Table for the Transmitting Antenna Module

Challenge	Solution
Signal attenuation	Installing a power amplifier to the transmitter
Jamming/noise	Employing different modulation techniques

Receiving Antenna Module and Angle of Arrival Estimation

The core of the receiving antenna module consists of a dual-plane phased antenna array, two SP4T (Single Pole Four Throw) RF switches, and two RTL-SDR receivers. Each plane incorporates four antennas, forming a phased array configuration. These antennas feed directly into the SP4T RF switches, whose outputs are subsequently sampled by the RTL-SDRs. The antenna arrays are arranged both vertically and planar. The vertical array is responsible for scanning the elevation angle, while the planar array scans the azimuth plane. This dual-plane structure enables full 3D spatial coverage for target detection and tracking.

In passive direction finding, the system detects and locates signal sources without actively transmitting signals, which is the case. A phased array offers significant advantages by enabling beamforming and spatial filtering, which enhance sensitivity and angular resolution. By adjusting the phase of signals received by each antenna, the array can steer its reception beam toward specific directions, isolating signals of interest while rejecting interference from other angles. For this system, the vertical antenna array determines the elevation angle of incoming signals. By sequentially switching and sampling the antennas, the system constructs an elevation profile of the target. The planar antenna array performs azimuth scanning, estimating the horizontal direction of the target signal.

In traditional phased array systems, each antenna in the array captures signals simultaneously, and these signals are individually sampled. The instantaneous data from each antenna is then compared to estimate the angle of arrival (AoA) of incoming signals. By analyzing the phase differences [3] between antennas, the system can determine the direction from which the signal originates.

In the proposed system, signals from the antennas are not sampled simultaneously. Instead, the antennas are sequentially sampled during each switching period. This sequential sampling simplifies hardware design by reducing the need for multiple ADCs (Analog-to-Digital Converters) or SDRs. The approach minimizes analog circuitry, lowering system complexity and cost. However, the lack of instantaneous sampling introduces phase discrepancies between antennas. These discrepancies can lead to inaccuracies in AoA estimation.

To address the phase differences caused by sequential sampling, robust digital signal processing algorithms are applied. By compensating for the non-instantaneous nature of the samples, the system effectively reconstructs the signals as if they were captured simultaneously. This reconstruction yields four signal data per plane, corresponding to the four antennas. Once the signal data is processed, MATLAB is used for advanced filtering and post-processing. Techniques such as Kalman filtering or adaptive algorithms are employed to filter out noise, reject false readings, and reduce tracking jitter or overshoot. This ensures accurate and reliable direction-finding performance.

Table 8. System-level requirements table for receiving antenna module

System-level requirements
Receive the signal transmitted from the target in a reliable and robust fashion

Capture the transmitted signal at an appropriate rate so that the 3 second requirement is met.

Potential Challenges and Alternative Concepts

One challenge mentioned above is the error in the phase difference of the signals and the resulting measurement challenge due to finite switching time. One possible approach to solve this problem is to first convert the RF signal coming from each antenna by mixers and then compare their phases in IF with cheap phase comparators. Phase comparators give DC signal output proportional to the phase difference. This signal is then sampled via Arduino or appropriate ADC component to process in Raspberry Pi 5. This approach allows measuring the phase difference in real time, but the necessity of implementing an analog circuit possibly in a PCB and the cost of RF components like mixers proposes difficulties in implementing this design

Whether the above approach or the main approach is used, there may still remain a problem. The antennas should space as distant as possible to better measure the angle of arrival from the phase difference data. However, when the distance is bigger than the wavelength divided by 2, the solution of the angle of arrival estimation yields more than one solution. This ambiguity can be solved by various approaches. One approach is to use additional highly directional antennas to obtain a rough direction which solves the ambiguity. In our case, this could be either the utilization of SNR values of array antennas, or additional antennas connected to additional SDRs or any receiving unit that can accomplish power-based measurements such as RSSI or SNR. Such hybrid methods are utilized in some recent applications[6].

Another alternative concept would be using multiple RTL-SDR in order to eliminate the utilization of the RF switch. As mentioned, utilization of RF switch requires a control signal and the samples to be compared do not belong to the very same time instant. By using multiple RTL-SDR, received signals from different antennas can be compared simultaneously, which would eliminate the time delay caused by switching period. However, to be able to compare the phase characteristics of different signals received by different SDR channels, time-synchronization must be established. The internal clocks of RTL-SDRs are different than each other, therefore phase characteristics of signals cannot be compared in a consistent way. To ensure such synchronization, there are several methods. One of them is to connect all RTL-SDR to a single external clock to match the clock cycles of the RTL-SDRs. Another method is to synchronize the received waveform time instants with respect to a reference signal, which can be a FM radio station nearby since it provides a reliable, strong signal for both receiver channels. This reference source could also be a noise source component such as Keysight 346C[5]. One last solution would be to use a correlation method to explore the clock difference of two channels. By employing this method, the inherent time difference of both channels will be found, and the further received signals will be compensated. All these proposed values will be experimented with by our team. The feasibility of these techniques will be compared.

Another considered alternative concept is to utilize phase shifters for every phased array antenna. The main challenge throughout this module is to collect the signals received from different antennas and to compare them in a reliable fashion. Such an RF phase shifting card would let our team to first collect all the received signals from a signal SDR, and then distinguish them from each other by using the phase shifters. These phase shifters can be replaced with gain blocks to obtain a single numerical data which corresponds to the superposition of the received signals.

One final implementation would be changing the antenna array configuration. Due to system constraints, precision of azimuthal angle estimation is more important than elevation angle estimation and elevational angle change will be much less than azimuthal angle difference due to physical constraints. Such facts may change the antenna configuration. In other words, more antennas could be used for azimuthal direction finding and antennas dedicated to elevational direction finding may be reduced.

Table 9. Challenge and Solution Table for the Receiving Antenna Module

Challenge	Solution
Noise/jamming/multipath	Apply appropriate filtering and processing methods such as difference[7] calculation.
Clock mismatch	Clock synchronization. / Reference signal matching.

Processing Module

The processing modules mainly consists of two units, which are Raspberry Pi 5 and Arduino Uno. Below, these two units are elaborated separately.

Table 10. System-level requirements table for the Processing Unit

System-level requirements
Calculation of angle-of arrival for target tracking in a precise fashion with respect to error below 5 degrees by utilizing different signal processing methods.

Raspberry Pi 5 (Main Processor)

The Raspberry Pi 5, "work machine", is responsible for capturing signal samples from the SDR/antenna module, processing them (using MATLAB/C/C++), and determining the target angle. Its main tasks are listed below.

- Perform angle-of-arrival and signal strength computations.
- Run a GUI that provides real-time system monitoring.
- Send the calculated angle commands to the Arduino via a serial link.

The digital signal processing methods which will be utilized for the methods described previously will run within a MATLAB/C/C++ implementation on Raspberry Pi 5. Our main method will be using a correlation method between the captured and sampled signals in order to extract the phase difference information. This phase difference information will be then converted to an interpretable data for the control system. Another technique to obtain the phase difference between received signals is to use brute force methods. By forcing potential phase difference values on the captured waveforms, we may be able to obtain the correct time and phase difference between the received signals and this data will be interpreted in a similar fashion.

Arduino Uno (Control Loop)

Arduino executes the low-level, real-time control of the motors. It receives angle targets from the Pi and drives the motor module (e.g., stepper or servo motors) to the correct orientation. Below are the main tasks of Arduino Uno.

- Interface with motor drivers through PWM, direction, and enable lines.
- Implement a control algorithm (e.g., PID) to ensure fast and precise aiming.
- Read feedback sensors (e.g., encoders) at high frequency for deterministic control.

The communication between the Raspberry Pi and Arduino will employ UART interface using the Serial Bus. The Pi sends target angle commands to the Arduino at a suitable baud rate (e.g., 115,200 bps). The Arduino can respond with status updates, such as "target lost" or angle feedback. For the communication between the RF Front End and Pi, communication will often happen over USB (or SPI), streaming raw RF data to be processed in almost real time.

Why choose a Two-Controller Setup?

- **Real-Time Motor Control**: The Arduino's dedicated microcontroller architecture ensures consistent timing for motor pulses, avoiding Linux scheduling delays.
- **Task Separation**: The Pi handles computationally intense signal processing and the GUI, while the Arduino focuses on stable, low-level control.
- **Hardware Compatibility**: Arduino has abundant libraries and shields for motor control and sensor reading, speeding up development.
- **Fault Protection**: In case of an electrical fault from the motor module side, the worst scenario would be the losing the Arduino which is extremely cheaper compared to Pi.

In terms of power requirements and physical enclosure, we plan to supply the module using a power bank. Raspberry Pi will be powered up with a 15 W power bank (5V @ up to 3A), which is sufficient under most workloads. Arduino is typically powered through USB, ensuring motors have a separate power source, this case a Li-Po battery. Also, a Raspberry Pi case will protect the Pi from dust and shocks, with consideration for heat dissipation if the Pi is under heavy load.

By combining the Raspberry Pi's computing capabilities with the Arduino's deterministic control loop, this design achieves effective RF signal processing, rapid response, and precise motor actuation. This two-tiered approach balances performance, flexibility, and real-time reliability.

Potential Challenges and Alternative Concepts

Table 11. Challenge and Solution Table for the Processing Module

Challenge	Solution
Serial Bus latency	If higher data rates are required, SPI or I²C could be used.
Synchronization	Ensuring angle error calculation aligns with real-time RF data may need careful buffering or timestamps.
Lack of USB Ports on Pi	SPI communication may be employed for Arduino communication.

Motor Module

1. Motor Selection and Mechanics

The range of motion of NEMA 23 stepper motor is full 360° rotation. Its step size is 1.8° per full step. It employs a PI (Proportional-Integral) controller which regulates the step commands based on angle error feedback. Below are the several reasons behind this stepper motor choice.

- NEMA 23 typically offers high positional accuracy and holding torque (often in the 1–1.5 N·m or more range), making it top preference larger antenna assemblies.
- No mechanical stops, enabling a full 360° sweep and a continuous motion.

The range of motion of MG995 servo is 0°–90° in this application. It consists of metal gear in internal assembly. A simple P (Proportional) controller will adjust the servo angle via a PWM signal according to the elevation error. Servos require just one PWM signal for positioning. The MG995 can move quickly through its 0°–90° range, meeting typical elevation speed demands.

2. Motor Driver and Power Supply

L298N is an H-bridge driver that can control the direction and speed of DC or stepper motors. For the stepper (NEMA 23 40mm), the L289N can drive the two coils by toggling its outputs according to step pulses. The MG995 servo typically requires its own power line and control signal (PWM), so the L289N is not directly driving the servo's PWM but can supply power if properly regulated. Although this motor driver comes in very handy with its easily affordable price, it also comes with some considerations.

- The L289N is a classic driver but not optimized for modern "micro-stepping" control. For higher precision, stepper-specific drivers (e.g., A4988 or DRV8825) could be considered.
- The L289N can dissipate heat when driving higher currents, so a heat sink and proper airflow are recommended if the motors draw near the driver's limit.

The 3-cell Li-Po battery nominally supplies 11.1 V (3.7 V per cell), up to ~12.6 V when fully charged with its 1750 mAh capacity. The stepper motor and the servo will draw from the Li-Po through the L289N. Careful attention to current drawing is needed, as stepper motors under load and servo motors under stress can spike in current consumption. Over-discharge protection is important to extend Li-Po battery life. A voltage tester module will be attached to the Li-Po to monitor the Li-Po cell voltages during the procedure.

3. Control Logic and Speed Requirements

The speed requirement is at least 15°/s to track rapidly moving targets. Stepper motor control loops will function as listed below.

- The Raspberry Pi calculates the desired azimuth angle error and sends it to the Arduino.
- The Arduino's PI controller adjusts the step rate (and direction) for the motor.
- Feedback will come from an internal encoder from NEMA 23. Position feedback can also be inferred from step counts (open loop stepping), although encoders improve reliability.

The MG995 can typically rotate the 90° range in well under a second, so it meets or exceeds typical elevation speed requirements. The Arduino adjusts the servo PWM duty cycle proportionally to the angle error. Fine-tuning the proportional gain ensures smooth operation without excessive oscillation or overshoot.

Both motors should be sized to handle the weight of the antenna assembly plus any additional components (e.g., cables, protective housing). The NEMA 23 is often rated for moderate torque (e.g., 1.0–1.5 N·m) which is sufficient for rotating a small to medium antenna array if the assembly is balanced. MG995 can handle moderate loads (torque ~ 10–12 kg·cm at 6 V), but for heavier antennas or offset loading, a servo with higher torque capacity or mechanical linkages could be required.

By upgrading to a NEMA 23 stepper motor, the antenna tracking system gains higher torque and improved load-handling capacity on the azimuth axis. The MG995 servo remains a practical choice for quick, 0°–90° elevation control. Driven by an L289N H-bridge and powered by a 3S Li-Po battery, this module is designed for moderate speed (≥15°/s in azimuth), secure holding torque, and a direct P or PI control approach. While this setup is compact and cost-effective, attention to current draw, driver heat dissipation, and mechanical optimization is crucial. Adopting dedicated stepper drivers, higher-torque servos, or additional mechanical aids can further enhance stability, precision, and long-term reliability.

Table 12. System-level requirements table for the Motor Unit

System-level requirements

The motor should meet the speed requirement for achieving track within 3 seconds after power on (or losing track) and for operating at least 15 degrees per second in azimuth. Also, the maximum angle error should be 5 degrees.

Potential Challenges and Alternative Concepts

Table 13. Challenge and Solution Table for the Motor Module

Challenge	Solution
Limited Control Resolution with L289N	i. Upgrade to a micro-stepping driver (e.g., A4988, TMC2208). ii. Use mechanical gearing or a belt reduction to achieve finer control.
Heat Dissipation in the L289N	Add a heat sink or cooling fan.

Power Module

The power module will also supply energy to the RF switches in addition to the stepper motor and Raspberry Pi 5. Given the high current draw of the power module, thicker, heat-resistant cables will be used to ensure safe and efficient power delivery. This will minimize the risk of overheating and voltage drops, preserving the stability of the system during extended operation.

To maintain continuous performance, the Li-Po battery and power bank levels must be regularly monitored and recharged as needed. Ensuring these power sources remain sufficiently charged will prevent interruptions in system operation. Additionally, careful attention must be given to the power cable connections to avoid loose or faulty wiring, which could disrupt the power flow or damage sensitive components.

Overall, effective power management and proper cabling will be essential to maintaining system reliability and preventing power-related failures during operation.

Table 14. System-level requirements table for the Power Unit

System-level requirements
Power Module must be capable of supplying enough current and voltage to the subsystems.

Potential Challenges and Alternative Concepts

Table 15. Challenge and Solution Table for the Power Module

Challenge	Solution
Limited current supplied by Power bank	Upgrade to better power bank with higher current rating.

Test Results

To validate the performance and feasibility of the RF-based Antenna Tracking System (RFATS), a series of subsystem tests were conducted focusing on the two critical modules: the motor module and the antenna module. These tests aimed to evaluate the accuracy, response time, and overall reliability of the system under controlled conditions. The primary goal was to ensure the motor could rotate the antenna accurately in azimuth and elevation while the antenna subsystem could reliably estimate the direction of the incoming RF signal through phase-based steering calculations. Through these tests, the team was able to identify errors, limitations, and challenges within our system. Additionally, new requirements emerged to address these issues, and further solutions were explored to enhance the system's performance and accuracy.

Test Setup and Procedures

The motor module tests are conducted mainly for two different motors. Firstly, two high torque geared N20 DC motors used to rotate the module in elevation and azimuth axis. Secondly the motor module tested using an Arduino Uno controller paired with MG995 and SG90 servo motors to simulate azimuth and elevation adjustments. A MATLAB interface allowed real-time user input to control the motor’s rotation, with the desired angles compared to the actual angles achieved. The test parameters included rotations in 15-degree increments up to 180 degrees in azimuth and 90 degrees in elevation.

For the antenna module several tests have been conducted to experimentally analyze and compare the possible solution methods.

The initial test focused on evaluating the system's ability to differentiate signal amplitudes by comparing the SNR values of the two receiver antennas. The receiver antennas were directional Vivaldi antennas. The objective was to observe a noticeable SNR disparity between the received signals, allowing the system to determine the transmitter's relative position. A signal was transmitted via the omnidirectional transmitter antenna which was connected to Tx port of the ADALM-PLUTO SDR, while the receiver antennas were connected to a PC using two RTL-SDRs and monitored through *SDRsharp* software. By systematically moving the transmitter antenna to various locations, the experiment analyzed how SNR variations in the receiver channels correlated with the transmitter's proximity. This test demonstrated the system's capability to detect amplitude differences and localize the transmitter in a very general fashion. This test assumed that the noise in the environment was common to both receiver channels, therefore examining the SNR would yield a direct intuition regarding the signal strength at receiver channel.

Next test module comprises two directional receiver antennas and one omnidirectional transmitter antenna, just as the previous one. Its purpose is to measure the steering angle—the angle relative to the axis perpendicular to the line connecting the receiver antennas—and estimate the direction by analyzing phase differences between the signals received. With this approach, we analyzed the capabilities of our system with respect to phase-comparison based methods. These phase differences are influenced by the transmitter's distance and direction relative to the receiver antennas. The antennas are interfaced with a computer using an ADALM-PLUTO SDR. While the receiver antennas remain stationary during the process, the transmitter antenna, connected via a long coaxial cable, is manually moved to predetermined angles and distances following a specific pattern. A printed protractor and a tape measure ensure precise positioning of the transmitter. This controlled movement generates a phase difference in the signals received by the two receiver antennas, which is used to calculate the steering angle.

Results

During the initial testing phase of our first solution, we encountered unexpected and challenging results, particularly in controlling the DC motors. While the motors were able to reach the target positions within the required 3-second threshold outlined in the project specifications, the positional errors observed were significantly higher than acceptable margins. These deviations rendered the system unreliable for precise tracking. As a result, we opted to discontinue the use of DC motors and proceeded with our alternative solution.

This strategic shift aimed to ensure that the tracking system met the project’s performance requirements, minimizing errors and enhancing overall reliability.

The results from our second testing phase demonstrated significantly greater accuracy compared to the initial solution. In terms of speed, the performance of the second test module closely matched that of the first, with no noticeable differences in response times. This outcome aligned with our expectations, as servo motors are inherently designed for more precise rotational control, making them better suited for our tracking requirements.

As detailed in Appendix XXXX, the azimuth angle error measurements ranged between 1 and 8 degrees, with positional errors, when evaluated as percentages, varying from 2.22% to 6.7%. For elevation angle measurements, error values fell between 3 and 8 degrees, corresponding to percentage errors of 8% to 20%. These results clearly indicate a substantial improvement in accuracy compared to the first test module. In terms of speed, the shortest rotation during testing was recorded at 0.23 seconds, while the longest movement took 0.95 seconds. Both values fall well within the acceptable limits specified in the project requirements, confirming the system’s capability to meet performance benchmarks effectively. The second round of testing revealed three key strengths that contributed to the success of our refined solution. First, the servo motors demonstrated sufficiently precise rotational capabilities, allowing for accurate adjustments during operation. Second, the motors were able to rotate quickly enough to meet the project’s speed requirements. Lastly, the motors operated efficiently using the 5V pins on the Arduino, eliminating the need for an external power supply – an advantage in terms of simplicity and power management.

However, the tests also highlighted two primary areas of concern. The first issue became evident when comparing the elevation axis motor to the azimuth axis motor. The elevation motor consistently produced greater positional errors. Upon further investigation, we determined that this discrepancy stemmed from the quality of the SG90 servo motors used for elevation control. Reviews of similar projects utilizing SG90 motors confirmed that while these motors are suitable for basic applications, they lack the precision required for projects demanding finer, more accurate rotational control. Consequently, we concluded that the SG90 motors are not ideal for the elevation axis in our design. The second limitation concerns the 180-degree rotational limit inherent to the servo motors used. While this rotational capacity was sufficient for initial testing, the final project will require a motor capable of multiple full rotations to achieve continuous scanning functionality. A motor module with unrestricted or extended rotational capability is essential to enhance the system’s tracking and scanning performance.

The results of previously mentioned and described tests for antenna module were crucial to analyzing the performance of the antenna subsystem. Regarding the first test, the results clearly indicated that an amplitude-comparison based method would not be able to solve the problem because of insufficient performance. The expected difference between SNR values of received signals were not distinct as expected. Without being able to achieve a significant difference between SNR values, no further interpretations could be made. Moreover, the interference and multipath effects influenced the results so that we often obtained higher SNR values for a further located antenna. Therefore, the method based on amplitude comparison was insufficient in terms of detecting the direction of arrival of the transmitted signal and could not meet the project specifications. Due to these conclusions based on the r, amplitude comparison methods were not considered as a possible solution with the current setup and such techniques were abandoned temporarily. Another conclusion was that the properties of the experiment setup, specifically the ones regarding the antennas such as gain, and directivity had a clear influence on these poor results.

During the same test, phase-comparison methods and algorithms were also applied to the received signals. However, significant clock synchronization issues between the two RTL-SDRs were observed, which rendered the phase-comparison method ineffective. Since these

methods are overly sensitive to clock coherence to ensure phase stability, the lack of synchronization emerged as a critical limitation in the current setup.
The results of the subsequent tests demonstrated consistent system performance, yielding rough direction estimation values in accordance with the test procedure. Detailed results for this evaluation are provided in Appendix XXX. For a test range of -45° to 45° in angle and a distance range of 0.5 m to 1.25 m, the outcomes were thoroughly analyzed. Measurements taken closer to the receiver antennas exhibited higher accuracy and a lower error rate, validating the system's precision within this range. However, certain angles, such as 30°, consistently displayed unexpected behavior, prompting further investigation into potential sources of interference and the exploration of methods to mitigate them. Despite these anomalies, the system successfully demonstrated its ability to track the transmitter antenna at a distance of 0.5 m with an error margin well within the specified project requirements. These results confirmed that phase-comparison-based methods are more reliable and reproducible for the current system setup, reinforcing their suitability for achieving accurate and repeatable direction estimation. Moreover, this test enabled us to explore the limitations of our current system, which had a direct negative influence on the performance. By detecting these limitations, some further considerations were done to overcome them.
The phase-comparison method, as utilized in the second test setup, was chosen as the primary solution for the system. The results met the performance requirements, with error rates falling within acceptable limits.

Discussions

To address the limitations identified during the second test, our initial solution involved implementing a 1:10 gear mechanism for the servo motors. This modification allows the system to achieve five full rotations for every 180-degree turn of the servo motor. While this approach extends the rotational capacity, it introduces a significant trade-off in precision. With the gear system in place, the motor shifts from rotating in 1-degree increments to 10-degree increments. This tenfold increase in step size leads to a notable decline in rotational accuracy, compromising the system's ability to track signals with the required level of precision. Given the project's objective of maintaining an angular error of less than 5 degrees, this loss of fine control renders the gear-based solution insufficient for meeting project specifications.
Another alternative solution involves repurposing the MG995 motor, which demonstrated powerful performance during testing, for use on the azimuth axis. Since the elevation axis requires only 0 to 90-degree rotation, the MG995 motor is well-suited for this limited range. For the azimuth axis, where multiple full rotations are necessary, we plan to replace the servo motor with a stepper motor capable of providing continuous and precise rotation. The primary drawback of using stepper motors lies in their high torque requirements. To achieve the necessary torque, the system will need a 12V power supply, introducing complexities in power management. This requirement means the system will rely on an external Li-Po battery to provide sufficient power, adding to the overall design's complexity. Despite this, the trade-off between increased power needs and enhanced precision makes stepper motors a promising solution for the azimuth axis, ensuring the system meets the project's performance and accuracy requirements.
Our first test revealed that the system was incapable of reliably detecting the transmitter using amplitude-comparison-based methods. However, the poor performance was directly influenced by the current antenna properties, specifically their gain and directivity as mentioned. This suggests that with the implementation of antennas featuring narrower beams, higher directivity, or increased gain, and with measures to mitigate multipath effects, amplitude-comparison methods could still be viable.
Moreover, we encountered challenges with coherence and clock synchronization between the RTL-SDRs. However, if we can overcome these issues using the approaches mentioned, such as connecting the SDRs to a shared external reference clock, using RF switches or employing

mathematical synchronization techniques like signal correlation, we could expand the system by incorporating additional antennas and RTL-SDRs. Increasing the number of antennas would enhance our ability to refine the phase-comparison methods, improving precision and providing more accurate direction estimation in future tests and applications.
Finally, there is potential to integrate amplitude comparison into a hybrid approach alongside phase-comparison methods. Such a hybrid system could combine the strengths of both techniques, leveraging amplitude comparison for additional validation or complementing the phase-comparison method to enhance overall accuracy and reliability.

Planning

The planning and the management of the project is a major aspect of the project. The project needs to proceed according to the timing and the schedule. To be able to ensure this, all members need to follow our schedule. In this report the management and planning process is divided into three subtopics.

Schedule

We decided to divide the main project into smaller, more manageable, and smaller pieces. That would help us to manage the tasks more easily. All our group members will have their own small tasks. There are also tasks that several people need to work on at the same time. In order to do these tasks, the people who are interested in that task need to be in the same place at the same time. At the beginning, we were meeting as a team, after a few group meetings, we were able to basically divide the project into smaller parts. In this way, we were able to meet two or three people and do our job without needing to wait for other members to join.
It can be said that our project is divided into two subtasks. The first subgroup is the antenna and signal processing group, while the second main group is the motor and mechanical design group.

Figure 8. Project Timeline Gannt Chart

Mainly our members, Alkım and Özgür, are responsible for the antenna module. Sevda, Emirhan, and Bora are responsible for the motor module. At the first team meetings, we choose the project that we want to work on and roughly draw the roadmap. The project consists of two submodules. But before the two submodules were defined, we roughly decided

on the connections between the modules. The antenna module needs to process the data and give output as the angle degrees. Meanwhile the motor module needs to take the output of the antenna module as the input and turns to the corresponding angle. At the beginning we, as a team, decided on the connection between the submodules. That was the responsibility of all. After that the responsibilities of the members have become specialized. Obtaining the position of the target is the responsibility of the antenna group's, Alkım's and Özgür's. We also need to obtain the corresponding angle values for the position in terms of the coordinates that we defined. The details of this process are explained in the system solution part. After obtaining the angle the motors need to turn the antenna module to the target. Here, we need to create a control algorithm. Also there needs to be a mechanism that carries the motors, antenna, and other components. The mechanical design and definition of the control algorithm is the responsibility of the motor group's, Sevda's, Emirhan's, and Bora's.
There are also some other responsibilities of members. Sevda is the CEO of the company. She is responsible for the main management, scheduling, reporting, documentation, and budget planning. Özgür is also responsible for budget planning. Alkım is also responsible for the documentation. Emirhan and Bora are responsible for 3D printing.

Risk Analysis

Table 16. Risk Analysis Table

Risk name	**Risk type (technical, cost, and timeline)**	**Solution**
Risk1: Antenna design will not finish in time.	Timeline	Buying commercial antennas.
Risk2: Error smaller than 5 degree cannot be satisfied.	Technical	Change of DoA estimation method.
Risk3: Finite switching time due to RF switch.	Technical	Utilization of a clock-matched sampling structures
Risk4: Long Processing Time	Technical	Utilization of efficient algorithms or implementations.
Risk5: Supply chain interruption	Timeline	Handmade solutions (DIY Approach)
Risk6: Communication delay induced late response preventing tracking	Technical	Advanced coding and communication techniques can be employed
Risk7: Heating in motors due to friction etc.	Technical	Utilization of a heat sink
Risk8: Limited current supplied by Power bank	Technical	Upgrade to better power bank with higher current rating.

Cost Analysis

Table 17. Cost Analysis Table

Component	**Single Cost**	**Amount**	**Total Cost**
NEMA-23 Stepper Motor	14.56$	1	21.3$
MG 955 Servo Motor	5.49$	1	5.49$

Raspberry pi 5	102.47$	1	74.9$
Arduino Uno	4.93$	1	4.93$
FR4 Copper Plaque	1.43$	8	11.44$
RF switches	8.94$	2	17.88$
RTL-SDR	20$	2	40$
L298N Motor Driver	2.05$	1	2.05$
3D Filament	14.89$/kg	400 grams	5.95$
Slipper Ring	12.77$	1	12.77$
SMA cables	5.12$/m	5m	25.6$
u.FL to SMA cable	3.2$	1	3.2$
TOTAL ESTIMATED COST			225.51$

The project aims to develop a system for real-time target tracking. The key deliverables include a portable device, user software, and clear documentation to support use and future development. The physical deliverable is a compact tracking device with antennas mounted on top, capable of rotating along both the elevation and azimuth axes to follow targets. Motors, controlled by an Arduino, will manage the movement to ensure smooth and accurate tracking. The Arduino will be responsible for motor control, while a Raspberry Pi 5 will handle all processing tasks and provide seamless coordination between the components. The device will be lightweight and designed for easy transport and deployment. The software deliverable consists of a GUI that displays technical parameters and real-time plots of the motor angles. This software will visualize the antenna's movement and track the real-time path of the target. The interface will be simple and intuitive, displaying all relevant graphs on a single screen without requiring user navigation or input. This ensures users can monitor the system effortlessly. Testing documentation will explain the design process, system setup, and testing procedures. It will include detailed reports on system performance, tracking accuracy, and any issues encountered during development. The goal is to provide a clear overview of the project, ensuring users understand how to operate and maintain the system effectively. The RFATS project aims to deliver a practical, reliable, and easy-to-use antenna tracking system that is supported by necessary tools and comprehensive documentation to facilitate future growth and development.

The project introduces several ethical considerations related to privacy, security, and misuse potential. One primary concern is the risk of unauthorized tracing as the system's capability to track RF signals could potentially be exploited to monitor private communications or track individuals without their consent. Additionally, the system’s flexibility against jamming could raise questions about its application in sensitive environments. Ethical concerns also arise regarding the environmental impact of increased RF emissions and the possibility of interference with existing communication networks. To decrease these risks, the project must prioritize secure design, private access implementations, and ensure compliance with relevant communication and data protection regulations.

Test Plans

In the future, we plan to conduct comprehensive tests for both the antenna and motor modules. For the motor module test, we will initially use the monitor connected to Raspberry Pi 5 to operate a pre-installed GUI. Through this interface, we will input positional data into the system. The motor's azimuth and elevation positions will then be compared against ground truth data to calculate and record positional errors.

Following this phase, the monitor will be disconnected from the Raspberry Pi 5, and the motor module will operate autonomously, responding to input from the antenna module. The motor system's ability to track the target for 3 seconds will be evaluated, and we will verify whether the motor can align with the target within an angular error of less than 5 degrees. For the antenna module, the testing process will begin by connecting a monitor to Raspberry Pi 5. Using MATLAB/C/C++, we will record the positional measurements of the moving target's angle. These measurements will then be compared against the ground truth to calculate and log error values.

Finally, we plan to test the overall system to see if the system fulfills the requirements. By submodule testing we may be able to success, but we need to be sure that the overall system runs the processes correctly.

Conclusion

In conclusion, the development of the project aims to tackle significant challenges in wireless communication. This project is centered on creating an autonomous system capable of tracking mobile RF transmitters by combining SDR technology with rotation in elevation and azimuth axis. The design emphasizes cost-effectiveness and modularity. The system is being developed for a range of applications like military operations.

Initial tests on the motor and antenna subsystems have shown encouraging results. The prototype, which uses servo motors, successfully achieved smooth rotation in both azimuth and elevation, keeping positional errors within acceptable limits. The antenna module, equipped with two Vivaldi antennas and the Pluto SDR, utilized phase comparison monopulse techniques to track targets at various distances. Although there were minor inaccuracies, the system has consistently met key performance goals.

As the project progresses, the next steps will focus on refining each subsystem, conducting long-range tests, and evaluating the system's resilience in diverse environmental conditions. This project aims to contribute to the development of robust, high-precision antenna tracking systems that strengthen modern wireless communication capabilities.

Appendix 1: Weighted Objective Tree

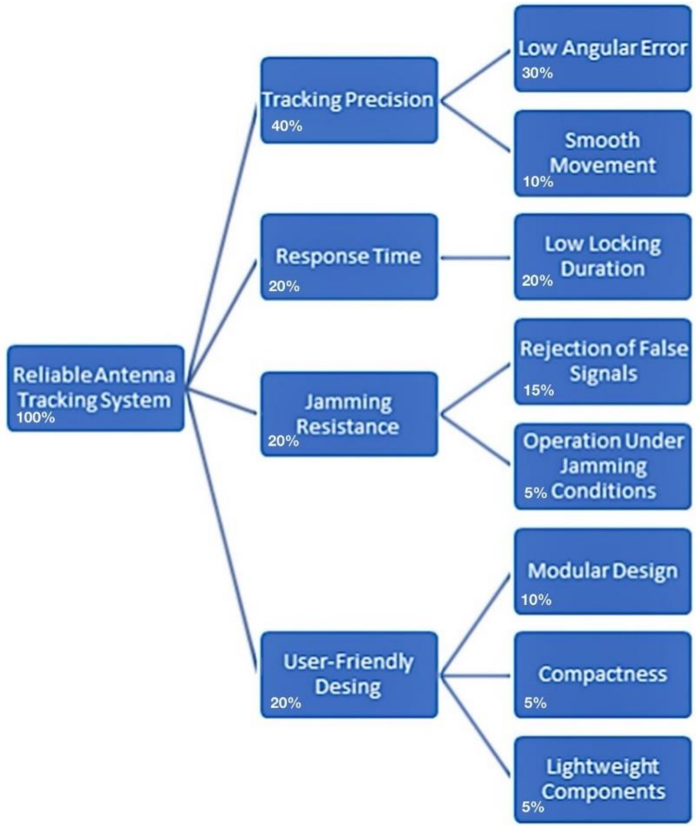

Figure 9. Weighted Objective Tree

Table 18. Weighted Objective Table

Objective	Weight (%)	Sub-Objectives	Sub-Objectives Weight (%)
Tracking Precision	40	Low Angular Error	30
		Smooth Movement	10
Response Time	20	Low Locking Duration	20
Jamming Resistance	20	Rejection of False Signals	15
		Operation Under Jamming Conditions	5
User-Friendly Design	20	Modular Design	10
		Compactness	5
		Lightweight Components	5

Appendix 2: Test-1

Table 19. Angle Error Test Table

Parameter Value	**Actual Performance**	**Expected Performance**	**Error**
Azimuth angle 15°	14°	15°	1° (6.67%)
Azimuth angle 30°	28°	30°	2° (6.67%)
Azimuth angle 45°	44°	45°	1° (2.22%)
Azimuth angle 60°	56°	60°	4° (6.67%)
Azimuth angle 75°	72°	75°	3° (4%)
Azimuth angle 90°	86°	90°	4° (4.44%)
Azimuth angle 105°	101°	105°	4° (3.81%)
Azimuth angle 120°	114°	120°	6° (5%)
Azimuth angle 135°	127°	135°	8° (5.93%)
Azimuth angle 150°	142°	150°	8° (5.33%)
Azimuth angle 165°	158°	165°	7° (4.24%)
Azimuth angle 180°	172°	180°	8° (4.44%)
Elevation angle 15°	12°	15°	3° (20%)
Elevation angle 30°	26°	30°	4° (13.33%)
Elevation angle 45°	40°	45°	5° (11.11%)
Elevation angle 60°	55°	60°	5° (8.33%)
Elevation angle 75°	69°	75°	6° (8%)
Elevation angle 90°	82°	90°	8° (8.89%)

Table 20. Arriving Duration depending on the desired angle in second Test Table

Parameter Value	**Actual Performance**	**Expected Performance**	**Error**
Azimuth angle 45°	0.20 s	0.23 s	-0.03 s (13.04%)
Azimuth angle 90°	0.48 s	0.46 s	0.02 s (4.35%)
Azimuth angle 135°	0.71 s	0.69 s	0.02 s (2.9%)
Azimuth angle 180°	0.95 s	0.92 s	0.03 s (3.26%)
Elevation angle 45°	0.27 s	0.23 s	0.04 s (17.39%)
Elevation angle 90°	0.47 s	0.46 s	0.01 s (2.17%)

Table 21. Direction Finding Test Table

Parameter Value	**Actual Performance**	**Expected Performance**	**Error**
Rough Direction Estimate at -45°	-1	-1	0

@distance = 0.5m			
Rough Direction Estimate at -30° @distance = 0.5m	-1	-1	0
Rough Direction Estimate at -15° @distance = 0.5m	-1	-1	0
Rough Direction Estimate at 0° @distance = 0.5m	0	0	0
Rough Direction Estimate at 15° @distance = 0.5m	1	1	0
Rough Direction Estimate at 30° @distance = 0.5m	1	1	0
Rough Direction Estimate at 45° @distance = 0.5m	1	1	0
Rough Direction Estimate at -45° @distance = 0.75m	-1	-1	0
Rough Direction Estimate at -30° @distance = 0.75m	-1	-1	0
Rough Direction Estimate at -15° @distance = 0.75m	-1	-1	0
Rough Direction Estimate at 0° @distance = 0.75m	0	0	0
Rough Direction Estimate at 15° @distance = 0.75m	1	1	0
Rough Direction Estimate at 30° @distance = 0.75m	1	1	0
Rough Direction Estimate at 45° @distance = 0.75m	1	1	0
Rough Direction Estimate at -45° @distance = 1m	-1	-1	0
Rough Direction Estimate at -30° @distance = 1m	-1	-1	0
Rough Direction Estimate at -15° @distance = 1m	-1	-1	0
Rough Direction Estimate at 0°	-1	0	-1

@distance = 1m			
Rough Direction Estimate at 15° @distance = 1m	0	1	1
Rough Direction Estimate at 30° @distance = 1m	1	1	0
Rough Direction Estimate at 45° @distance = 1m	1	1	0
Rough Direction Estimate at -45° @distance = 1.25m	-1	-1	0
Rough Direction Estimate at -30° @distance = 1.25m	-1	-1	0
Rough Direction Estimate at -15° @distance = 1.25m	0	-1	1
Rough Direction Estimate at 0° @distance = 1.25m	-1	0	1
Rough Direction Estimate at 15° @distance = 1.25m	1	1	0
Rough Direction Estimate at 30° @distance = 1.25m	1	1	0
Rough Direction Estimate at 45° @distance = 1.25m	1	1	0

Table 22. Alignment Test Table

Parameter Value	**Actual Performance**	**Expected Performance**	**Error**
Steering angle @distance = 0.5m	-17.34°	-15°	-2.00°
Steering angle @distance = 0.5m	-15.30°	-10°	-5.30°
Steering angle @distance = 0.5m	-7.80°	-5°	-2.80°
Steering angle @distance = 0.5m	2.13°	0°	2.13°
Steering angle @distance = 0.5m	6.21°	5°	1.21°
Steering angle @distance = 0.5m	11.20°	10°	1.20°
Steering angle @distance = 0.5m	20.30°	15°	5.30°

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