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EEE-493 Industrial Design Projects I: CM1 Report

RF/Radio Signal Delta-Position Calculation Project

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1. Project Summary

This project aims to design a radio-navigation subsystem capable of calculating partial kinematic measurements, specifically delta-position, using RF signals. The system will be implemented in two phases to track the movement of an RF receiver in relation to one or more RF transmitters. In the first phase, the goal is to measure the total distance moved between two points using a single RF transmitter and a single RF receiver. The RF receiver will collect data during movement, which will be stored and processed for signal analysis to determine the delta-position. The second phase involves expanding the setup to include three RF transmitters with pre-defined locations. Here, the objective is to calculate the RF receiver's 2D vectorial movement relative to these transmitters. By recording changes in the receiver’s relative positions over time, this phase aims to provide a more detailed understanding of the receiver's movement and trajectory. Throughout both phases, the data collected by the receiver will be stored for later analysis. The core components of the project are Software Defined Radios (SDR) which will function as both the receiver and the transmitters. MATLAB will be utilized to generate test signals, while GNU Radio will be employed for real-life simulations. The project seeks to demonstrate the feasibility of using RF signals for kinematic measurements, offering an alternative to satellite-based navigation systems. The expected outcome is a reliable, low-cost RF-based navigation solution capable of providing kinematic data specifically in environments where traditional GNSS systems may not be viable.

The project assigned by ASELSAN founded in 1975 to meet the Turkish Armed Forces' communication needs, it is Turkey's largest defense electronics company, with over 10,000 highly skilled engineers. Its extensive product portfolio includes radar and electronic warfare, avionics, and communication technologies. ASELSAN develops unmanned systems, land, weapon, and naval systems, air defense and missile systems, command and control systems, and solutions in transportation, security, traffic, and medical systems.

2. Motivation and Novelty

GNSS-based navigation systems are widely used and effective in many scenarios. However, they come with critical limitations that can impact their reliability and success. GNSS signals are highly vulnerable to atmospheric distortion. This can reduce signal accuracy, as well as multipath propagation, which occurs when signals are reflected off buildings or other large structures. This often results in significant errors, especially in urban environments or areas with dense structures. In addition, GNSS requires a clear line of sight to multiple satellites. In regions with a limited sky view, like deep canyons or forests, accurate positioning can be difficult to achieve [1].

Security concerns are also linked to GNSS-based structures. GNSS is suspectable to intentional interferences, such as jamming and spoofing, which are critical issues in both civilian and military contexts. Jamming devices emit frequencies that disrupt GNSS signals, can cause navigation systems to lose accuracy or even fail entirely. Spoofing can manipulate location data, posing risks to various industries that rely on accurate geolocation [2].

These weaknesses underscore the need for alternative navigation technologies that can operate independently of GNSS. As a solution, ASELSAN requires a radio-navigation system using RF signals to create a more accessible and cost-effective solution. Such a system would not only enhance security by reducing reliance on vulnerable satellite networks but also improve accessibility for applications where satellite-based systems are impractical or too costly to deploy and maintain. Alternative systems like these could even have a broader application across industries providing reliable location data without the need for extensive GNSS infrastructure.

ASELSAN aims to use this system as a dependable alternative to satellite-based navigation, with primary applications in defense and security. By implementing this solution, ASELSAN can ensure continuous navigation in military and critical environments without depending on GNSS, which is suspectable to vulnerabilities.

The completed product is designed to function either as a standalone solution or as an adaptable component within ASELSAN's existing product lineup, enhancing the flexibility and reliance of its offerings across different sectors. This adaptability allows ASELSAN to broaden its applications and strengthen product versatility within both defense-focused and potentially commercial navigation solutions.

This project offers a novel approach to cost-effective and resilient navigation solution by utilizing RF signals to determine delta-position independently of GNSS infrastructure. Traditional navigation systems, like GNSS-SDR, while cost-effective and accessible due it its open-source structure, rely on GNSS signals, making them vulnerable to interference, jamming, and environmental factors such as atmospheric conditions. GNSS-SDR is particularly affordable since it primarily requires an SDR device and a computer for operation, enabling broad accessibility on GNSS signals for positioning makes it suspectable to signal disruption [3]. In comparison, ASELSAN's project maintains the cost-effectiveness of SDR technology but aims to eliminate satellite reliance, providing a standalone solution that addresses these security vulnerabilities directly.

SDR-Fi, another similar technology also uses SDR to achieve Wi-Fi like positioning, offering accurate location data with relatively low cost. However, SDR-Fi's precision can vary depending on the complexity of the environment, and it typically requires additional infrastructure to maintain consistent accuracy [4]. ASELSAN's project offers an innovative alternative, allowing it to function without supplemental infrastructure, thereby widening its application potential to environments where GNSS or Wi-Fi-based systems may fail.

The novelty of ASELSAN's system lies in its distinct approach to delta-position determination through RF signals, which differs from GNSS's full kinematic data acquisition. Instead of providing absolute positioning, it calculates relative movement and velocity, streamlining operations and reducing costs while maintaining high accuracy. This delta-position methodology not only simplifies the system design but also enhances its adaptability for diverse applications across defense, industrial, and commercial sectors. Existing solutions, while functional, do not address these unresolved challenges, particularly in situations where traditional positioning systems may fall short due to interference or high-security requirements.

At this stage, securing a patent for our project may be challenging due to existing navigation solutions that use RF-based technologies. For instance, Spirent's SimAltNav system combines RF signals with GNSS to enhance navigation reliability in kinematic applications [5]. Similarly, the APNT pseudolite approach utilizes pseudolite transmitters to provide GNSS-like signals for passive ranging [6]. However, as we progress, the patent potential of our project increases, particularly if we develop novel solutions for critical challenges, such as synchronizing multiple SDRs and resolving associated timing issues. An innovative approach to signal synchronization across multiple RF sources could yield a unique method that if implemented effectively, can be patentable, adding both originality and critical value to the field of navigation solutions.

3. System Requirements Specifications

This final product will deliver both software and hardware components. The software deliverables consist of the algorithms for delta-position computation including both Phase 1 and 2D vectorial movement for Phase 2, error correction algorithms so as to reduce noise and oscillator drift, CDMA signal acquisition algorithms, tracking algorithms involving delay-locked loop (DLL) and phase-locked loop (PLL), and algorithms for smoothing and filtering for raw I/Q signals.

For the hardware deliverables, there will be pre-programmed transmitters including ADALM-Pluto SDR for Phase 1 and Phase 2, as well as a receiver with ADALM-Pluto SDR, synchronized and configured simultaneously with a computer. These hardware components are illustrated with diagrams, and a block diagram of ADALM-Pluto is included to present a comprehensive hardware system. The final product will be capable of computing autonomously the delta position with respect to the initial position for 1D in phase 1 and 2D in phase 2 which is initiated by user control. The project outlines both functional and non-functional system requirements specifications.

3.1 Functional System Requirements

The project's functional requirements #SRS-01 comprises three sub-requirements. The functional requirements include the requirements for signal transmission and reception, the signal processing algorithm, and distance measurement.

Table 1: The Functional System Requirements

#	Requirement
SRS-01-10	Transmission and Reception of Signals
SRS-01-20	Signal Processing Algorithm
SRS-01-30	Distance Measurement

3.1.1 Transmission and Reception of Signal Requirements

The project requires transmission and reception components that can operate at a frequency of 1575.42 MHz and a minimum bandwidth of 2 MHz which is required by ASELSAN. A similar approach from literature is found as the GNSS-SDR project which operates at 1575.42 MHz and is designed to analyze GPS L1 signals [7].
The project also requires the use of Code Division Multiple Access signals with a 1 ms code period and three unique, pre-assigned PRN codes to ensure precise signal separation. A similar method is represented in the GPS L1 C/A code structure, which has a 1 ms coding period and assigns distinct PRN codes to each satellite [8].

Additionally, the system requires a chipping rate of 1.023 Mbps for PRN code transmission, which can be also observed from the GPS-SDR-SIM project's requirement having the chipping rate of 1.023 Mcps [9].

Table 2: The Transmission and Reception of Signal Requirements

#	Requirements	Project's Requirements	Example Implementations
SRS-01-11	Frequency and Bandwidth	RF Tx/Rx components capable of operating at a frequency of 1575.42 MHz, with a minimum BW of 2 MHz	SDR implementation that operates at 1575.42 MHz for GNSS-SDR project which is designed to process GPS L1 signals [7]
SRS-01-12	CDMA	CDMA signals at a 1 ms code period using three distinct, pre-assigned PRN codes	GPS L1 C/A Code at 1575.42 MHz with a 1 ms code period and distinct PRN codes assigned to each satellite [8]
SRS-01-13	PRN codes	chipping rate of 1.023 Mbps	GPS-SDR-SIM project uses a chipping rate of 1.023 Mcps [9]

3.1.2 Signal Processing Algorithm Requirements

The Project's Signal Processing Algorithm requirements are specified according to the modulation, phase and delay locked loops, and filtering. The project requires Binary Phase Shift Keying (BPSK) modulation at 1575.42 MHz with a chipping rate of 1.023 Mbps which is provided with respect to the frequency requirements of the signal. BPSK modulation 1575.42 MHz is also utilized in the NavSdr Project to provide reliable signal delivery [9].

In addition to modulation specifications, the system's PLL/DLL components must have configurable bandwidths to enable for precise tracking, successful locking (within 2 seconds), and effective multipath mitigation. This adaptive bandwidth strategy is comparable to one used by the Stanford GPS Lab to achieve rapid lock and reduce urban multipath error [10]

Moreover, a digital low-pass filter with a cutoff frequency greater than 2 MHz is necessary to suppress high-frequency noise. The criteria of 2MHz is specified due to the nyquist criterion. This approach is consistent with digital filtering techniques used in real-time kinematic (RTK) GPS/GNSS location to improve signal clarity and accuracy [11].

Table 3: The Signal Processing Algorithm Requirements

#	Requirements	Project's Requirements	Example Implementations
SRS-01-21	Modulation	BPSK modulation at 1575.42 MHz, chipping rate 1.023 Mbps	BPSK modulation at 1575.42 MHz in NavSdr Project [9]

SRS-01-22	PLL/DLL	rapid locking within 2 seconds, and multipath mitigation	Adaptive bandwidth control by the Stanford GPS Lab [10]
SRS-01-23	Filtering	digital low-pass filter at >2 MHz for reducing HF noise	real-time kinematic GPS/ positioning using filtering methods [11]

3.1.3 Distance Measurement Requirements

The requirement for the distance measurement which is set by ASELSAN,specifies measuring the distance between two points (A and B) with an accuracy of ±5 cm (1-sigma error). The distance measurement requirement specification is a critical criterion for assessing project success.

This requirement ensures the system's effectiveness in precision measurements, a key performance indicator. For comparison, the SDR-Fi project achieves a mean distance accuracy of 0.99 meters and a 50th percentile accuracy of 0.77 meters [12], while another SDR-based project has demonstrated high precision with an accuracy consistently within 1.2 cm, a mean error of 6 mm, and a standard deviation of 2.2 mm [13]. This example implementation signifies the importance of sustaining ASELSAN's accuracy standards to validate the project's success in practical applications.

Table 4: The Distance Measurement Requirements

#	Requirements	Project's Requirements	Example Implementations
SRS-01-31	1D-Distance Calculation	distance between two points (A and B) with an accuracy of ±5 cm (1-sigma error)	SDR-Fi with mean of 0.99m and 50^{th} 0.77m [12]
SRS-01-32	1D-Distance Calculation	distance between points with an accuracy of ±5 cm (1-sigma error)	accuracy of 1.2 cm, with a mean error of 6 mm SD of 2.2 mm [13]

3.2 Non-Functional System Requirements

The non-functional constraints of the final product #SRS-02 includes the requirements for the cost, environmental interference, temperature range to ensure reliable operation, power consumption, safety issues, and health constraints. The project does not include non-functional requirements for size, weight, or social factors, since ASELSAN has not provided requirements regarding the specific use case of the final product.

Table 5: The Non-Functional System Requirements

#	Requirement
SRS-02-10	Cost
SRS-02-20	Environmental Interference

SRS-02-30	Temperature Range
SRS-02-40	Power Consumption
SRS-02-50	Safety Issues
SRS-02-60	Health Constraints

3.2.1 Cost

The maximum allowable cost of the project is 50,000 Turkish Liras, as specified by ASELSAN. Up to the committee meeting, approximately 30,000 Turkish Liras of the budget has been utilized to acquire three ADALM-Pluto SDRs to initiate the distance calculation procedures. The estimated total cost of the final product is projected to be around 40,000 Turkish Liras.

3.2.2 Environmental Interference

Environmental interference caused substantial challenges during transmission and reception testing, especially in urban and indoor environments with considerably high RF noise. This interference has an impact on signal quality and accuracy, emphasizing the need for strong noise tolerance measures to maintain reliable operation. Therefore, a specification about high precision is required to enable RF noise tolerance tests and avoid poor performance in demanding urban and indoor contexts.

3.2.3 Temperature Range

With respect to the ADALM-PLUTO SDR requirements, the system is intended to operate reliably throughout a temperature range of 0°C to 70°C (32°F to 158°F), allowing it to function efficiently in both indoor and outdoor conditions [14]. Although ADALM-PLUTO's humidity tolerance is not specified, it is recommended to avoid high humidity and direct moisture exposure for maximum performance.

3.2.4 Power Consumption

The system's power consumption ranges from 1.2W to 2.5W during operation, translating to approximately 240mA to 500mA at 5V. In Phase 1, this applies to two units (x2), while in Phase 2, three units (x3) will be used, increasing overall power requirements [9]. Additionally, the real-time processing of the computer can consume power in the range from 100W to 400W [14]. Consequently, the maximum power consumption of the final product will be approximately 420W.

3.2.5 Safety Issues

The design of the product considers safety over both electrical and radiofrequency exposure factors. All electronic components must follow specific safety standards to avoid hazards such as electric shocks, overheating, and potential malfunctions when subjected to variable power conditions. Besides, RF transmission power will be rigorously managed to ensure that it remains below acceptable limits, in accordance with regulatory regulations governing human exposure to RF fields. This can be crucial for longer exposure to the system, since persistent adherence to RF safety requirements shields users from the potential health concerns associated with long-term RF exposure.

3.2.6 Health Constraints

The design of the project does not directly violate any health constraints, but the RF exposure levels must be considered and kept within safe limits, according to guidelines issued by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) or comparable organizations. This procedure alleviates the possible health concerns about the longer exposure to the final product.

3.3 Standards of the Project

Due to the fact that the hardware deliverables of the project is mainly combination system of Adalm-Pluto Software Defined Radios, the standards of the project coincides with the ADALM-PLUTO Regulatory Compliance stated in [15]. The device is complied with the requirements of a Class B digital device following the FCC Rules in Part 15, which approves the usage and installation of the device within an environment. Apart from its FCC statement, the device acquires Industry Canada licence exempt in RSS standards, which states that device meets the requirement for CAN ICES-3(B)/NMB-3(B).

Additionally, the overall system satisfies the safety requirement for the testing, measurement, control, and laboratory usage of the electrical equipments provided in IEC 61010-1, UL/CSA 60950-1 [16]. Since the operational frequency of the project which is 1575.42 MHz included in the range of 0 Hz to 300GHz, the device and the overall hardware system complies with IEEE C95.1, which highlights the standard for the safety levels of human exposure the magnetic, electric, and electromagnetic field within the range [17]. Besides, the device also sustains a declaration of conformity with respect to EN ISO/IEC 17050-1:2010 [18]. Apart from the safety regulations, the technical standards for the wireless communication IEEE 802.11 is also highlighted within the final product so as to acquire an architecture within the standards of the 802.11 [19]. Consequently, due to the limited range of products utilized in the project, mostly the standards of the device itself are followed in addition to technical standards listed.

4. Methodology and Project Implementation

4.1 Work Breakdown Structure (WBS) and Project Plan

The project’s WBS consists of 7 work packages (see Figure 1).

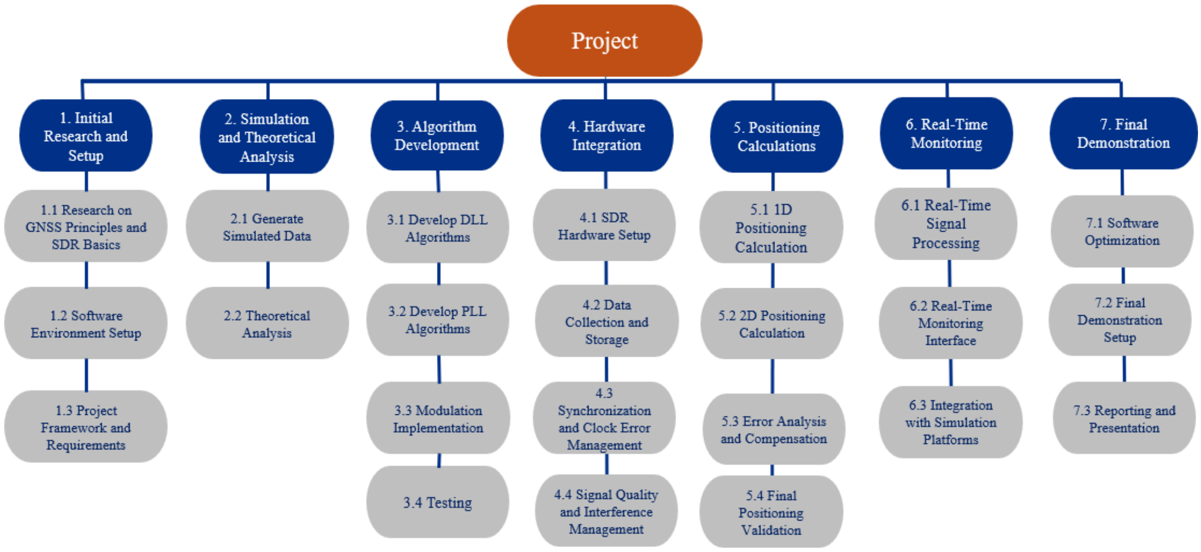

Figure 1: The Work Breakdown Structure for the Project

4.1.1 Project's Work Packages

WBS #1 Initial Research and Setup includes three parts: WBS #1.1 focuses on learning GNSS and SDR basics, covering signal configurations and concepts like PLL and DLL through open-source GNSS-SDR projects and academic literature. WBS #1.2 involves setting up the software environment for SDR development, including MATLAB, Simulink, and GNU radio, with initial testing to verify functionality. WBS #1.3 defines project specifications, identifies potential risks, and establishes a version control and documentation structure for effective project management.

WBS #2: Simulation and Theoretical Analysis has two parts. WBS #2.1 involves generating simulated data in MATLAB, focusing on IF sample signals to test system performance under various RF noise and multipath interference scenarios, and analyzing the impact of clock errors. This step is critical for system refinement before real-world application. In WBS #2.2, theoretical analysis for PLL and DLL will be conducted, deriving equations to assess performance, modelling noise effects, and developing mitigation techniques to enhance signal accuracy. All findings will be documented for future reference.

WBS #3: Algorithm Development has four sections. WBS #3.1 focuses on implementing an early-late discriminator in the DLL for precise code tracking, testing its robustness under different noise levels, and optimizing settings for accuracy and stability. WBS #3.2 develops PLL algorithms with carrier phase tracking to ensure reliable phase alignment, fine-tuning for quick signal lock and stability in various SNR conditions. WBS #3.3 implements BPSK modulation for PRN code transfer, using MATLAB/Simulink to evaluate and adjust modulation parameters for signal quality. Finally, WBS #3.4 validates and tests DLL and PLL performance in MATLAB, comparing results with theoretical predictions, with findings documented in a mid-term report.

WBS #4: Hardware Integration consists of four parts. In WBS #4.1, the Adalm-Pluto SDR will be purchased, set up, and calibrated to ensure optimal performance and compatibility. WBS #4.2 focuses on data collection and storage, implementing time-stamped logging protocols and addressing large data management. WBS #4.3 manages synchronization and clock error by analysing SDR clock drift, exploring external clock synchronization, and developing correction algorithms to ensure reliable operation. WBS #4.4 enhances signal quality and interference management through RF noise reduction, shielding, and validation tests to confirm hardware reliability and signal integrity for system integration.

WBS #5: Positioning Calculation includes four parts. WBS #5.1 focuses on 1D positioning calculation, developing and testing algorithms for linear delta-position changes. A controlled linear motion experiment will validate these algorithms, and adjustments will be made to minimize errors. Findings and improvement suggestions will be documented. In WBS #5.2, 2D positioning calculations will be implemented using multilateration algorithms. Experiments with three transmitters will test accuracy, considering multipath interference and noise, with optimizations for real-time processing and accuracy. WBS #5.3 is dedicated to error analysis and compensation. Error sources, such as RF noise, will be identified, and compensation strategies like signal smoothing will be applied and assessed for effectiveness against raw data. Finally, WBS #5.4 covers final positioning validation. The system will be rigorously tested in various scenarios, evaluating its performance against accuracy standards. Results, successes, and any identified issues will be recorded.

WBS #6: Real-Time Monitoring and Integration includes three parts. In WBS #6.1, positioning algorithms will be adapted from MATLAB/Simulink to a real-time environment like GNU Radio, ensuring continuous data streaming from SDR and optimizing code for low-latency processing to meet real-time requirements. System performance will be tested to ensure timely data handling. WBS #6.2 focuses on creating a real-time monitoring interface that displays positioning data alongside diagnostics, with visual indicators for signal quality and noise levels. Real-time alerts will improve reliability, and usability testing will ensure the interface is user-friendly. Finally, WBS #6.3 integrates the real-time monitoring system with simulation platforms like Simulink and Python to analyze system performance under conditions such as interference and signal loss. Insights from simulations will refine real-time algorithms for enhanced accuracy and stability, with outcomes documented for reference.

WBS #7: Final Implementation and Demonstration comprises 3 parts as Software Optimization, Final Demonstration Setup, Reporting and Presentation. This WBS task is not linked to any milestone since it includes direct requirements for the project such as presentation and final setup as well as the optimization of the software codes for efficiency which can be considered as further steps. In WBS #7.1, the software optimization will be done by converting codes into near real time operating systems and enhancing its performance and efficiency. In WBS #7.2, the final demonstration setup and a demo will be made for both Phase 1 and 2. In WBS #7.3, the presentation and report will be finalized in order to present the outcome for the committee.

4.1.2 Milestones

The project comprises four milestones which are intended to assess the successful implementation of algorithm development phase, 1D and 2D positioning calculations, and real-time processing of the system.

In the first milestone of the project, the successful implementation of the phase-locked loop (PLL), delay-locked loop (DLL), and the modulation algorithm being utilized for two and more SDRs is intended. The criteria for the success of the milestone are assessed through the completion status of WBS packages #3.1, #3.2, and # 3.3. The tentative due date for the first milestone is assigned as 08/12/24.

The second milestone of the project is considered as completed after accomplishing the 1D positioning calculation regarded as the Phase 1 of the project by utilizing two SDRs simultaneously. The second milestone of the project is also regarded as the sufficient achievement to consider the project as successful with respect to ASELSAN’s requirements. The criteria of success of the second milestone are evaluated according to the accuracy of positioning the receiver sdr within the range of -/+5 cm which is considered as 1-sigma error. Moreover, the criteria for the success of the milestone are assessed through the completion status of WBS packages #5.1.1, #5.1.2, and # 5.1.3. The tentative due date for the second milestone is assigned as 12/01/25.

The third milestone of the project is regarded as completed after accomplishing the 2D positioning calculation regarded as the Phase 2 of the project by utilizing four SDRs concurrently. The third milestone’s criteria of success are assessed with respect to the accuracy of positioning the receiver sdr within the range of -/+5 cm, which is similar to the second milestone of the project. On the other hand, the implementation of the Phase 2 requires more complex coding and system to efficiently perform a positioning calculation. Furthermore, the success of the third milestone is also assessed through the completion status of WBS packages #5.2.1, #5.2.2, #5.2.3 and # 5.2.4. The tentative due date for the second milestone is assigned as 09/02/25.

The fourth milestone of the project has been achieved with the successful implementation of real-time processing for the entire system in both Phase 1 and Phase 2. The success criteria for this milestone are based on the ability to process the simulation in real-time and monitor the results with minimal delay, without any post-processing of the received signal. This milestone is critical due to the system's integration with various subsystems in a real-life scenario. However, achieving this goal is challenging due to the operational characteristics of the ADALM-PLUTO SDR, which transmits and receives data in bulk. Despite this limitation, the aim is to minimize processing delay as much as possible to support real-time operation of the system.

The project's Gantt Chart is shown in Figures 2, 3, and 4. Certain work packages are assigned to specific team members, while others require collaboration from all team members. The duration of each work package is scheduled from the beginning of Week i to the end of Week j (where i, j ∈ [1, 33]), allowing us to track the project across multiple sprints, thus enhancing efficiency. Each work package is associated with a WBS # (see Figures 2, 3, and 4). Additionally, the milestones and tentative deadlines for each are clearly highlighted.

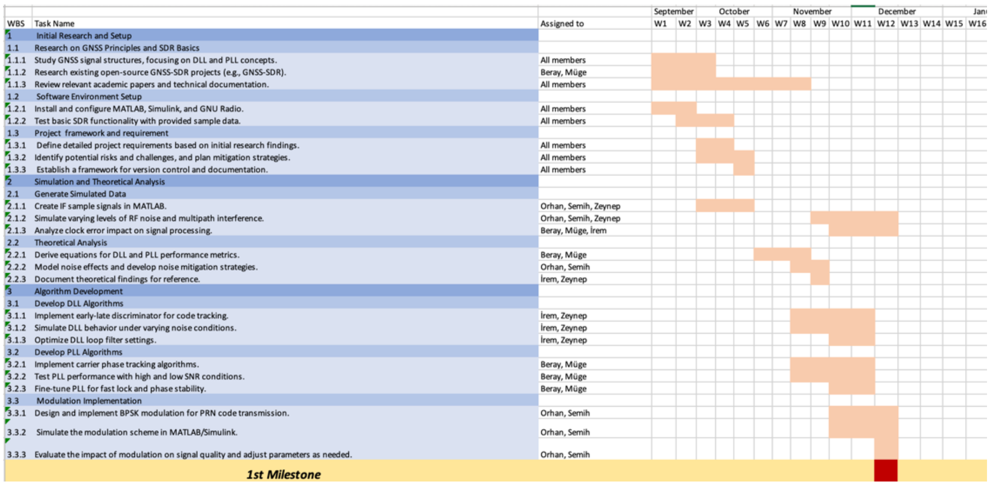

Figure 2: The Gantt Chart of the Project including the 1st Milestone

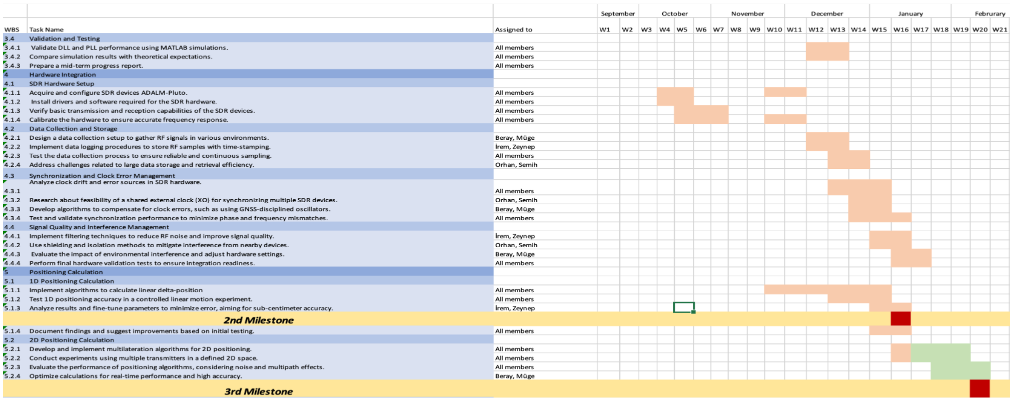

Figure 3: The Gantt Chart of the Project including the 2nd and 3rd Milestone

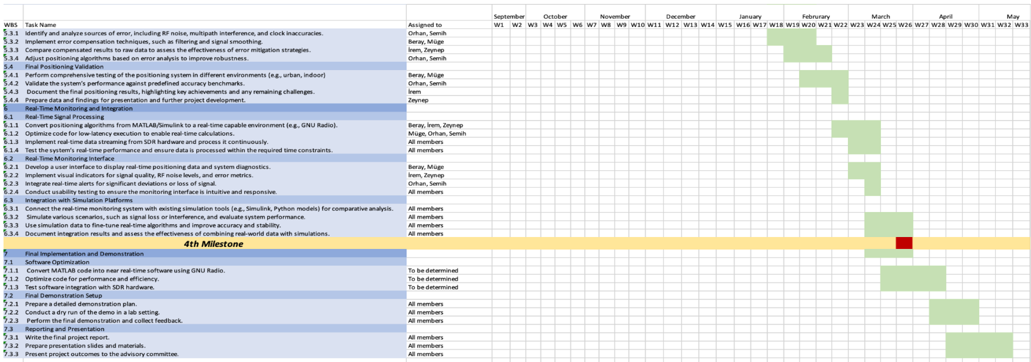

Figure 4: The Gantt Chart of the Project including the 4th Milestone

4.2 Methods and Progress

There are three major tasks in our project. These can be listed as “Signal modelling and simulation”, “algorithmic design and optimization”, and “positioning calculation”. The methods and progress will be examined in three different subsections.

4.2.1 Signal Modelling and Simulation

Signal modelling and simulation task includes the functionality check of the Adalm-Pluto SDR and our ability to successfully transmit and receive the signals. For this task we will use three different methods.

4.2.1.2 RF Channel Modelling

RF channel modelling is used to predict how the signals behave as they travel from a transmitter to a receiver. During this process, the signals may face obstacles or go through some alterations. RF channel modelling is used to come up with an artificial environment in which the signals act similar to the real-world scenario. Usage of this artificial environment increases the accuracy for real-life tests as it suggests a way regarding what could go wrong with the design before testing it on the hardware setup. This process involves creation of models which would simulate the effects of path loss, shadowing, multipath fading and doppler shift.

In our project we have a moving transmitter. With this movement, we will see the effects of doppler shift. Models tried in MATLAB and GNU Radio. In MATLAB, while creating the rectangular pulse to be transmitted, complex exponentials were added to the signal to simulate the effects of doppler shift. The testing for accuracy of this RF channel modelling can only be made when at least two SDRs are present.

4.2.1.2 High-Fidelity Signal Simulation

For simulations we used three different programs. These programs can be listed as MATLAB-Simulink, GNU Radio and MATLAB.

We started with MATLAB-Simulink. For the simulation we used the block diagram in figure 5. For this block diagram we combined the receiver and transmitter of the Adalm-Pluto SDR to transmit and receive data simultaneously. As the block diagram shows we used QAM Modulation (Quadrature Amplitude Modulation) to transmit our signals. QAM Modulation consists of two dimensions which are orthogonal to each other. These dimensions can be named as in-phase and quadrature components. With the usage of QAM Modulation one can double the transmission rate, as the signal will be carried in two different waves in this case. Sine and cosine waves are used commonly for this modulation due to their orthogonality [20].

With this modulation the signals are transmitted with both real and imaginary components. Adalm-Pluto SDR requires the transmitted signal to include an imaginary part. Hence this modulation covers for that requirement as well. For the receiver part, the in-phase and quadrature parts are separated using the orthogonality and trigonometric relations.

Another modulation that is required to be used in the project is the BPSK (Binary Phase Shift Keying) Modulation. For this modulation type a finite number of phases are each assigned to a unique pattern of binary digits. Each phase of the incoming data usually consists of equal number of bits. At the demodulator, these the phase is determined and then assigned to the symbol it represents [21]. For BPSK, only one sinusoid is taken as the basis function and modulation is achieved by varying the phase of the sinusoid depending on the message bits. The carrier signal's phase is shifted by 180 degrees for each symbol. When there is no phase shift a binary 1 is sent and when a phase shift of 180 degrees occurs a binary 0 is sent. Constellation diagram of BPSK includes two points separated by 180 degrees lying on the x-axis (in-phase). There is no projection on the y-axis (quadrature). Hence, all of the information sent lies in the in-phase part of the signal. This is because there is one basis function. Moreover, since the carrier phases are 180 degrees apart, the signal has a constant envelope [22].

For signal simulations in MATLAB-Simulink environment, the modulations were performed using block diagrams which are already present in Simulink. Since the values that needs to be adjusted for a better performance of the blocks are mostly fixed, the data obtained was very noisy. These results can be seen in Figures 5, 6, and 7. As the outcome of this system was not suitable for further analysis for both cases (the receiver and transmitter connected with a cable or using antennas), we decided to check whether we could transmit and receive signals properly without many distortions by checking the receiver and transmitter properties in GNU Radio.

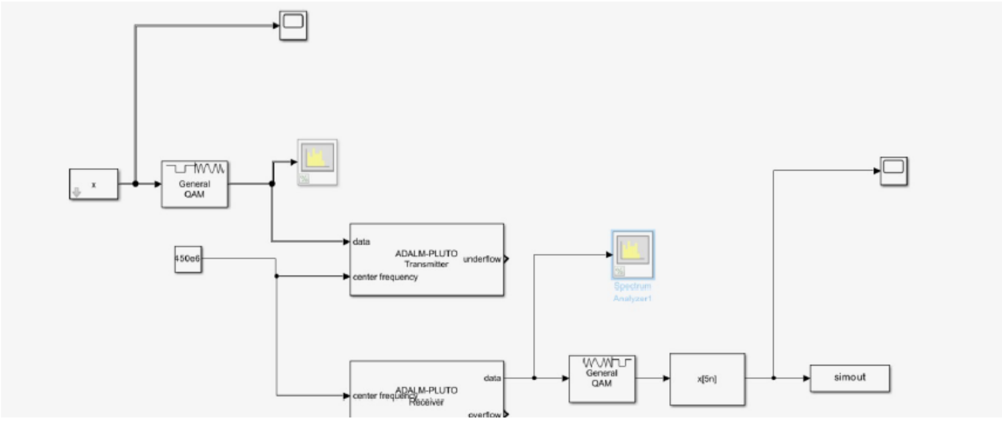

Figure 5: Block Diagram to Check the Transmitted and Received Signal Simultaneously

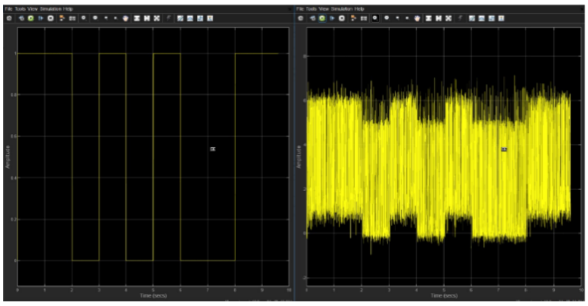

Figure 7: Output while Transmitter and Receiver connected with a Cable

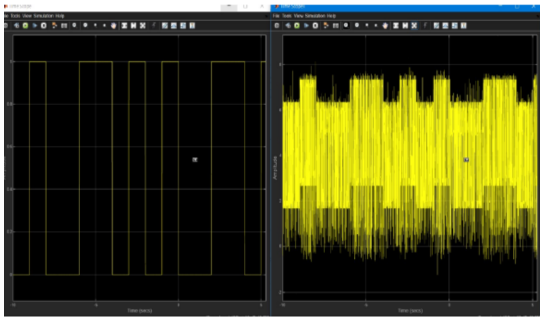

Figure 6: Output while using the Antennas

Up to now GNU Radio was used as a tool to get familiar with the modulation and real time signal transmission and reception processes of the SDR. For these purposes, we checked for Binary Phase Shift Keying (BPSK) modulation and real time signal transmission and reception in GNU Radio (see Figure 10 and 11). While doing this, the in-phase and quadrature components of the signals were checked as well. It showed that for the given circumstances (when each phase represents a symbol), by only using the information coming from the phase component, we can reconstruct the signal we were provided.

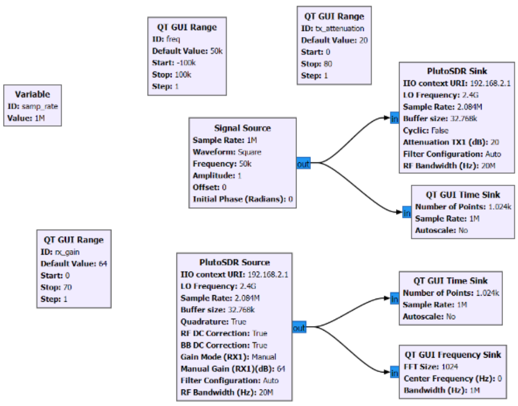

Figure 8: Block Diagram for Signal Transmission

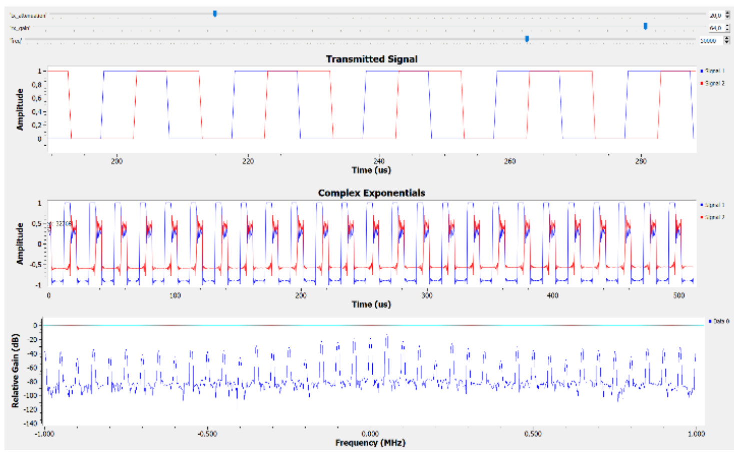

Figure 9: Output for 50kHz Square Wave

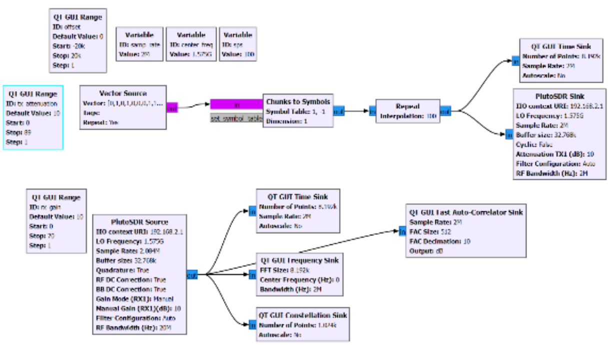

Figure 11: Block Diagram BPSK

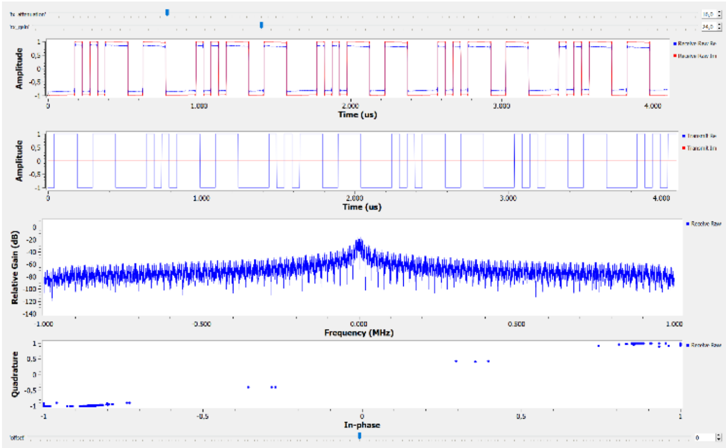

Figure 10: Output for the BPSK

After making sure that the transmission and receiving functions were working properly, the signal processing moved back to MATLAB. After these steps GNU Radio will be used as a tool to try different PLL and DLL algorithms.

In MATLAB, a square wave was created with the specifications mentioned above (with a frequency of 1575.42Mhz, code period 1msec, chip period 1/1023msec). This wave was transmitted through SDR and for each frame we defined we stored the transmitted and received data and then we checked for the delay and phase shift that occurs in the received signal compared to the transmitter signal.

Another important thing we checked was the I and Q components of the signal. These components can be seen in Figure 12.

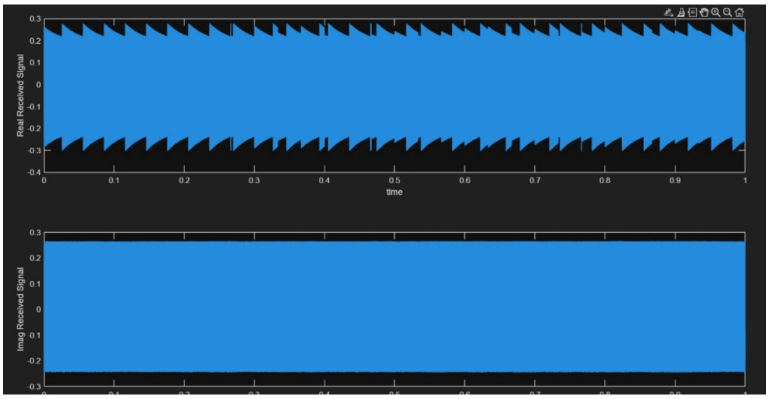

Figure 12: The I and Q Component of the Received Signal from Tx/Rx Adalm-Pluto SDR

Later we checked for the circular autocorrelation of the received signal. Autocorrelation of a signal is used to determine the similarities between two consecutive observations [23]. In our case, since we have a periodic signal which is distorted by noise, or delays, when we use autocorrelation, we can determine when the pattern occurs clearly. To demonstrate, the output images in figures 13, 14 are shown.

Using this method, one can determine the delay between each reception process and hence it is expected to give the time difference between two samples. This time difference is a key factor in delta position calculation as the distance will be measured using the difference between arrival times.

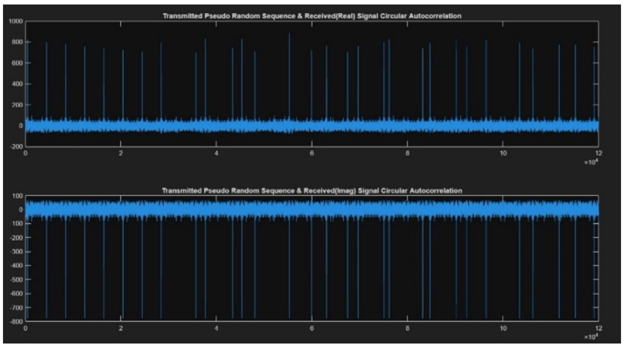

Figure 13: The Circular Autocorrelation of transmitted pseudo random sequence and I/Q Components of the Received Signal

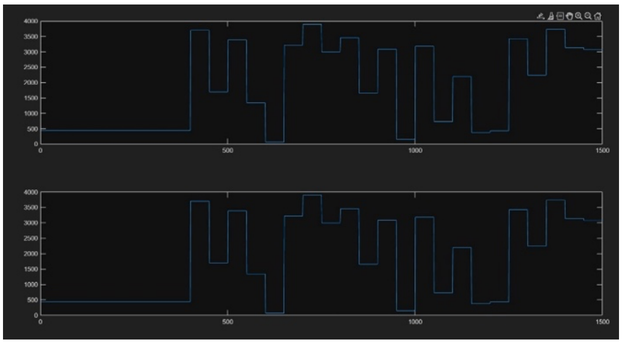

Figure 14: The Framed Circular Autocorrelation of transmitted pseudo random sequence and I/Q Components of the Received Signal

4.2.1.3 Clock Error Detection

Clock error detection covers for a crucial point for our project. The clocks of different SDRs must be synchronized in order to make an assumption related to the time difference between samples received. The delays for SDRs are especially important when a loop-back operations are performed from transmitter to receiver. These delays are functions of internal buffers and FIFOs of the host PC and Pluto SDR itself [24]. By using our simulations tools such as GNU Radio and MATLAB, when more SDRs are received we will detect the clock errors and if the clocks of different Pluto SDRS cannot be synchronized, we will add an external atomic clock to the design hence the clock error problem will be resolved.

4.2.2 Algorithmic Design and Optimization

4.2.2.1 Modulation Techniques

For our RF Delta-Position project, we will transmit 2 MHz baseband limited square signals with a chipping rate of 1023 Mbps at the center frequency of 1575.42 MHz. There are several modulation techniques available for transmitting digital data with analog carriers such as Amplitude Shift Keying (ASK), Frequency Shift Keying (FSK), Phase Shift Keying(PSK) and Quadrature Amplitude Modulation(QAM).

4.2.2.2 Binary Phase Shift Keying

The ADALM-PLUTO SDR accepts baseband IQ-modulated signal for transmission. In analog domain, I and Q components of the signal are multiplied with $cos(\omega t)$ and $sin(\omega t)$ respectively and $\omega = 2 * \pi * f_c$ where f_c is the carrier frequency or center frequency. Circuit representation for modulation and demodulation schemes is indicated in Figure 15.

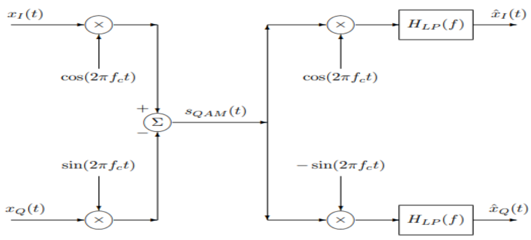

Figure 15: BPSK Circuit Representation for Modulation and Demodulation Schemes [25]

The array we want to transmit is a square wave consisting of ± 1 elements and the Q component is not required for calculating the phase difference of transmitted and received signal. Therefore, we use Binary Phase Shift Keying (BPSK) modulation-demodulation and the constellation diagram as Figure 16.

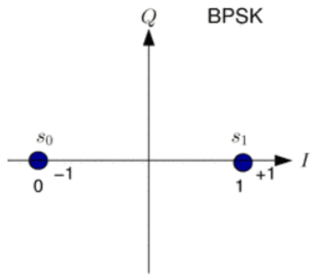

Figure 16: The Constellation Diagram of the Square Wave Array

If somehow, we could drive the local oscillators of the transmitter and receiver with the same crystal, we could achieve this exact constellation for the receiver side also; however, due to imperfect synchronization between receiver and transmitter, clock constellation in the receiver side becomes a rotated version of the above constellation, and we observe both I and Q components in our signal instead of only I.

4.2.2.3 Phase-Locked Loop

A phase-locked loop (PLL) is a control system designed to synchronize the phase of an input signal with a reference signal by adjusting based on their phase difference. For our project, implementing a PLL will be essential to handle frequency and/or phase offsets between the transmitters and the receiver.

Given a binary discrete signal $m[n]$, it will be transmitted as $m(n/T_s)\ cos\ (2\pi f_c t)$ where T_s is the sampling period, f_c is the center frequency, and $m[n]\ \in\ \{-1,1\}$. If there is a discrepancy between the local oscillators of the transmitter and receiver, the received signal, disregarding additive noise, will be:

$$r(t) = m(n/T_s)\ cos\ (2\pi f_c t)(cos\ (2\pi(f_c + f_o)t + \theta) - j\ sin\ (2\pi(f_c + f_o)t + \theta))$$

where f_o is the frequency offset and θ is the phase offset. The sampled baseband message can then be expressed as:

$$r[n] = m[n]\ exp\ (j2\pi f_o n T_s + j\theta).$$

To estimate the complex envelope that modulates the message, a PLL structure can be applied in several ways. For instance, the instantaneous phase, $\theta[k] = arctan\,(\frac{Im\{r[k]\}}{Re\{r[k]\}})$, can be calculated for each sample and fed into the PLL. Alternatively, for a frame of samples, the discrete Fourier transform (DFT) of $r[n]$ can be calculated and fed into the PLL, allowing for detection and removal of the frequency offset.

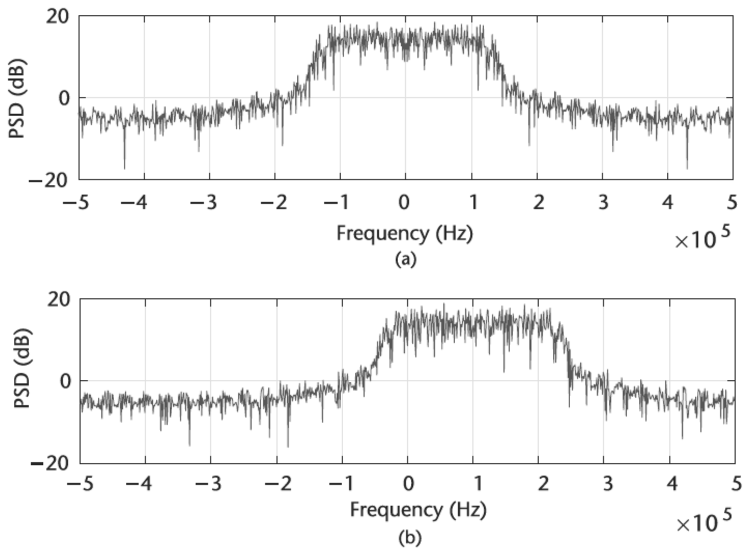

Figure 17: PSD of a Baseband Signal with (a), and without (b) Frequency Offset [26]

We have initiated the algorithm development for phase-locked loop (PLL) during our cm1 phase. Our current progress consists of investigating the open source GNSS codes so as to implement PLL algorithm such that it successfully works with real time GNSS signals. In Figure 18 and 19, we examined the results of two channel Glonass L1 Band which is GL1 signals through MATLAB simulation. We investigate whether the phase difference is successfully eliminated. The discrete time scatter plots indicated in Figure 18 and 19 demonstrates a low phase difference on left side, a high phase difference on the right side.

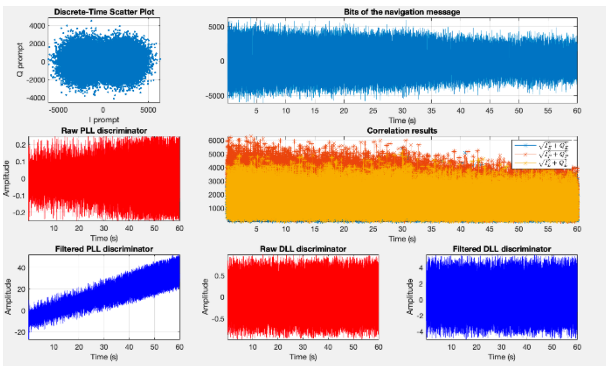

Figure 18: Signal Tracking Performance for Channel 5

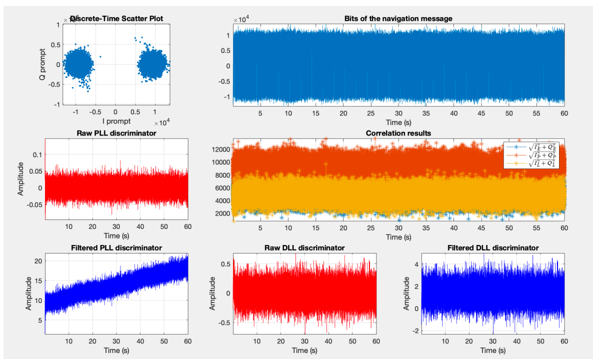

Figure 19: Signal Tracking Performance for Channel 6

After understanding how PLL algorithm works in open source GNSS code, we started to create our own PLL algorithms. First, PLL algorithms for basic signal was created and implemented (see Figure 20). Additionally, phase error over time was plotted and it was observed that phase errors of samples go to zero and steady state is reached (see Figure 21).

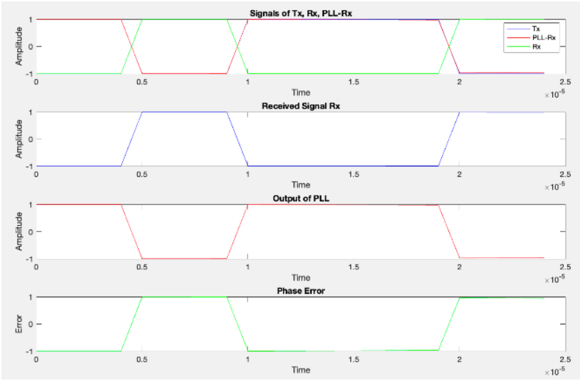

Figure 21: Preliminary Design of PLL Algorithm

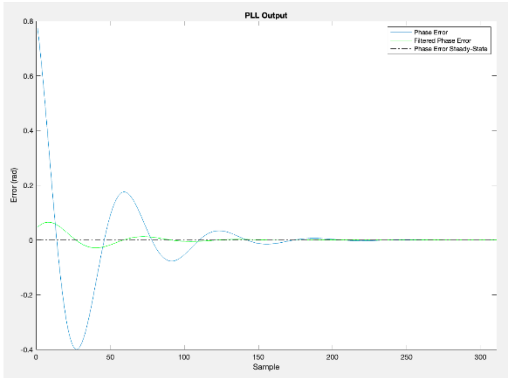

Figure 20: Phase Error Output after PLL Algorithm

Currently, we are working on applying PLL algorithm to real-time received signal from Adalm- Pluto.

4.2.2.4 Delay-Locked Loop

Delay-locked loops can be considered as feedback loops that lock the phase of the output to the input by adjusting the delay instead of the frequency and phase difference which was the case in phase-locked loops. DLLs are considered as less sensitive to input noise and phase noise. Main components of DLL are the delay line, a phase detector, a loop filter and a voltage-controlled oscillators. From these components, the delay line introduces controllable delays to the output signal. After addition of the delays, the phase detector compares the phase difference between the input and delayed output signals. For our case this comparison will be done by checking the cross correlation between the input and delayed output signals. The points were the cross correlation gives the maximum result will point out the point where the signals resemble each other the most. After this comparison, the phase detector will create an error signal based on the phase difference. The loop filter will then process the error signal to obtain a suitable control signal. Using this control signal we will then align the output and input by adding the corresponding delay. This feedback loop operates continuously until the phase difference between the signals are sufficiently small.

DLLs are commonly used where a precise phase alignment is required such as in clock and data recovery circuits, high-speed data transmission systems and memory interfaces as these loops can achieve fast alignment [27]. For our case we are planning on implementing a DLL loop to minimize the phase difference between the input and output signals in a fast and efficient way.

4.2.2.5 Noise and Multipath Mitigation

In RF communication systems, noise refers to unwanted disturbances that blur or alter the transmitted signal. Sources include thermal noise, electronic interference, and other environmental factors. Techniques like filtering, error correction, and modulation schemes (like BPSK) are used to reduce the impact of noise on signal quality, ensuring reliable data transmission.

Multipath occurs when transmitted signals reflect off surfaces like buildings or walls, causing multiple versions of the signal to arrive at the receiver at different times. This can lead to interference, signal distortion, or delays, complicating accurate data interpretation. Strategies like using phase-locked loops (PLL), and circular cross-correlation help distinguish the original signal from reflected copies, improving the accuracy of positioning calculations and data quality.

4.2.3 Positioning Calculation

4.2.3.1 Phase Difference of Arrival

In the first phase of the project, only one-dimensional changes in position will be calculated. This will be done by measuring changes in the distance between the transmitter and the receiver. To determine the change in distance, the phase shift of the CDMA codes must be estimated. The transmitter will periodically send the CDMA code, and at the receiver's end, the delay in the code's phase will be calculated by performing circular cross-correlation between the received code and the previously transmitted code.

Each transmitter will send a unique CDMA code. The receiver will have a stored set of CDMA codes and will know in advance which code corresponds to each transmitter. The CDMA codes are pseudo-random sequences, with each sequence assumed to be independent of the others; furthermore, each sample within a code is independent of other samples in the same code. This independence ensures that different CDMA codes will have no cross-correlation with each other, and a single CDMA code will have zero autocorrelation with any delayed version of itself. This allows for the separation of each code, even when they occupy the same channel.

Let $c_1[n], c_2[n], c_3[n]$ represent three different CDMA codes, each of length N. Each c_i consists solely of elements 1 and -1). The inner product $< c_i[n], c_j[n-n_0] >$ will equal N only when $n_0 = 0$ and $i = j$; and approximately zero otherwise.

Assuming a periodic code $c[n]$ of length N is transmitted, the receiver will have a stored copy of $c[n]$ but will receive a delayed version $c_r[n] = c[n-\phi]$ due to the speed of light delay and other component delays. The delay ϕ can be found as

$$\phi = argmax_{\phi} < c_r[n], c[n-\phi] > \quad .$$

When ϕ is recalculated every N samples, it will remain constant if the distance between the receiver and transmitter is fixed and will vary if the receiver moves closer to or farther from the transmitter. With changes in ϕ , the period of $c[n]$, and the speed of light, the change in distance can be determined.

4.2.3.2 Multilateration

For Phase 1 of our project, we will determine the receiver's position along the 1D movement. The transmitter will stay still, and the receiver will be put at a predetermined location. The receiver will calibrate itself at this location and then calculate the delta position using this calibration using the phase difference of arrival. Since the direction of the movement is fixed and is 1D, we do not need to use multilateration for Phase 1.

For Phase 2, we will determine the delta position for the 2D movement of the receiver, and this time we will implement multilateration. Multilateration is the generalised concept of triangulation. The idea in multilateration is to calculate the possible position given the light-speed delay of the received signal. For instance, for one transmitter, we might be at any location at the sphere's surface such that its center is the transmitter, and its radius is the corresponding length of the delay calculated.

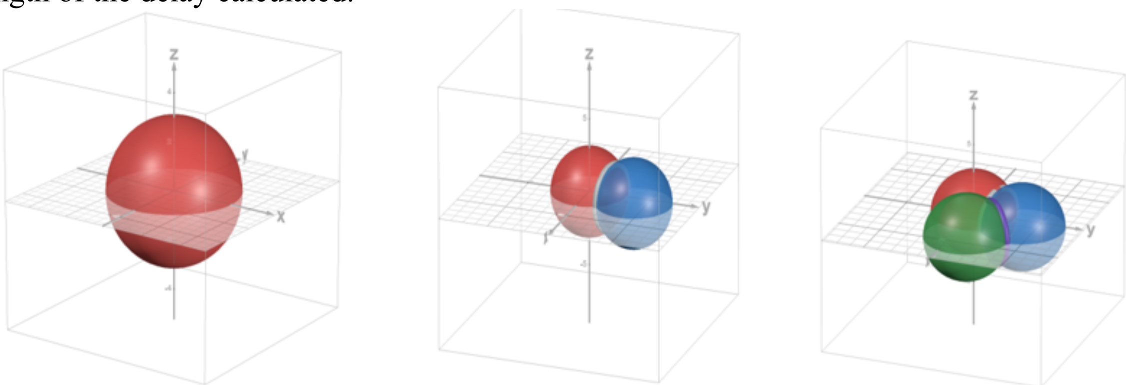

Figure 22: An Example Approach to Multilateration

When the number of transmitters is increased to two, the position could be anywhere at the circle where the two spheres coincide, such as the grey ring plotted (see Figure 22). Finally, to find the exact location in 2D, we need an extra transmitter to decrease the plausible positions from a ring to two points. Since we are considering 2D, one of these two points will be eliminated, leaving us with one plausible position.

Overlap of grey and purple rings will leave us with two positions. The projection of these two points on the 2D plane (our plane is x-y plane) leaves us with the position of the receiver (see Figure 23).

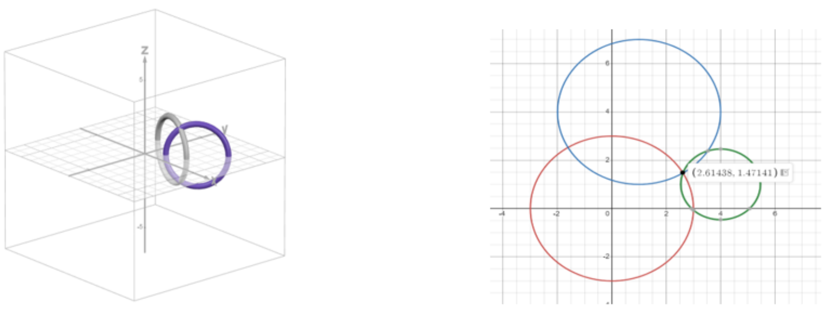

Figure 23: The Determination of the Position with respect to a 2D plane

4.2.3.3 Field Testing

Throughout the development phase of this project, field testing has been conducted to ensure the robustness and accuracy of the implemented algorithms and codes. Testing has been performed in parallel with development to identify and address any bugs or performance issues in real-time. Various scenarios were simulated to assess the system's reliability under different conditions, and adjustments were made based on the observed results. The ADALM-PLUTO SDR was a primary tool used for signal transmission and reception, enabling us to evaluate modulation, synchronisation, and signal processing functions under practical conditions.

5. Equipment List

The equipment list comprises a variety of items needed to complete the project (see Table 6). An Adalm-Pluto SDR was both provided (1 unit) and purchased (3 units) from the company, with the purchased units totalling 27,119.55 TL. The GNU Radio software was downloaded as an open-source tool at no cost. Six MATLAB licenses were provided by the department free of charge. Additionally, a Baofeng UV8R analog radio was borrowed from a team member at no cost.

The main component of the project is Adalm-Pluto SDR including components to support RF-to-IQ signal conversion and processing. Its fundamental component is the AD9363 Transceiver, which handles much of the signal processing, including input multiplexing, low-noise amplification, gain control, and signal mixing in the analog domain. Additionally, the AD9363 includes the analog filters, ADCs/DACs, and fixed digital filters, with programmable 128-tap FIR filters for baseband processing.

Table 6: The Equipment List of the Project

Equipment	Quantity	Cost per Unit	Total Cost	Acquisition Method	Source
Adalm-Pluto SDR	1	Free	0	Provided	Company
Adalm-Pluto SDR	3	9039,8504TL	27119,5512TL	Purchase	Company
GNU Radio	1	Free	0	Download	Open Source
MATLAB Licence	6	USD 55	0	Provided	Department
Analog Radio Baofeng UV8R	1	USD 40	0	Borrowed	Team Member

6. References

[1] Inertial Labs. "What Are the Limitations of GNSS?" *Inertial Labs*, [Online]. Available: https://inertiallabs.com/what-are-the-limitations-of-gnss/. [Accessed: 11-Nov-2024].

[2] Skybrary. "GNSS Jamming and Spoofing." *Skybrary*, [Online]. Available: https://skybrary.aero/articles/gnss-jamming-and-spoofing. [Accessed: 11-Nov-2024].

[3] J. A. García, E. S. Lohan, and F. Dovis, "GNSS-SDR: An Open Source Global Navigation Satellite System Software Defined Receiver," 2018 International Conference on Localization and GNSS (ICL-GNSS), IEEE, 2018, pp. 1-6.

[4] E. Schmidt, D. Inupakutika, R. Mundlamuri, and D. Akopian, "SDR-Fi: Deep-Learning-Based Indoor Positioning via Software-Defined Radio," IEEE Access, vol. 7, pp. 1-1, 2019. doi: 10.1109/ACCESS.2019.2945929.

[5] Spirent Federal Systems, "Alternative RF PNT & Spirent's New Alt PNT Simulator," Spirent Federal, Nov. 17, 2021. [Online]. Available: https://spirentfederal.com/blogs/alternative-rf-pnt-spirents-new-alt-pnt-simulator

[6] S. Lo, "Alternatives for Alternate Positioning, Navigation, and Timing (APNT)," *White Paper,* Dec. 2011.

[7] J. A. García, E. S. Lohan, and F. Dovis, "GNSS-SDR: An Open Source Global Navigation Satellite System Software Defined Receiver," 2018 International Conference on Localization and GNSS (ICL-GNSS), IEEE, 2018, pp. 1-6.

[8] E. D. Kaplan and C. J. Hegarty, Understanding GPS: Principles and Applications, 2nd ed. Artech House, 2005.

[9] L. Heng, B. W. O'Hanlon, and G. X. Gao, NavSdr: Software-Defined Radio-Based Navigation Signal Processing, IEEE Journal of Selected Topics in Signal Processing, 2012.

[10] Per Enge, Stanford University GPS Laboratory Research Papers, Stanford University, 2010.

[11] T. Takasu and A. Yasuda, Development of the Low-Cost RTK-GPS Receiver with an Open Source Program Package RTKLIB, International Symposium on GPS/GNSS, 2009.

[12] E. Schmidt, D. Inupakutika, R. Mundlamuri, and D. Akopian, "SDR-Fi: Deep-Learning-Based Indoor Positioning via Software-Defined Radio," IEEE Access, vol. 7, pp. 1-1, 2019. doi: 10.1109/ACCESS.2019.2945929.

[13] G. Piccinni, F. Mazzenga, and F. Santucci, "Analysis and Modeling of a Novel SDR-Based High-Precision Positioning System," ResearchGate, [Online]. Available: https://www.researchgate.net/publication/327063429_Analysis_and_Modeling_of_a_Novel_SDR-Based_High-Precision_Positioning_System. Accessed: Nov. 1, 2024.

[14] Analog Devices Inc., "ADALM-PLUTO SDR Data Sheet," Analog Devices. [Online]. Available: https://www.analog.com/en/products/adalm-pluto.html. [Accessed: Nov. 4, 2024].

[15] Analog Devices, Inc., "ADALM-PLUTO Regulatory Compliance," Analog Devices Wiki. [Online]. Available: https://wiki.analog.com/university/tools/pluto/common/regulatory_compliance. [Accessed: Nov. 14, 2024].

[16] LVT Test Laboratories, "TS EN 61010-1: Safety Requirements for Electrical Equipment for Measurement, Control, and Laboratory Use," LVT Test Laboratories, 2019. [Online]. Available: https://www.lvt.com.tr/en/makale/ts-en-61010-1-olcme-kontrol-ve-laboratuvarda-kullanilan-elektriksel-donanim-icin-guvenlik-kurallari. [Accessed: Nov. 14, 2024].

[17] IEEE Standard for Safety Levels with Respect to Human Exposure to Electric, Magnetic, and Electromagnetic Fields, 0 Hz to 300 GHz, IEEE Std C95.1-2019, Oct. 2019.

[18] Turkish Standards Institution, "TS EN 61010-1: Safety requirements for electrical equipment for measurement, control, and laboratory use - Part 1: General requirements," 2011. [Online]. Available: https://intweb.tse.org.tr/standard/standard/Standard.aspx?081118051115108051104119110104055047105102120088111043113104073101089076089048116120052110084101. [Accessed: Nov. 14, 2024].

[19] IEEE 802.11 Working Group, "IEEE 802.11: The Working Group Setting the Standards for Wireless LANs," [Online]. Available: https://www.ieee802.org/11/. [Accessed: Nov. 14, 2024].

[20] “A Primer on Quadrature Amplitude Modulation (QAM) - Mini-Circuits Blog,” Mini-Circuits Blog, Sep. 10, 2023. Available: https://blog.minicircuits.com/a-primer-on-quadrature-amplitude-modulation-qam/

[21] “BPSK - Binary Phase Shift Keying,” GeeksforGeeks, Oct. 04, 2023. Available: https://www.geeksforgeeks.org/bpsk-binary-phase-shift-keying/

[22] “Binary Phase Shift Keying (BPSK) – modulation and Demodulation – GaussianWaves.” Available: https://www.gaussianwaves.com/2010/04/bpsk-modulation-and-demodulation-2/

[23] “0.6 Correlation and Auto-correlation.” Available: https://www.appstate.edu/~grayro/comphys/lecture10c_11.pdf

[24] “Analog Devices perpetual eBook license - Artech House copyrighted material.” Available: https://www.analog.com/media/en/training-seminars/design-handbooks/Software-Defined-Radio-for-Engineers-2018/SDR4Engineers.pdf

[25] Prust, C. J. (2018). *Laboratory 2: Amplitude Modulation*. Electrical Engineering and Computer Science Department, Milwaukee School of Engineering.

[26] Di Pu, Travis F. Collins, and Alexander M. Wyglinski, Software-Defined Radio for Engineers. Norwood, MA: Artech House, 2018.

[27] Vemeko FPGA, What is Delay Locked Loop?, https://www.vemeko.com/blog/what-is-delay-locked-loop.html (accessed Nov. 12, 2024).