An Indoor Positioning System Based on Global Positioning System: Design, Implementation and Analysis

by
Kerem ÖZSOY

Submitted to the Graduate School of Engineering and Natural Sciences
in partial fulfillment of
the requirements for the degree of
Master of Science

Sabanci University
Summer 2009

An Indoor Positioning System Based on Global Positioning System: Design, Implementation and Analysis

APPROVED BY

Assoc. Prof. Dr. İbrahim TEKİN (Thesis Supervisor)	....
Assist. Prof. Dr. Ayhan BOZKURT	....
Assoc. Prof. Dr. Bahattin TÜRETKEN	....
Assist. Prof. Dr. Güllü KIZILTAŞ ŞENDUR	....
Assoc. Prof. Dr. Meriç ÖZCAN	....

DATE OF APPROVAL: ....

To my loving family

&

AslıUzun

Acknowledgments

I would like to express my utmost gratitude to Dr. İbrahim Tekin for giving me the opportunity to have worked with him with a variety of projects that helped to shape my abilities throughout my education. Thank you for guiding me as an mentor and academician. Moreover, I want to thank all of my professors in microelectronics group in SabancıUniversity for their support and teachings during my undergraduate and master degree. I am thankful to my thesis defense committee members; Ayhan Bozkurt, Bahattin Türetken, Güllü Kızıltaş Şendur and Meriç Özcan for their comments and presences.

During my master study, I was supported by the scholarships supplied by TÜBİTAK. I am very grateful for these foundations that enabled my education. My bosses and my colleagues in Vestek Electronics also deserve a thanks for their patience.

Moreover, I would like to thank my loving friends who always supported me. Special thanks to Muharrem Bayraktar and Emre Özeren for accommodating me in their room on weekends. Thanks to Mustafa Doğan for helping me to measure the antennas.

AslıUzun, my dear fiance, it would be impossible to get my master degree without you. Thank you for your endless support and encouragement. Additionally, I want to thank my parents in law for their support and love.

Finally, I would like to thank to my sisters, Bilgen Herdem and Burcu Özsoy-Çiçek for always being with me. Last but not least, I want to thank my parents, Nihal Özsoy and Ahmet Özsoy who gave me a chance to pursue my ambitions and career, always supported, encouraged and loved me. Thank you with all my heart.

An Indoor Positioning System Based on Global Positioning System: Design, Implementation and Analysis

Kerem ÖZSOY

EE, MS Thesis, 2009

Thesis Supervisor: Assoc. Prof. Dr. İbrahim TEKİN

Keywords: GPS, Indoor positioning, Directional Antennas, RF Repeaters

Abstract

Civil Global Positioning System (GPS) has become very popular in recent years and it has widespread use in many areas such as traffic management, medical emergency services and location finding in wireless handsets. Owing to the latest technological advances, GPS receivers are able to locate themselves with an error of 5 meters outdoors. Although GPS positioning is very successful in outdoor areas, it is hard to decode GPS signals indoors due to the additional signal loss caused by the buildings and walls. In this thesis, in order to solve indoor coverage problem, an indoor positioning system based on GPS infrastructure is proposed, designed and analyzed. Designed indoor positioning system consists of GPS repeaters and a GPS receiver with improved positioning algorithms. In order to analyze the proposed indoor positioning system, directional GPS antenna, GPS repeater with amplifiers is designed, manufactured and measured. Positioning algorithms are implemented and operated real time on live GPS data. All the system components are integrated and positioning is obtained for evaluation of the system performance. Results of the experiments show that the proposed system can be used for indoor positioning thus continuation of the GPS service can be expanded to indoors with a hardware addition to the buildings and a software update to the standard GPS receivers where indoor coverage is needed.

GPS ile İç Mekan Konumlandırma Sistemi: Tasarım, Uygulama ve Analiz

Kerem ÖZSOY

EE, Yüksek Lisans Tezi, 2009

Tez Danışmanı: Yrd. Prof. Dr. İbrahim TEKİN

Anahtar Kelimeler: GPS, İç Mekan Konumlandırma , Yönlü Anten, RF Tekrarlayıcılar

Özet

Sivil Küresel Konumlandırma Sistemi (GPS) son zamanlarda popülerleşip, trafik yönetimi, tıbbi ilk yardım servisleri ve kişisel konumlandırma gibi geniş kullanım alanları bulmuştur. Son teknolojik gelişmelerle beraber GPS alıcıları dış mekanlarda 5 metre hatayla konumlandırma yapabilir hale gelmiştir. Her ne kadar GPS alıcıları dış mekanlarda çok başarılı sonuçlar verse de, iç mekanlarda aynı performası sergileyemezler. Kapalı mekanlarda uydulardan gelen sinyallerin güçleri, duvarlar ve binalar yüzünden düşer ve GPS alıcıları, bu düşük güçteki sinyalleri çözümleyemezler. Bu tezde, bu problemi çözmek için, GPS kapsama alanını iç mekanlara genişleten bir kapalı alan konumlandırma sistemi geliştirildi. Önerilen sistem tekrarlayıcılardan ve gelişmiş konumlandırma algoritmalarından oluşmaktadır. Sistemin analizini yapabilmek için yönlü antenler, yüksek frekans yükselticileri tasarlanıp ölçülmüştür. Konumlandırma algoritmaları tasarlanıp, gerçeklenmiştir. Bütün sistem bir araya getirilip sistemin analizi gerçek zamanlı GPS sinyalleri ile yapılmıştır. Deney sonuçları gösteriyor ki, önerilen sistem iç alanda konum bulmak için kullanılabilinir. İç mekanlarda konum hesabı ihtiyacı duyulan binalarda donanım eki yapılarak ve kullanılan standart GPS alıcılarına yazılım eklentisi yapılarak GPS kapsama alanı genişletilebilinir.

Table of Contents

List of Figures

List of Tables

Chapter 1

Introduction

Civil Global Positioning System (GPS) has become very popular in recent years and it has widespread use in many areas such as traffic management, medical emergency services and location finding in wireless handsets. With the latest technological advances such as Differential GPS (DGPS), Assisted GPS (AGPS), civilian GPS receivers are able to locate themselves with an error of 5 meters outdoors [1]. Although GPS positioning is very successful in outdoor areas, it is hard to decode GPS signals indoors due to the additional signal loss caused by the buildings and walls. GPS signals are transmitted from the satellites orbiting around 20.000 km in the sky. When these signals reach the earth surface, the strength of the signals is very low due to free space loss. For indoors, signals go through additional loss of 10-30 dB [2] in which case, signal levels are too low for an off-the-shelf GPS receiver to detect the satellite signal. In this thesis, in order to solve the indoor coverage problem, an indoor positioning system that uses the GPS infrastructure is proposed and designed. Designed indoor positioning system consists of GPS repeaters and a GPS receiver with improved positioning algorithms. GPS repeaters are used to pick up a satellite signal from a specific part of the sky, amplify and then retransmit into the building in which there is no GPS signal coverage and the GPS receiver with improved positioning algorithms is used to find exact position of the receiver in a closed area. In order to accomplish this, a directional GPS antenna is designed, manufactured and measured. A GPS repeater system with amplifiers is designed, manufactured and measured. Data acquisition with a GPS receiver that is capable of extracting raw GPS data is also provided. Finally, positioning algorithms are implemented on a Matlab platform. All the system is implemented and real time positioning is obtained for the evaluation of the system performance.

The rest of the thesis will be organized as follows: In the following section, a literature survey of indoor positioning systems will be detailed. In chapter 2, brief explanation of GPS working principles will be presented. Further, the design of the indoor positioning system will be explained in details. In Chapter 3, the hardware, in chapter 4, software of the system will be explained. In Chapter 5, the measurement results for the GPS indoor system will be shown, and finally the thesis will be concluded with conclusion and future work.

1.1 Survey of Indoor Positioning Systems

Indoor positioning systems have become popular in the last few years. These systems are used in many applications such as position detection of products in a warehouse, position detection of equipment or personnel in a hospital, position detection of firemen in a building on fire, and finding tools scattered all over a plant [3].

Indoor positioning systems are used to find position of a target in a closed area. These systems basically consist of reference points with known positions, a target that is tried to be found and a physical layer that is used for measurements between the reference points and the target. There are different types of indoor positioning systems, these systems may be classified based on the type of positioning method, physical medium for measurements and lastly whether it uses an existing physical layer or it develops its own physical layer[3, 4].

In order to compare the existing indoor positioning systems, types of the positioning methods should be analyzed. There are three main positioning techniques that are used in existing indoor positioning systems. These are triangulation, scene analysis and lastly proximity [3].

Triangulation uses basic geometric principles of triangles to find positions. Basically, estimation of the position is done by measuring the distance or the angle between the position of the target and multiple reference points. After angle or distance measurements, basic triangle principles are used to find the target position. Measurements based on angles are called angle of arrival [3]. After measuring the angle between the target and the reference points, by triangulation the position can be found. However, positioning with this method requires expensive and calibrated antennas to calculate angle sensitively also when the target object is far away from the reference points, the error in the AOA method may increase and this will lead to lower accuracy [4]. Positioning systems that uses triangulation mostly measure the distance between the target and the reference point instead of angles. These distance measurements can be done by using received signal strength (RSS), time of arrival (TOA) and time difference of arrival (TDOA). Measurements based on RSS uses a receiver that measures the received power and computes the attenuation of the emitted signal strength. After measuring attenuation, with a propagation model, distance can be calculated. However, RSS method is not very reliable for indoor environment. Due to severe multipath fading and shadowing present in the indoor environment, path-loss models do not always hold [3]. As a result of this, RSS leads to high error for indoor positioning. Instead of RSS, in order to find the distance between the reference points and the target position, time of arrival (TOA) or time differences of arrival (TDOA) are used. These methods give better results for indoor environments. In these methods travel time of the wave between the reference point and the target is measured. The actual distance is multiplication of the wave velocity and the travel time. In systems that uses TOA or TDOA, time synchronization is the most important part because the system basically measures the travel time. After finding distance of target with reference to several reference points by triangulation the position is found.

Another indoor positioning method is finger printing in other words scene analysis. Fingerprinting has two phases. These are offline training phase and online position determination phase [3]. During offline training, pre-measurement is done in the indoor environment. During online positioning, pre measured location data is used as a look up table. Online measurements are compared with the look up table and most likely position is found. This method requires pre measurements and is not very reliable because changes in the indoor environment will lead to error in the positioning system.

Last method for indoor positioning is proximity. In this method, various sensors are deployed in the indoor environment and as the target passes near them, closest sensor became active and positioning is done. Such a system needs densely deployed sensors and their maintenance. Therefore it is not applicable to all indoor environments.

Another classification of indoor positioning systems is the physical medium. Four different medium is used in existing indoor positioning systems. These are infra red (IR) signals, ultrasound waves, vision based and lastly and mostly used medium is radio frequency (RF) signals [4]. An IR based positioning system can calculate position of the target without error. However, it needs line of sight communication between transmitter and receiver and also they suffer from a strong interference such as sun [5]. Therefore, although IR based systems are very accurate they are not applicable to every indoor environments. Second physical medium is Ultra-sound [6]. Ultra-sound solutions are good and cheap solutions for indoor positioning. They use ultra sound waves to measure the distance between the target and the receiver. The disadvantage of these systems is that the noise sources affect the communication between the reference and the target [4]. Another way of indoor positioning is Vision-based Positioning in indoor environment [7]. Vision based systems uses cameras for positioning. These systems also have some drawbacks. This system is not reliable in a dynamic changing environment because it uses pre-saved visions in the data base. Also, video recording cannot be applicable for all indoor environments.

Most of the indoor positioning system uses radio frequency signals as a physical medium for distance measurements. The main reason of using radio frequency signals is that the radio waves can travel through walls, obstructions and human bodies, therefore by using radio frequency signals, it is possible to cover an indoor area with less hardware than other methods. There are eight different indoor positioning systems that uses radio frequency. These systems use different frequency bands and different communication types. These systems are RF-ID, WLAN, Bluetooth, UWB, pseudolites, High sensitive GPS, Assisted GPS and GPS repeaters [3, 4, 8]. RFID positioning systems uses RFID tags for positioning and it uses proximity technique, therefore, it needs numerous components deployed and maintained in the indoor area. Another technique is using WLAN. WLAN is very popular and it has been used in many public areas. WLAN based positioning reuse the existing WLAN infrastructure therefore it does not need further hardware installation. However, some of the WLAN positioning systems uses fingerprinting method [4]. Indoors are very dynamic environment. Therefore, usage of fingerprinting technique degrades the performance of the WLAN positioning systems and makes them unreliable. WLAN positioning that uses TOA gives better results and it is an accurate positioning system. However, WLAN positioning with TOA requires expensive access points that are synchronized with each other. Another method is using Bluetooth technology in location sensing. This technique also uses fingerprinting. Therefore, it also suffers from the drawbacks of fingerprinting positioning technique in the complex and changing indoor situations [9]. Furthermore, it needs dense deployment with respect to WLAN. Ultra wide band (UWB) positioning technique is advantageous over other positioning techniques. It does not need line of sight communication, it does not affect from multipath and it can easily penetrate from the walls [8]. In addition to these, it is very accurate. However, cost of the overall system is high because it does not use any existing infrastructure or receivers for measurements. Another indoor positioning technique is using Pseudolites [10]. Pseudolite is a combination of the terms pseudo and satellite. Pseudolites are transmitters that behave like GPS satellites. The basic idea in pseudolites is to reconstruct GPS constellation in a closed area. The advantage in the application of pseudolites is their use of similar signals to GPS. In this way, standard receivers can be used to decode pseudolites signals without any hardware updates. Only software updates are required in order to tell the receiver to search peseudolites, the disadvantage of the system is the hardware deployment. Another method is using High Sensitivity GPS (HS-GPS). A typical high sensitivity GPS (HS-GPS) positioning system uses highly sensitive GPS receivers therefore does not require any further infrastructure, other than that of the GPS. However, although the performance of the receivers are greatly improved, decoding GPS signals is very hard when the power level received is very low [8]. Thus, system is not robust and does not guarantee to work in every indoor environment.

Last classification of indoor positioning systems is whether the indoor positioning system uses an existing infrastructure or not. Some of the indoor positioning systems develop a signaling system and a network infrastructure for finding positions such as ultra wide band indoor positioning systems. The advantage of this approach is that the designers are flexible of physical specifications and therefore the quality of the positioning is high. However, the overall system is expensive. Second approach is using existing wireless networks such as WLAN positioning systems and HS-GPS. The advantage of this approach is that it avoids expensive and time consuming deployment of infrastructure. The disadvantage of these systems is that the error in the positioning is high because they are limited with the constraints of the existing infrastructure.

To sum up, there are different kinds of indoor positioning systems. These systems differ from each other with their positioning methods, their physical medium for measurements and lastly their usage of existing infrastructures. Each of the indoor positioning system has its own advantages and disadvantages. Offered indoor positioning system uses triangulation with time of arrival as the positioning method which is advantageous over RSS based positioning, proximity and fingerprinting. As a physical medium it uses radio frequency signals again it is advantageous over other IR based, vision based, ultrasound based physical mediums and lastly it uses GPS infrastructure for positioning, therefore standard GPS receiver can be used for positioning without a hardware update. Only a software update will enable standard GPS receivers to be used in indoor environments. The system requires infrastructure deployment. The deployed infrastructure is only compromised of repeaters. Therefore, deployed infrastructure is simple than any other positioning system that requires infrastructure installation.

Chapter 2

Basic Principles of GPS

The Global Positioning System (GPS) is a global navigation satellite system (GNSS). By using GPS, users can calculate time, position and velocity anytime, anywhere in an open sky in the world. GPS consists of constellation of satellites, ground stations, and users. Thus, the entire GPS system can be divided into three segments which are space segment, control segment and user segment [11]. Satellites form the space segments, and they are used to provide navigation messages to users. Navigation messages are sent by radio frequency (RF) signals. Space segment consist of at least 24 satellites in 6 orbital planes. Each satellite is on Medium earth orbits (MEO) with an altitude of twenty thousand kilometers. Each satellite turns twice around the world each day and they are separated in a way so that they give highest coverage to the users [8]. Basically, mission of the space segment is to transmit navigation messages with radio signals to the receivers which enable users to find their position, time and velocity. Second segment is the control segment where ground stations control the satellites. Mainly, ground stations control the health, orbit configuration, clock biases and the ephemeris of the satellites. They communicate with the satellites and make necessary changes. Last segment is the users. This segment receives and decodes the GPS navigation signals that are transmitted by the satellites and calculates its position.

GPS signals that are transmitted from the satellites are in two different frequencies called L1 and L2 bands. Civilian GPS use L1 frequency which is at 1575 MHz at UHF band with a 1 MHz bandwidth. L2 band is at 1227 MHz and it is used for military applications. Transmit power of the satellites on L1 band is less than 50

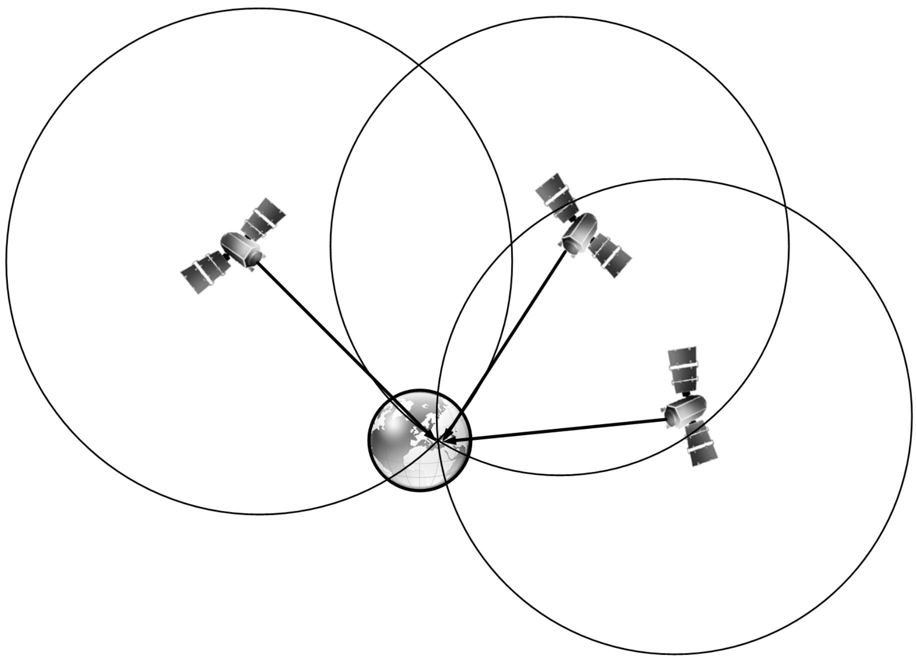


Figure 2.1: Basic idea of GPS positioning.

watts. Satellites transmit data at 50 Hz. As a modulation scheme, GPS uses code division multiple access (CDMA). Every satellite has a pseudo random code and the navigation message is modulated with this code. Every satellite has an orthogonal code to each other and all the satellites use the 1 MHz bandwidth. By decoding the satellite codes, receivers get the navigation messages of each satellite. A navigation message basically involves ephemeris which includes orbital parameters of the satellite, satellite related information such as clock bias and health, date and lastly almanac which is the reduced subset of ephemeris of all satellites.

GPS determine position by measuring the distance between the satellites and the receiver. In order to understand the working principle, assume that the receivers can precisely calculate their distance to the satellites and also they know the position of satellites. By intersecting three spheres which requires 3 distance measurements, position of the receiver can be found as seen Fig. 2.1. Actually, there will be two solutions for the intersection of the spheres. However, one of the solutions will be on the world and the second will be a distant point on the space. Assuming receiver is not around somewhere in space, exact position can be calculated.

In this manner, in order to calculate the position of the user, distance between the satellites and the receiver and also the position of the satellites must be calculated. Radio frequency signals are used for the distance measurements and getting information to calculate satellite position. Satellites orbit around the world and orbital parameters of each satellite is transmitted in the navigation message of the satellite. Thus, when the receiver decodes GPS signal it also acquires the orbital parameters and it is able to find the position of the satellite by some mathematical calculations with these parameters. On the other hand, in order to calculate the distance, GPS uses time of arrival (TOA) technique. Now, assume that all the satellites and the receivers are time synchronized. In this manner when a satellite starts to send data with its own pseudo random code, receiver also starts a replica of the same coding. After some time, the transmitted signal reachs receiver. By comparing the received signal and the replica that is generated locally at the receiver, travel time of the RF waves can be measured. Then by multiplying this time by the speed of the RF signal which is speed of light, the distance between the satellite and the receiver can be calculated[11]. However, in order to measure the distance with time of arrival technique, all the satellites and the receiver should be time synchronized. For example, an error of 1 millisecond clock offset will result in an error of 300 km. Therefore, very accurate clocks are required at the satellites. In order to handle this, each satellite carries around four atomic clocks, which use the oscillation of cesium and rubidium atoms to keep very accurate time [8]. Thus, all satellites are time synchronized. However, GPS receiver does not have any atomic clocks. Atomic clocks would be very expensive and heavy to use at the receiver. Therefore, receivers uses crystal clocks. These clocks are not accurate clocks and also they are not time synchronized with the satellites clocks. As a result, the measured distance is not exactly the distance between the satellite and the receiver. It also includes the distance that are stem from the clock bias of the receiver. Therefore the distance measurement of the GPS receiver is called pseudorange rather than range. In order to solve this problem, GPS uses an additional measurement from a fourth satellite. Receivers not also solve the position but also solve the clock error by using Eq. 2.1 where p_i is the pseudorange measurements with respect to different satellites. x, y, z are the coordinates of the receiver and x_i, y_i, z_i are the coordinates of the satellites respectively, b is the clock bias and c is the light of speed.

$$P_i = \sqrt{(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2} + bc, \; i = 1, 2, 3, 4. \tag{2.1}$$

Unfortunately in the real world, it is not easy to calculate the distance between the satellite and the receiver. The TOA measurements are not perfect due to errors from atmospheric effects, satellite clock offsets, satellite instrumentation delays, relativistic errors, receiver instrumentation delay, multipath of signals and lastly earth rotation between the emission and the reception [11, 12]. Therefore, receivers are not able to calculate the distance precisely. However, some of these errors can be removed totally and some of them can be decreased dramatically. The algorithms and methods to eliminate errors will be explained in the following sections. Standard GPS receivers uses these algorithms and finally they find their position with an error of 2.5 meter in Circular Error Probable (CEP) and 5 meters in Spherical Error Probable (SEP) [1].

2.1 Overview of Indoor Positioning Based on GPS

As explained in the previous section, GPS is a successful navigation system around the world. Although it is very successful in outdoor areas, it is hard to decode GPS signals indoors due to the additional signal loss caused by the buildings. GPS signals are transmitted from the satellites orbiting around 20.000 km in the sky. When these signals reach the earth surface, strength of the signals is very low due to free space loss. For indoors, signals go through additional loss of 10 - 30 dB [2], in which case, signal levels are too low for an off-the shelf GPS receiver to detect the satellite signal. In order to solve indoor coverage problem, an indoor positioning system that uses GPS infrastructure is designed.

In closed areas, main problem of GPS is the path loss of the received signal due to signal propagation through walls. This loss can be eliminated by using repeaters

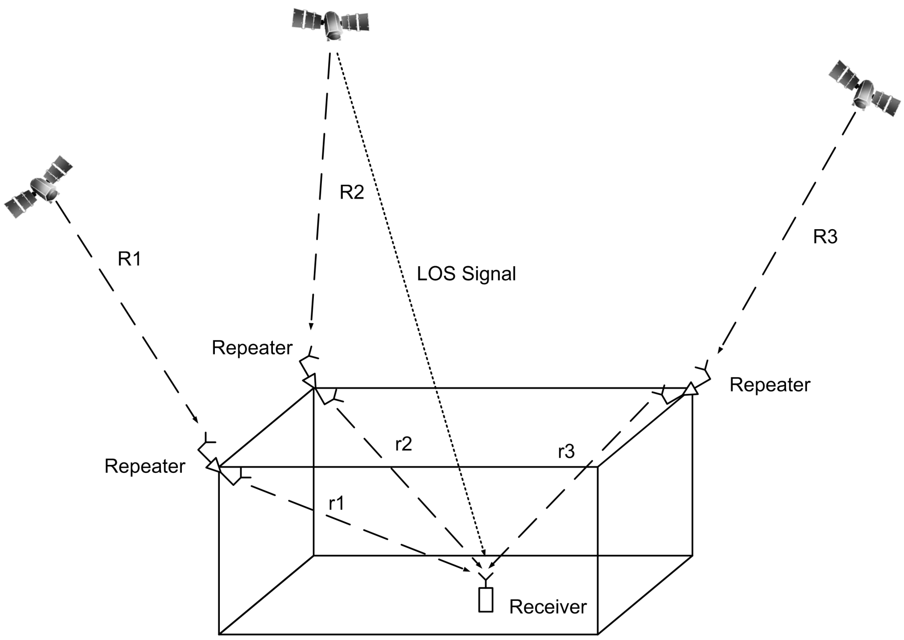


Figure 2.2: Over view of 2D indoor positioning system based on GPS.

as seen in Fig. 2.2. Repeaters can pick up a satellite signal, amplify and then re-transmit into the building in which there is no GPS signal coverage. In this way, loss of the radio signals in indoor areas can be compensated. However, this solution will lead to an error in the calculated position due to non line of sight propagation. With the use of repeaters, calculated distance will be different than the line of sight distance between the satellite and the receiver as seen in Fig. 2.2. Standard off-the-self receivers will solve the equations assuming the total distance $R_i + r_i$ is the line of sight distance and triangulation with this measurement will result in an erroneous position.

Nevertheless, the actual position can be determined with some extra calculations. As explained earlier, radio signals that are coming to GPS receiver from the satellites will first come to the repeater and then reach receiver as seen in in Fig. 2.2. So the calculated distance - pseudorange - in the GPS receiver will be as in Eq. 2.2 where P_i is the measured pseudorange with respect to satellites, b is the clock bias and c is the speed of RF waves.

$$P_i = R_i + r_i + bc \tag{2.2}$$

This distance is called pseudorange because it involves the clock bias of the receiver. As explained earlier, the internal clocks of the receivers are not synchronized to the clocks in the satellites. Offset between the receiver and the satellite clocks adds up to the distance measurements. In this application, repeaters are stationary, so the positions of the repeaters are fixed. The positions of the satellites can be calculated from the ephemerides which are broadcasted with satellite radio signal. With these known positions, distance R_i can be found by using Eq. 2.3 where x_{sat}, y_{sat} and z_{sat} are the coordinates of the satellite and x_{rep}, y_{rep} and z_{rep} are the coordinates of the repeater.

$$R_i = \sqrt{(x_{sat} - x_{rep})^2 + (y_{sat} - y_{rep})^2 + (z_{sat} - z_{rep})^2} \tag{2.3}$$

By subtracting the satellite to repeater distance from the pseudorange measurement, distance between the repeater and the receiver plus clock bias can be calculated easily which is;

$$p_i = r_i + bc \tag{2.4}$$

By using additional repeaters and calculating the distance from several repeater with the same method, triangulation can be made and the actual position of the receiver can be found. However, one should note that in this system, clock is also an unknown parameter. So, in order to solve clock bias, an additional measurement is needed which is also needed in the GPS algorithm. For a 3D positioning 4 equations and hence four pseudorange measurements are necessary as seen in Eq. 2.5. For 2D positioning, 3 pseudorange will be enough because only unknowns will be x, y and b. Three equations will be sufficient which is seen in Eq. 2.6 where the x_i, y_i and z_i are the coordinates of the repeaters and x, y and z is the coordinate of the receiver where z is constant.

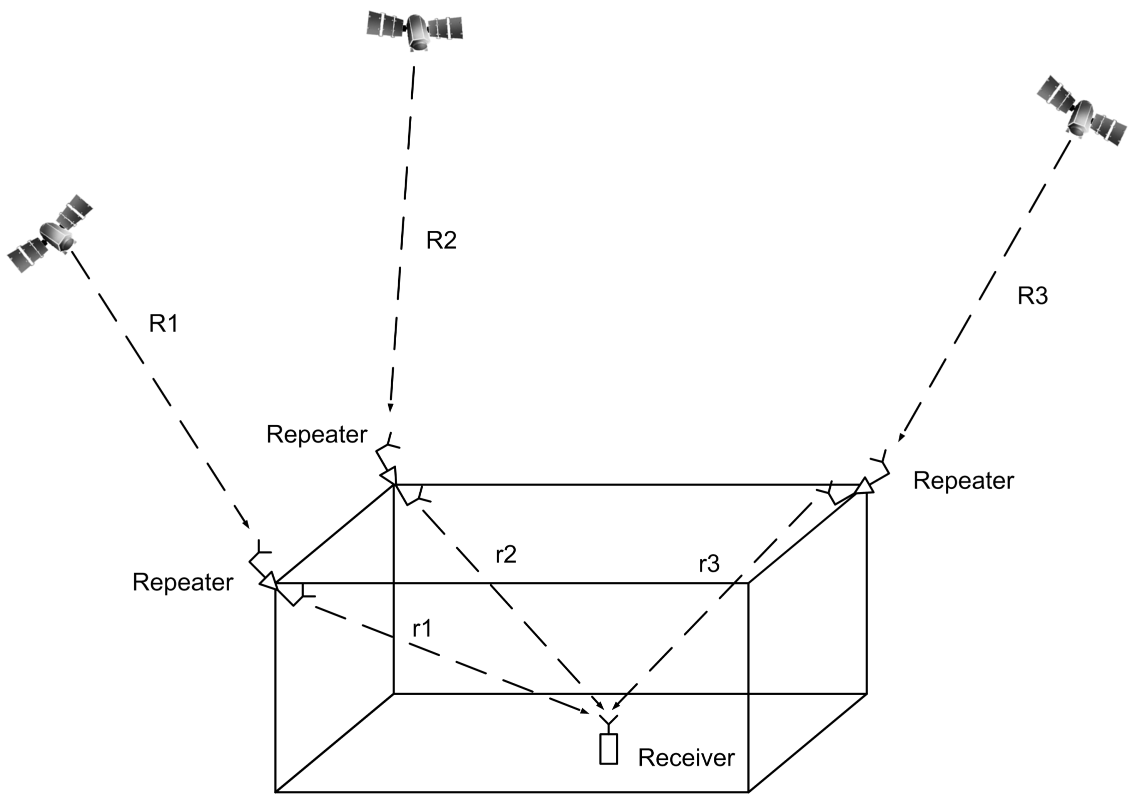


Figure 2.3: Over view of indoor positioning system.

$$p_i = \sqrt{(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2} - bc,\ i = 1, 2, 3, 4. \tag{2.5}$$

$$p_i = \sqrt{(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2} - bc,\ i = 1, 2, 3. \tag{2.6}$$

An example of 2D operation can be seen in Fig. 2.3. As seen in the figure, three repeaters pick different satellite signals, amplify them and transmit signal to indoor area. Receiver picks up satellite signals decode the navigation message and measure the pseudorange. By using ephemeris from the navigation message, position of the satellites can be found. Positions of the repeaters are fixed so the distance between the satellites and the repeaters can be calculated easily. By subtracting this distance from pseudorange, the distance between the repeater and the receiver plus clock bias can be calculated. Finally by using Eq. 2.6 position can be calculated. At this point one should note that it is crucial for repeaters to pick up the satellite signal only from a given direction in the sky and transmit the amplified signals to an indoor area. Same satellite signal that is used for positioning should not be sent to indoor area from different repeaters. Therefore directional antennas must be used to pick up satellite signal from a specific area of the sky. After picking up satellite signal, this signal should be amplified and then retransmited to indoor area. Also, a receiver is needed that is able to calculate a pseudorange and decode GPS navigation message and lastly in a platform the algorithm should be applied. Therefore, the following items are needed;

- Directional GPS and standard antennas
- Amplifiers
- GPS receiver capable of pseodoranging and decoding GPS signals
- A platform that can receive data from GPS receiver and run algorithms

Offered indoor positioning is based on two hypotheses. A satellite signal that is repeated must be received by the receiver and encoded properly and secondly a satellite signal that is used for positioning must be repeated to indoor area only from one repeater. In order to proof these hypothesis and implement the indoor positioning system, a directional GPS antenna is designed, manufactured and measured. A GPS amplifier is designed, manufactured and measured. By the combination of the directional GPS antenna, amplifier and a standard off the shelf GPS antenna, A GPS repeater is build. An off the shelf GPS receiver that is capable of extracting raw data and navigation messages is used as the GPS receiver. Hardware of the receiver is designed and manufactured. Data acquisition with a GPS receiver is constructed through MATLAB. Lastly, positioning algorithms are implemented in MATLAB. Finally, all the system is constructed and positioning is done with live GPS data.

Chapter 3

Hardware of the Indoor Positioning System

Hardware of the indoor positioning system consists of repeaters and a receiver. Repeaters are used to receive signals from satellites, amplify the signal and then re-transmit the signal to the indoor area. As indicated in the previous sections, the receiver antenna of the repeater should be directional and should receive signal from a specific part of the sky. In other words one satellite signal should not be sent to indoor area from two different repeaters. Therefore as a receiver antenna a directional GPS antenna should be used. After receiving the satellite signal, in order to increase the power of the signal, an amplifier is used in the repeater. The amplified signal is sent to the indoor area with a standard of the shelf GPS antenna. In addition to the repeater, a GPS receiver that is capable of extracting pseudorange and navigation messages is also used for the proposed indoor positioning system. Therefore, circuitry of the receiver and the data acquisition between the receiver and Matlab is also created. In the following sections, the design of the antenna and its measurements, the design of the amplifier and its measurements, the design of the receiver circuitry and the data acquisition, the path loss measurements and the delay measurements of the repeaters are explained in details.

3.1 Directional GPS Antenna

It is crucial to have directional receive and transmit antennas for proposed indoor positioning system. A repeater should be able to pick up the satellite signal only from a given direction in the sky, therefore, receiver antenna of the repeater must a directional antenna. There are several ways to design a directional antenna such as Yagi-Uda, horn, log periodic, reflector and parabolic antenna or phased array systems [13]. Among these antennas, reflector antenna type is chosen since these antennas are simple to manufacture, compact, robust in performance and low cost. Therefore, reflector GPS antenna that works in L1 frequency - 1575 MHz - with Right Hand Circular Polarization (RHCP) and a high directive gain is designed. A standard off the shelf GPS patch antenna is used in the design, and the directivity increase is achieved through the use of a conical reflector. The cone is fabricated and integrated with the standard GPS patch antenna and finally directional GPS antenna is measured.

3.1.1 Antenna Design

The directional antenna is comprised of a standard off the shelf GPS antenna and a conical reflector as illustrated in Fig. 3.1. Standard GPS antenna is a circularly polarized patch antenna operating at the frequency of 1575 MHz. The circular polarization is provided by truncation of the two diagonal corners and feeding the antenna asymmetrically with a coaxial probe under the patch [13]. The dimensions of the GPS patch antenna - 25 mm x 25 mm - are kept small by using high electrical permittivity ($\epsilon_r = 25$). Microstrip patch antennas are medium gain antennas. In order to further increase the directivity of the patch antenna, either a phased array system consisting of multiple radiating elements or a parasitic reflector system can be utilized. In our approach, a simple reflector system over other directional antennas is chosen. The conical reflector is simple, compact, robust in performance and low cost. Most importantly, as opposed to phase array antenna, reflector antenna does not need a beam forming network which decreases the received power and increases the noise figure of the overall system. Therefore, a reflector is designed to increase the directivity of the antenna.

The design of conical reflector together with the patch antenna is performed using Ansoft's High Frequency Structure Simulator (HFSS). First, off the shelf GPS patch antenna is simulated and parameters of the antenna are adjusted such that the specifications in the datasheet are obtained with good accuracy. In order to get

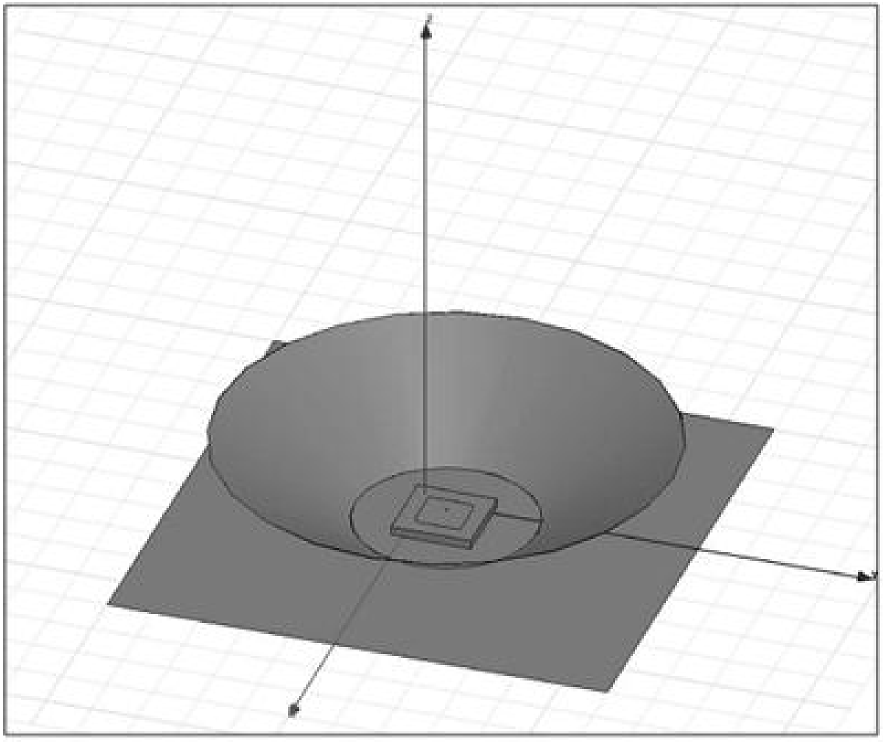


Figure 3.1: GPS patch antenna with the conical reflector

similar results with datasheet, dielectric constant of the patch antenna is changed. Then, the GPS patch antenna is placed in the middle of cone reflector. The reflector is left as floating reflector, i.e., it is not grounded. Optimizations are done iteratively by the simulation tool and more emphasis is given to three parameters of the conical reflector namely height of the cone, angle between the cone and the ground plane and the distance of cone to the patch antenna. The distance between the cone and the standard patch antenna basically affects all parameters. However, most importantly, it affects the return loss of the antenna. The height of the cone changes the half power beamwidth and the gain of the antenna. The cone angle mostly affects the radiation pattern of the antenna. In Fig. 3.3, one can observe the effect of the cone angle to the radiation pattern of the antenna with the other parameters set to optimum values. The manufactured antenna is shown in Fig. 3.2.

After simulation results, thickness of the conical reflector is chosen as 1 mm, the two of the three parameters are fixed with the best results acquired in simulations and the other parameters are optimized. The summary of the dimensions of the

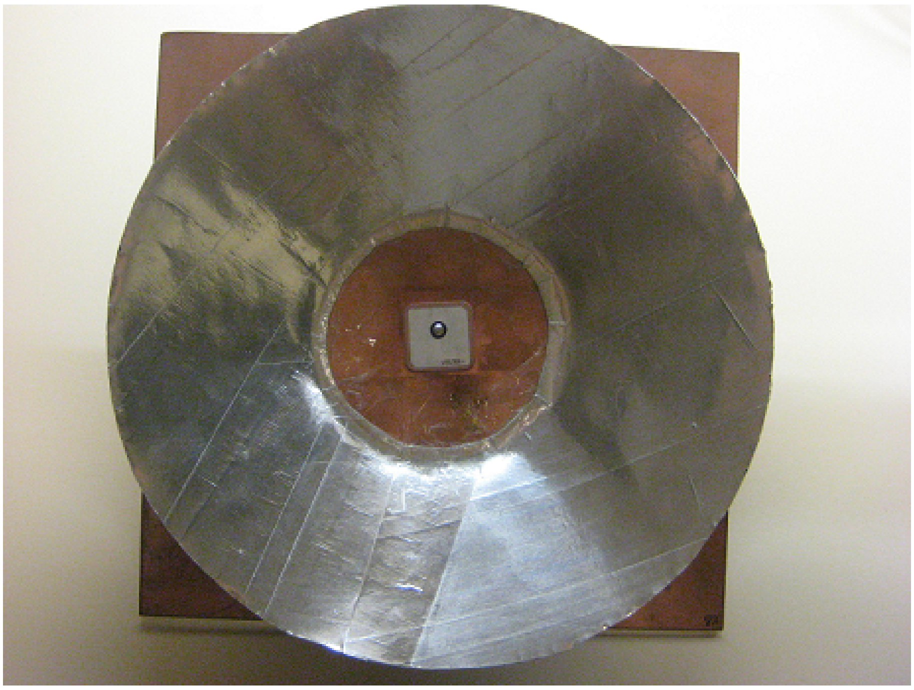


Figure 3.2: Manufactured directional GPS antenna

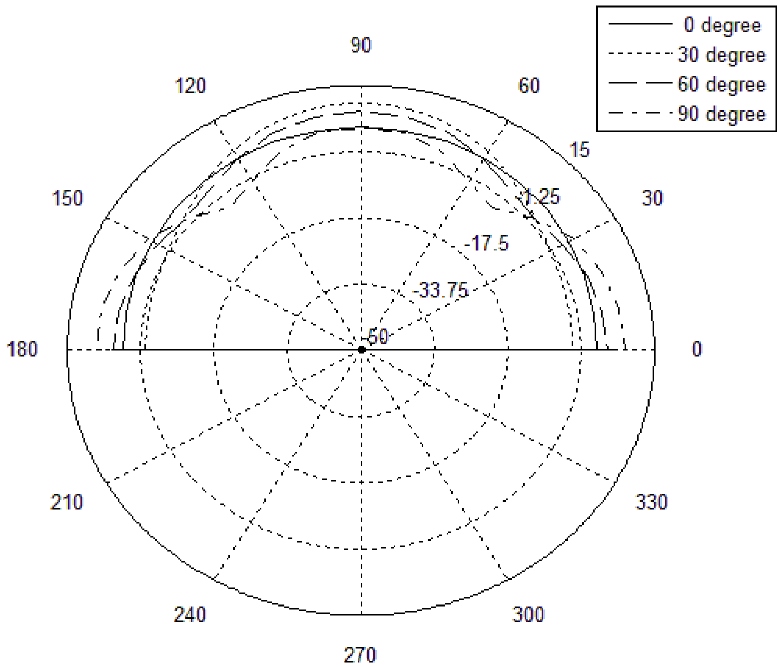


Figure 3.3: Radiation patterns with different cone angles

proposed antenna after the optimizations are given in Table. 3.1.

Table 3.1: Optimized directional antenna parameters

Radius of the cone at the ground plane	4 cm
Height of the cone	4 cm
Degree between the cone and the ground plane	30 degree

3.1.2 Simulation and Measurement results

Simulation results of the stand alone GPS patch antenna shows that the antenna has 4 dBi maximum directive gain and 120 degree half power beam width. Antenna is matched at GPS L1 frequency. These simulation results agree with the datasheet of the GPS patch antenna. The radiation patterns of the simulation results can be seen in Fig. 3.4, 3.5.

After the design of the cone and the integration of the cone with the GPS patch antenna, measurements are done in an anechoic chamber. The results show that the gain of the antenna is increased and the center resonant frequency of the overall system slightly changed which does not affect the overall performance. The simulated and the measured return loss of the directional antenna with the measured return loss of the stand alone GPS patch antenna can be seen in Fig 3.6. As seen in the figure, cone changes the input impedance slightly. However, directional antenna still matches at GPS L1 frequency. The change in the resonant frequency stems from the metallic effect of the cone.

The measured and simulated radiation pattern of the directional antenna can be seen in Fig. 3.4 and Fig. 3.5 with the ϕ angles 0 and 90 degree respectively. The beamwidth of the directional GPS antenna is 60 degrees. Decrease in the beamwidth angle can be seen in Fig. 3.7 in which the measured radiation pattern of the directional antenna and the simulated radiation pattern of GPS patch antenna are shown. Measured radiation patterns of two orthogonal phi angles can be seen in Fig. 3.8.

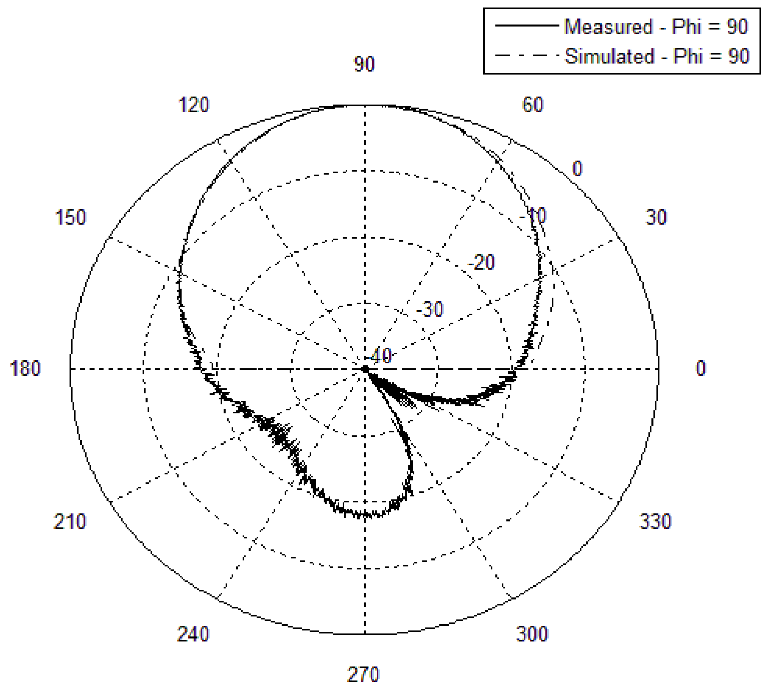


Figure 3.4: Measured and simulated radiation patterns, with 0 degree ϕ angle

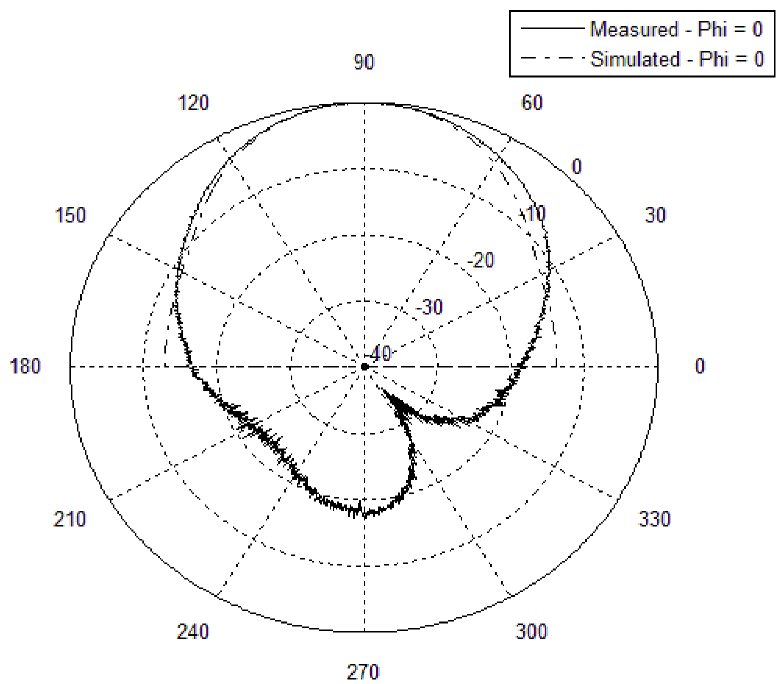


Figure 3.5: Measured and simulated radiation patterns, with 90 degree ϕ angle

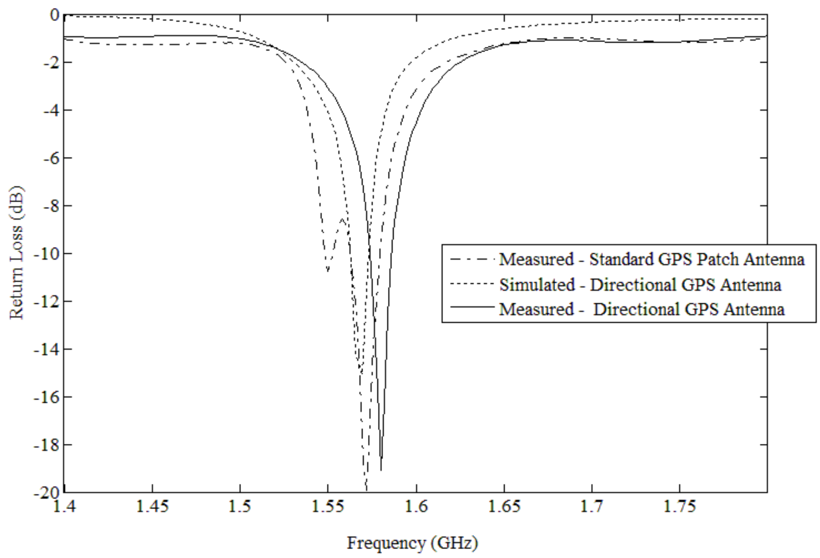


Figure 3.6: Measured return loss of the standard GPS patch antenna and directional antenna. Simulated return loss of the directional antenna

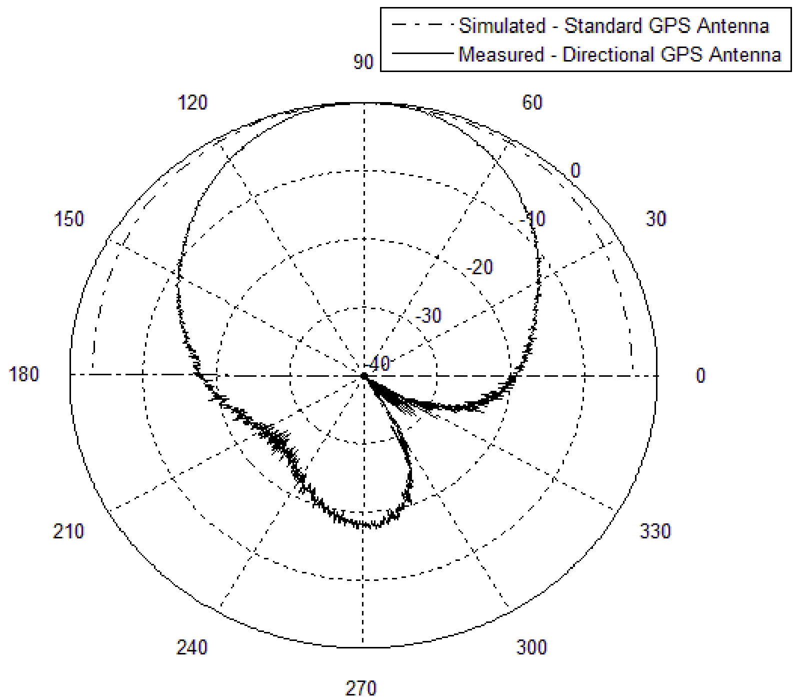


Figure 3.7: Measured directional antenna and simulated GPS patch antenna radiation patterns, with 0 degree ϕ angles

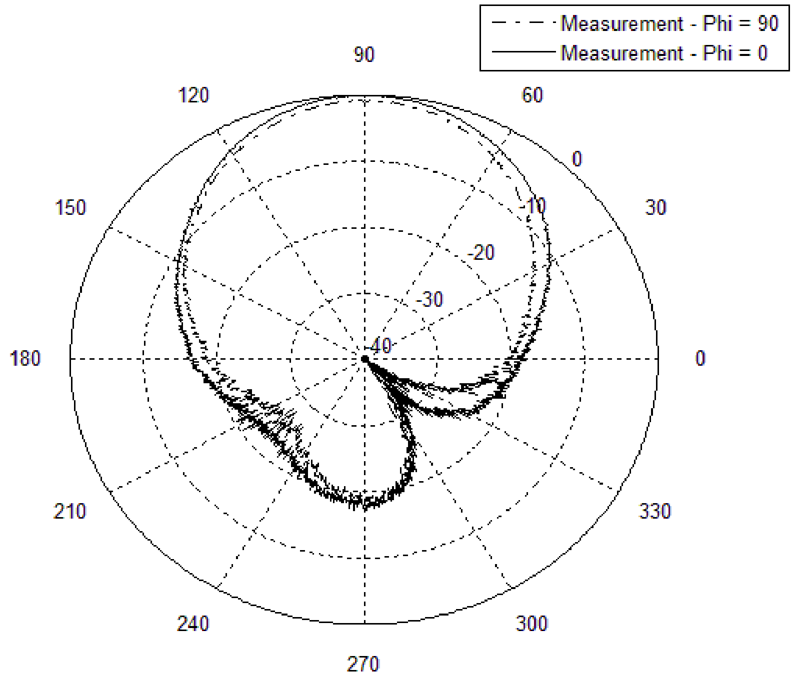


Figure 3.8: Measured radiation patterns, with 90 and 0 degree ϕ angles

As seen in the figure, axial ratio of the directional antenna is 1 dB which indicates that the antenna is circularly polarized. Simulated directional gain of the antenna is 10 dB and the measured maximum directional gain of the overall system is 9 dB. Cone brings an additional 5 dB gain to the patch antenna. The measurement results of the return loss, gain and the radiation patterns fit well with the simulation results. There is a slight difference between the simulation and measurement result that stem from the manufacturing differences.

3.1.3 Analysis of the Directional Antennas for Indoor Positioning System

The measurement results show that the beamwidth of the directional antenna is 60 degrees. In addition to this, gain difference between the 0 degree and the 90 degree theta is 20 dB. In a scenario in the figure 3.9, satellite 1 signal is received by directional antenna 1 and directional antenna 2. However, there is a difference of 20 dB between each other, therefore the effect of the directional antenna 2 is negligible with respect to directional antenna 1. As the angle of arrival increases the effect also decreases dramatically.

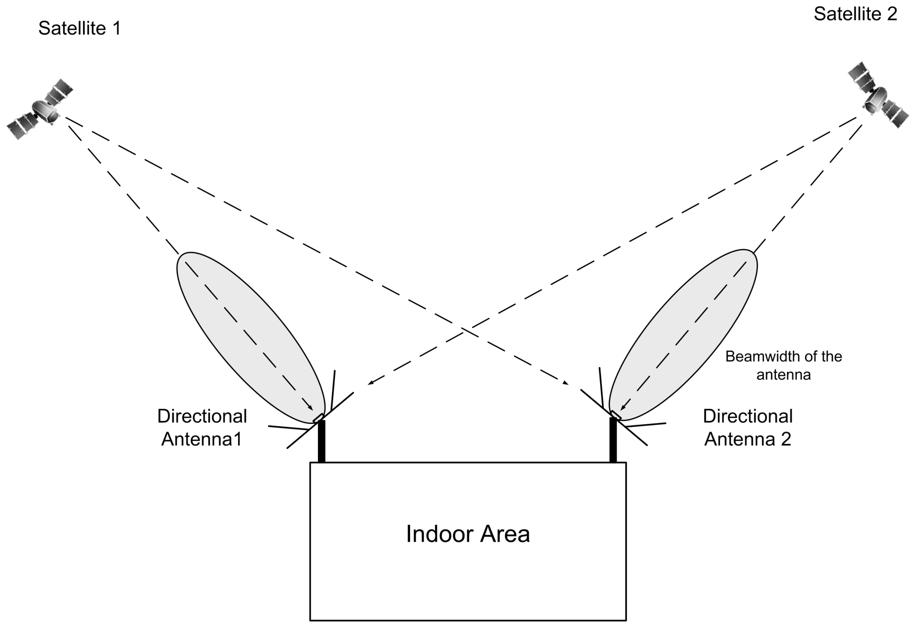


Figure 3.9: A satellite constellation scenario to analyze directivity of the antenna

3.2 Low Noise Amplifier

Amplifiers are used to increase the power of a signal. As a part of the repeater, amplifier is used to increase the power strength of the received satellite signals by directional antenna. The designed amplifier unit consists of several low noise amplifiers (LNA) and filters. In other words, it is a cascade system of LNAs and filters. Used LNAs and filters are off the shelf components.

The important criteria for the repeaters and the amplifiers are the noise figure, gain, 1 dB compression point, third order intercept point, power consumption and the filtering. Noise Figure is a ratio that shows how much noise power, the amplifier will contribute to the total received noise power. As the amplifier contributes more noise, the signal to noise ratio will degrade. The signal strength of the GPS signals that are reaching the earth surface is -130 dBm [8] which is very close to the noise floor. Therefore, signal to noise ratio of the received GPS signals are already low. Thus the additional amplifier noise should be very low. This is the most important criteria on the amplifier design.

Gain is the ratio of the input power to output power of the amplifier. Unlike noise figure, gain is not critically important in repeaters. But, it would be good to have enough gain for retransmitting the received signals. 1dB compression point and third order intercept point is related with the nonlinearities of the amplifier. Strong interferers can drive amplifiers into compression and result into suppress in the desired signal. Therefore, it is an important design constraint. Power consumption can be a criterion in repeaters as they will work with batteries. The lower the power consumption the better the amplifier is.

Bandwidth and filtering is critically important in amplifiers. If the out of band signals are not filtered out, the LNA's will amplify all the signals that are in their bands. Thus, a strong interferer will result to saturation of the amplifier. If the amplifier saturates, the desired signal will not be amplified as expected. Selection of the topology and the off the shelf components are done, in the light of these design criteria. In the following sections the selection of the topology and the selection of the components will be detailed.

3.2.1 Topology Selection

As indicated before, the most important criteria's for the GPS amplifier is the noise figure. The noise figure for cascaded systems can be calculated from Friis formula in Eq. 3.1.

$$F = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \frac{F_4 - 1}{G_1 G_2 G_3} + \cdots + \frac{F_n - 1}{G_1 G_2 G_3 \cdots G_{n-1}} \tag{3.1}$$

It is obvious that the noise figure of the first component will significantly affect the overall noise figure. If the first component has high gain, the effect of latter components on the noise figure decreases dramatically. Therefore, in order to keep the noise figure low, as a first element a LNA should be used. However, using a LNA as a first component is risky because any in band strong interferer will lead the LNA to saturation. In this manner, different topologies can be compared [14];

The topology in Fig. 3.10a, gives the best possible noise figure and gain but it does not use any filter. Therefore, any strong interferer in the bandwidth of the amplifiers will cause compression and inter-modulation. If the amplifiers saturate because of an interferer, the desired GPS signals will not be amplified as it expected. Therefore, this topology is not feasible.

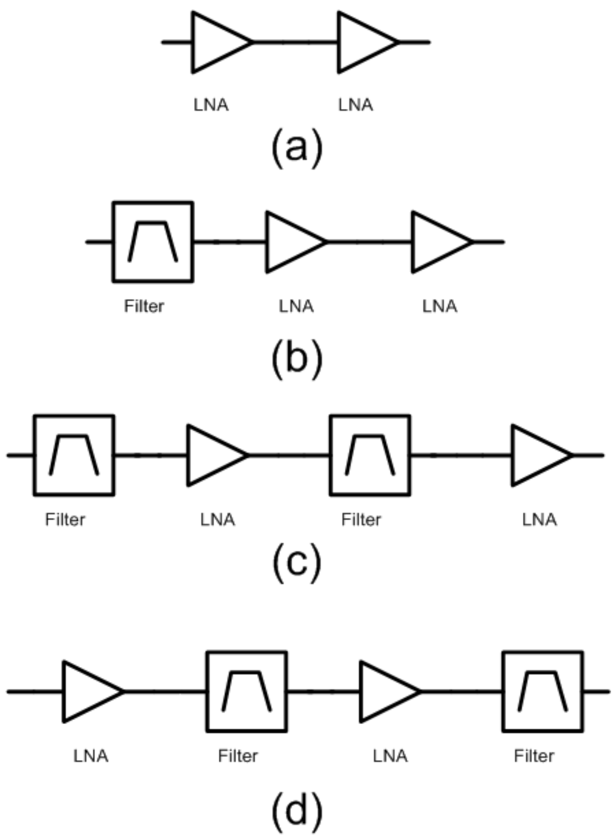


Figure 3.10: Four different cascaded amplifier topologies

The second configuration has a strong filter as a first element so it has high out of band rejection up front. This system is very robust. Strong interferers will cancel out in the filter. However, a strong filter will have a high insertion loss so high noise figure. Therefore this topology will have high noise figure.

In the third configuration, the filtering is distributed across the LNA, so one can use filters with low insertion loss which means low noise figures. This topology will give a good rejection and a better noise figure than the previous topology. However, noise figure will be still high for our application.

In the last configuration, by picking up a very robust LNA in a first stage, one can get a low noise figure and a stable active antenna. Among these four different topologies, the last topology is selected because the noise figure is vital in this application. However, in this topology 1dB compression point of the LNA should be as high as possible and it is bandwidth should be as low as possible.

3.2.2 Component Selection

As the noise figure is the most critical design parameter in this design, topology in the 3.10a is selected. After selection of the topology, many datasheets from various companies were analyzed. During the selection of the LNAs, noise figure, gain, operating voltage, operating current, bandwidth, third order intercept point and one db compression points are taken into account. In Table. 3.2, you can find the off the self LNA's and their characteristics that are appropriate for this application.

As a filter Triquint 856326 is selected because of its low insertion loss which is 0.53 dB and low bandwidth 2 MHz. In addition to this, component is matched to 50Ω at 1575 MHz.

After analyzing the components, here you can find the list of the important properties and the selected components in Table 3.3.

Table 3.2: Comparison of off-the-shelf LNAs

Company	Part	NF (dB)	Gain (dB)	V (V)	I (mA)	Freq(GHz)	IP3(dBm)	1dB Comp(dBm)
Avago	ALM-1106	0.8	14,3	3	8	0.9 - 3.5	4.7 (input)	1.8 (input)
Avago	ALM-1412	0.7	13	3	10	1.5 - 1.6	7 (input)	3.4 (input)
Hittite	HMC548LP3	1.3	21	5	21	1.2 - 3	21	11,5
Infenion	BGA615L7	0.9	18	3	5.6	1 - 2	-1 (input)	-10 (input)
MACOM	MAAL0077304	0.9	25.5	3	10	0.5 - 3	18	7
MACOM	MAALSS0042V1	1.15	27	5	20	0.5 - 3	-14 (input)	1
MACOM	MAALSS0044V1	1.55	21	3	8	1.5 - 1.6	-8 (input)	0
MAXIM	MAX2641	1.3	14.4	3	3	1.4 - 2.5	-4	-21
MAXIM	MAX2659	0.8	20.5	3	4.1	1 - 2.5	-5	-12
MAXIM	MAX12000	1	34.8	3	25	0.8 - 2	-12 (input)	-19 (input)
NEC	8231	0.8	20	3	3	1.5 - 1.6	- 10 (input)	-20 (input)
NEC	8232	0.95	17	3	3	1.5 - 1.6	-8 (input)	- 21 (input)
RFMD	2373	1.1	19	3	10	0.4 - 3	5 (input)	- 5 (input)

Table 3.3: Selected components and basic criteria of the selection

First LNA	First Filter	Second LNA	Second Filter
Low NF, Low bandwidth	Low Insertion Loss	Low Noise Figure	Low Insertion Loss
High IP3, 1dB Compression Point	Good Out of Band Rejection	Low Current, High IP3, High 1dB Comp.	Good Out of Band Rejection
Avago ALM1412	Avago ALM1412	NEC 8231	Triquint 856326

3.2.3 Budget Analysis

After selecting the components, a crude analysis is done with ADS to see the performance of the system. In this simulation, the noise figure, gain, 1 dB compression point and third order intercept point analysis is done. The simulation results can be seen in Fig. 3.11. In this analysis it can be seen that the overall noise figure is 0.873dB, 0 dBm 1dB compression point, 8.5 dB third order intercept point, 31 dB gain.

3.2.4 Modeling and Simulations of the Amplifier

GPS L1 band - 1575 MHz - is in the radio frequency band. Signals in these frequencies behave like waves; therefore transmission lines must be used to connect components. In this manner coplanar waveguide is used as the transmission lines. Coplanar waveguide, is a transmission line where there is the ground layer both in the bottom of the transmission line and also near the transmission line. The width

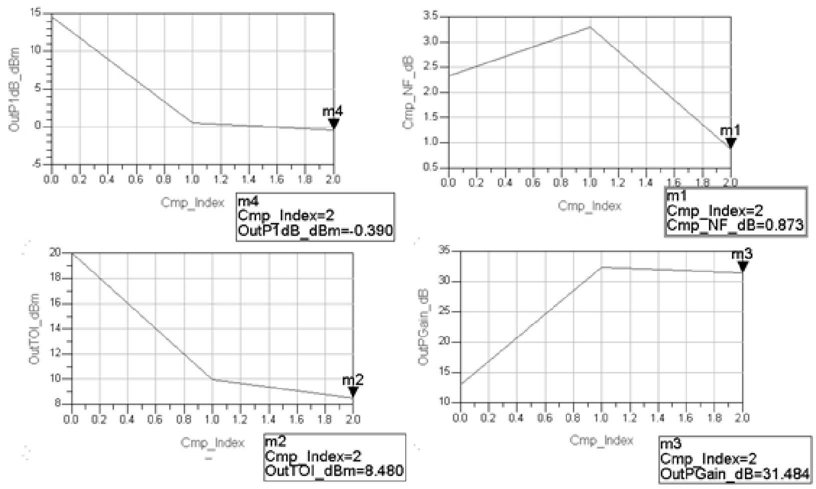


Figure 3.11: A crude budget analysis

of the transmission line and spacing with the ground are selected such that with the used board, transmission line gives 50Ω characteristic impedance. Two sided FR4 board is used for the designed circuitry where, the electrical permittivity ϵ_r is 4.16, distance between the planes is 1.6 mm and the thickness of a layer is 35μm. Calculated 50Ω coplanar waveguide has a width of 1 mm and a gap between the ground and the line is 0.2 mm. Every passive components that are used for matching is modeled. In the Fig. 3.12, a model of an inductor can be seen in the upper part. This model includes the self resonance capacitor, internal resistance and the pad of the inductor on the printed circuit board. The value of the internal resistance and the self resonance capacitor is taken from the data sheet.

In order to compare the effect of the model, a S-parameter analysis is done. In Fig. 3.13, S parameter analysis can be seen. The simulation environment can be also seen in Fig. 3.12, an inductor that is only connected with the transmission line is in the lower part and the modeled inductor is in the upper part. As seen in the results, the model is effective and should be used during impedance matchings.

The used capacitors are also modeled, however the effect of the capacitors is lower than the effect of the inductors. The internal inductances of the capacitors are low so only effect comes from the PCB pad modeling. The model of the capaci-

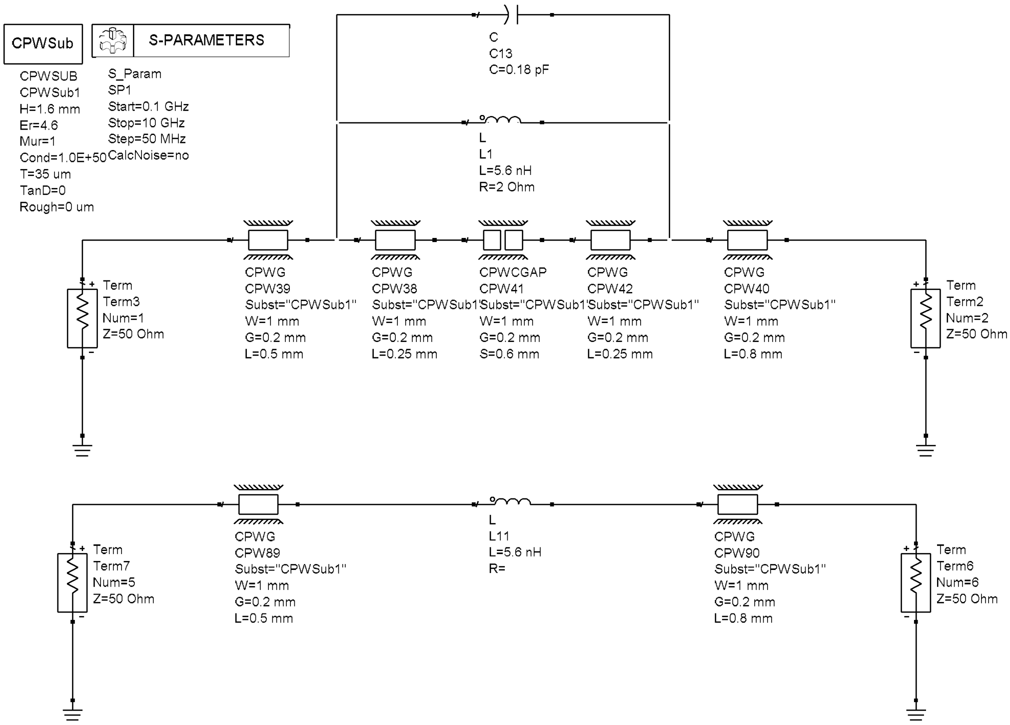


Figure 3.12: PCB model of an inductor and basic inductor

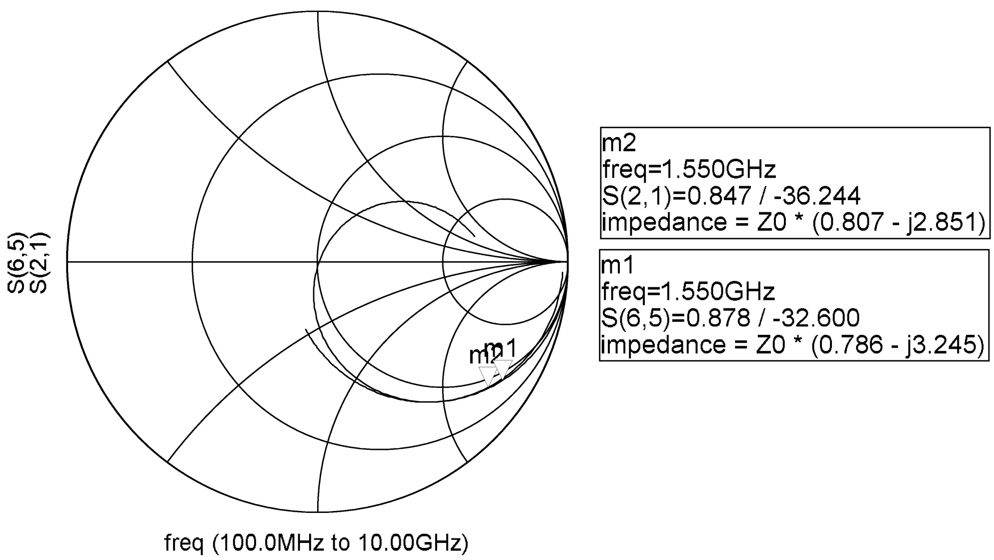


Figure 3.13: S parameter analysis of a inductor and a inductor with a PCB model

tor can be seen in Fig. 3.14, and the simulation results where the effect of the model is shown can be seen in Fig. 3.15.

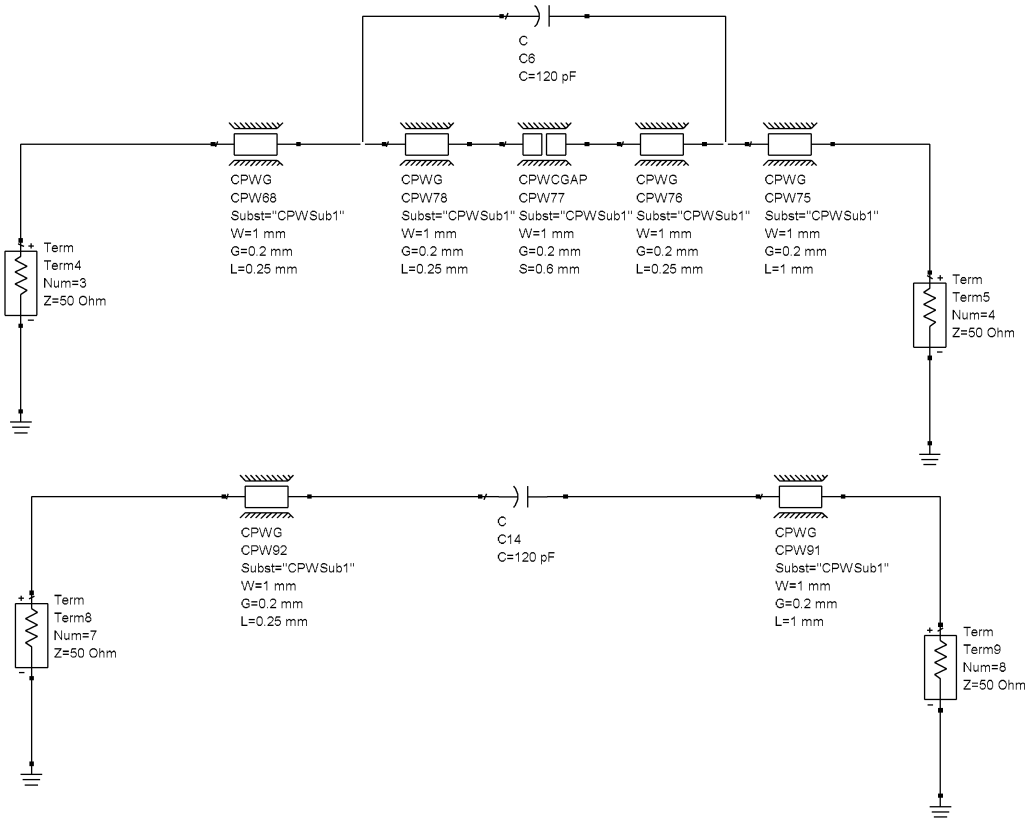


Figure 3.14: PCB model of a capacitor and basic capacitor

After modeling the passive components, input, output impedance matching of the off the self LNA's are done. ADS models of the LNA's and filters are used for this simulation and matchings are done with passive elements that are modeled. The schematic of the overall system can be seen with the matchings in Fig. 3.16.

The s parameter simulation results of the overall system with reference to 50Ω system can be seen in Figs. 3.17, 3.18. Input reflection coefficient - S11 - of the overall system is -13.4 dB. Output reflection coefficient of the overall system -S22- is -13.9 dB, which indicates the system is matched to 50Ω. Gain of the amplifier so the S21 is 30.3 dB which is highly satisfactory.

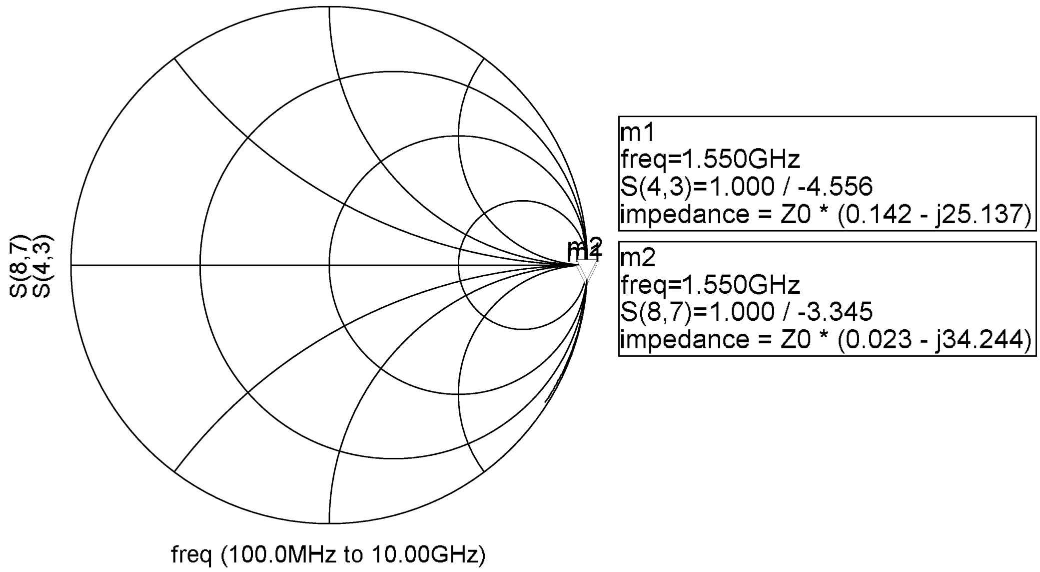


Figure 3.15: S parameter analysis of a capacitor and a capacitor with a PCB model

3.2.5 Layout

The layout is designed with program Eagle 4.16. Transmission lines are coplanar wave guides and the size of coplanar wave guide is drawn with respect to the simulations. Distance of every component is drawn based on the distances in the simulations. The layout is in Fig. 3.19(a). The placement of the components on the layout can be seen in Fig. 3.19(b).

This layout is printed on a FR4 board by lithography and wet etching and every component is soldered. The manufactured amplifier is shown in Fig. 3.20. The outer space of the amplifier is covered with FR4 board and this is grounded to protect the amplifier from outer interferer and also from the output of the amplifier. The manufactured amplifier can be seen in Fig. 3.21.

3.2.6 Measurements

The measurements are done with both spectrum analyzer and network analyzer. The results of the spectrum analyzer is in Fig. 3.20. The results of the network ana-

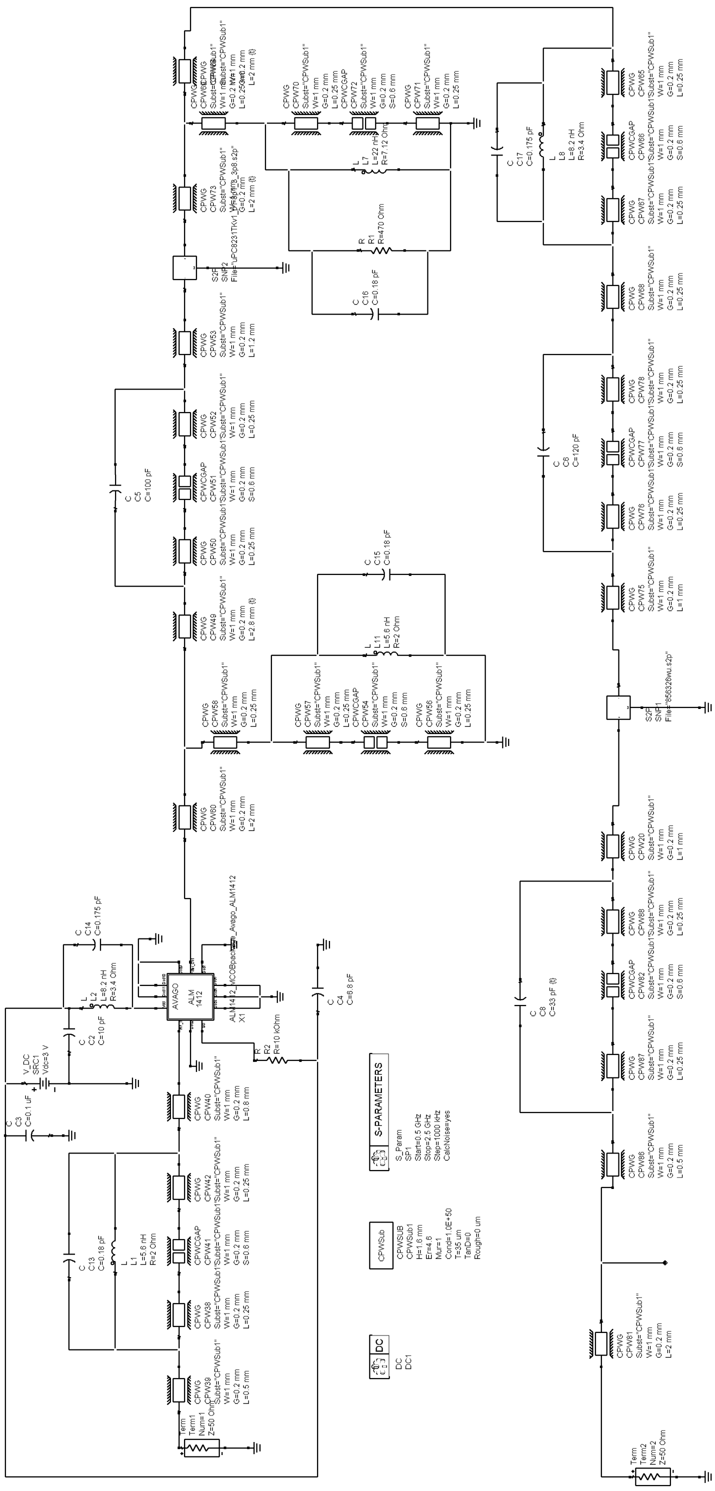


Figure 3.16: Schematic of the amplifier

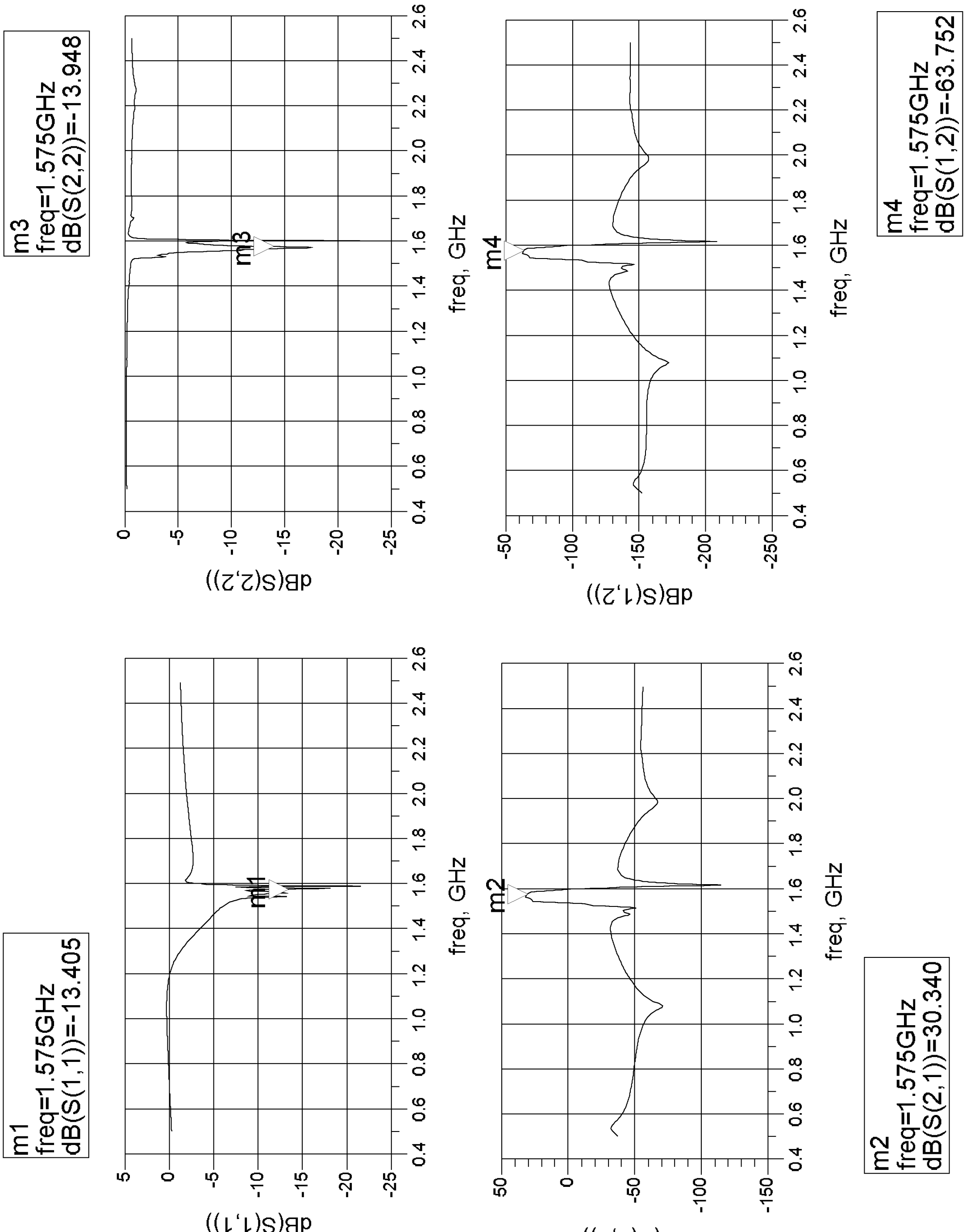


Figure 3.17: Wide band S-parameter results of the amplifier

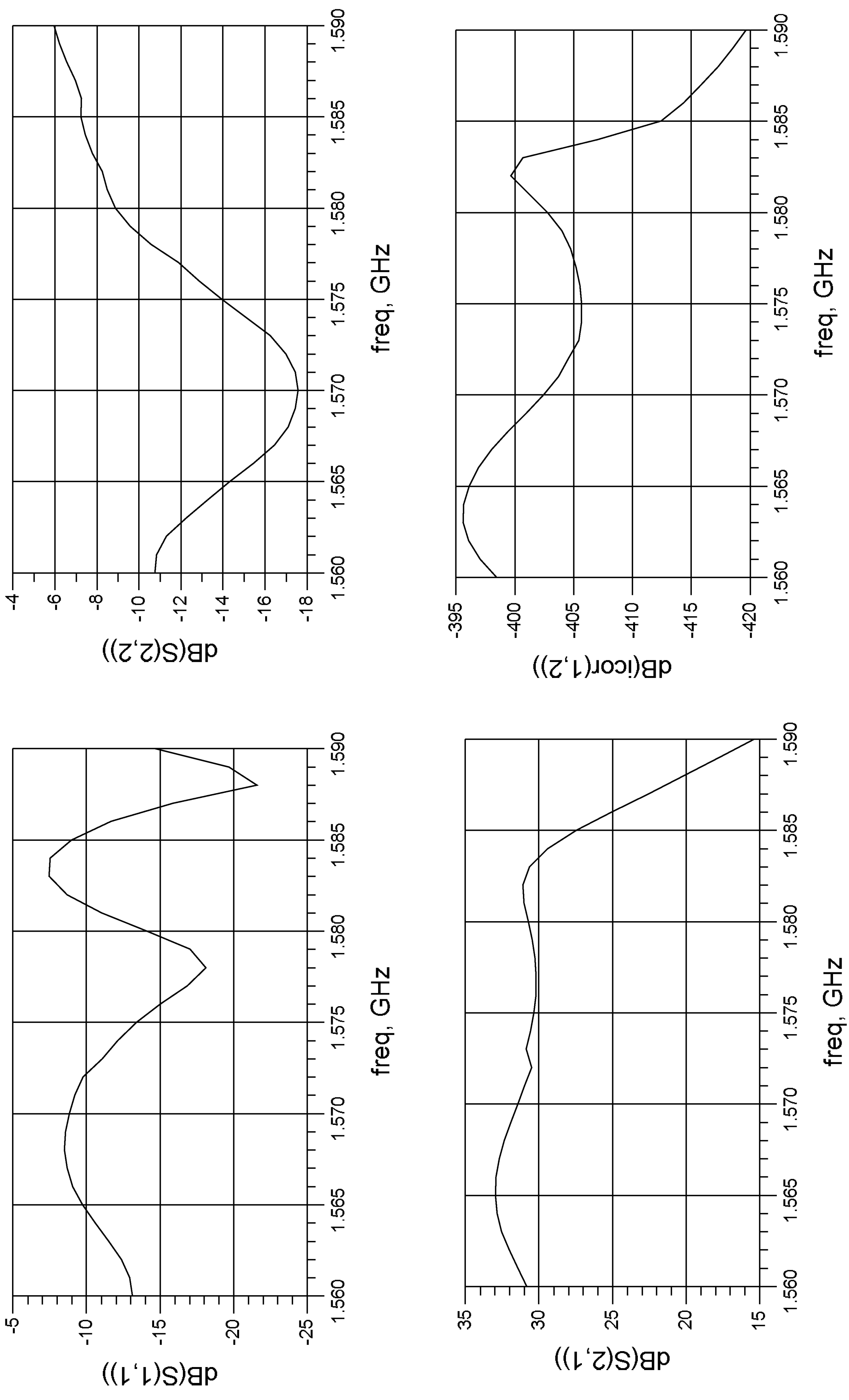
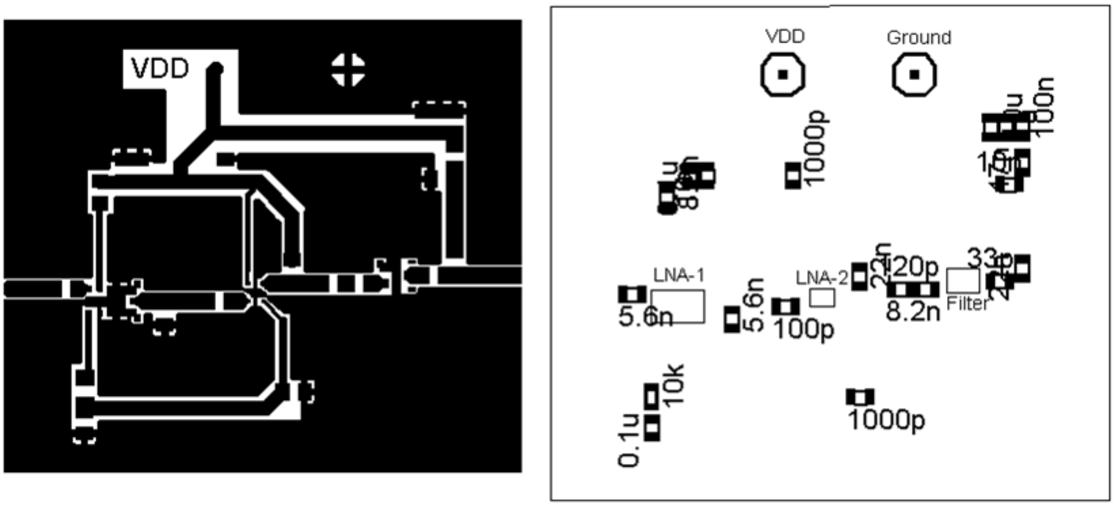


Figure 3.18: Narrow band S-parameter results of the amplifier

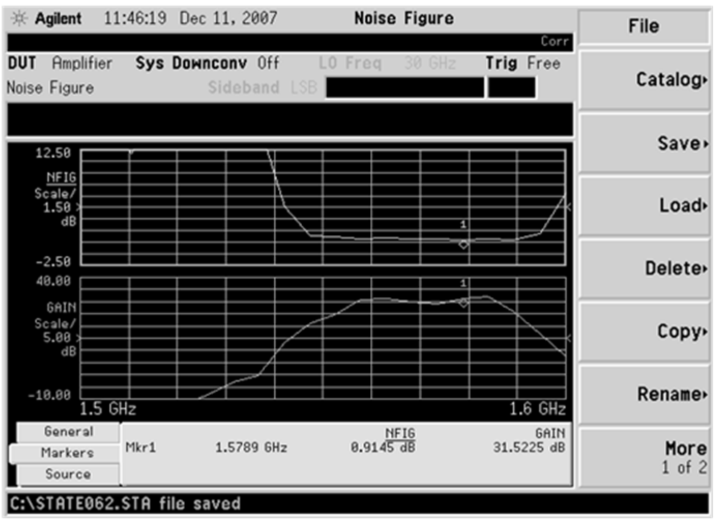


(a) (b)

Figure 3.19: Layout of the amplifier and the orientation of the components in the layout

Frequency	Noise Figure	Gain
1557894737	0.934067	30.8887
1563157895	0.979695	31.6277
1568421053	0.957098	30.3162
1573684211	**0.88767**	**29.3877**
1578947368	**0.949011**	**31.1288**
1584210526	0.928858	32.3887
1589473684	0.864489	26.5897
1594736842	1.60425	16.9561

(a)



(b)

Figure 3.20: Noise figure and gain measurements of the amplifier

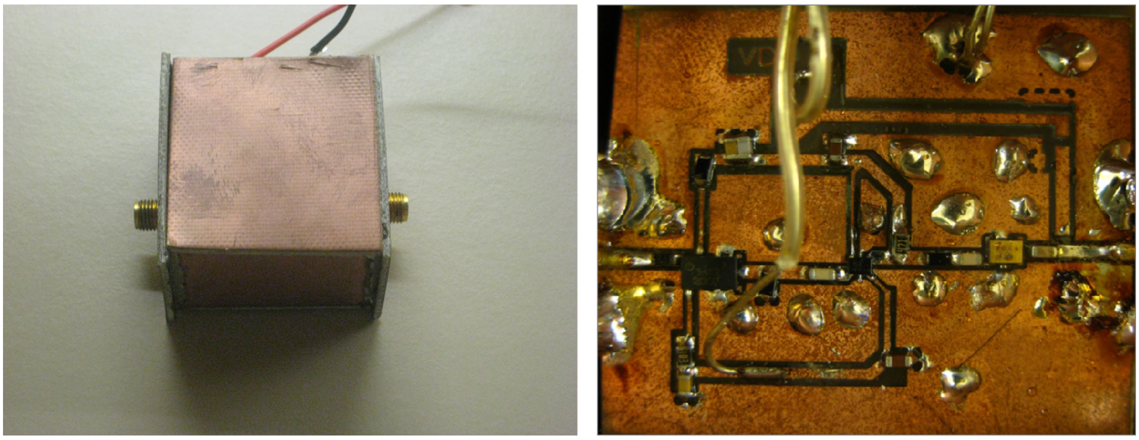


Figure 3.21: Manufactured amplifier

lyzer is in Fig. 3.22. The measurement results are well matched with the simulation results which is shown in Fig. 3.17.

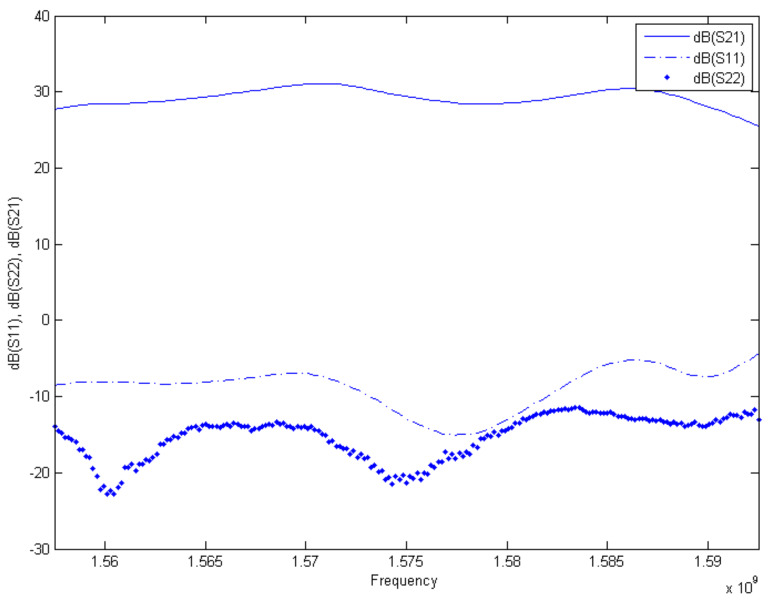


Figure 3.22: Measured S-parameter results of amplifier

In addition to S parameter results, group delay of the amplifier is also measured with network analyzer. The group delay is measured for 2 amplifiers that are manufactured. The group delay measurements are seen in Fig. 3.23.

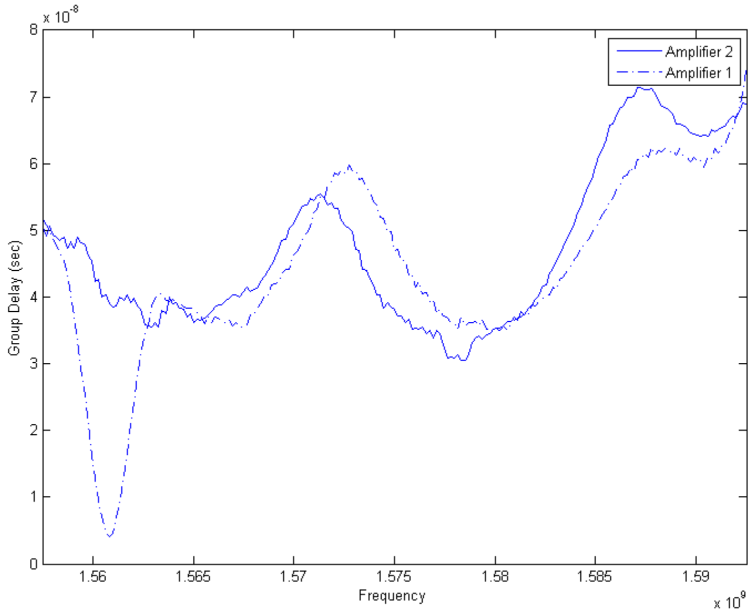


Figure 3.23: Measured group delay results of two manufactured amplifiers

3.3 GPS Receiver

All of the standard GPS receivers are able to decode GPS satellite signals and calculate position. These standard receivers communicate with a microprocessor by universal asynchronous receive and transmit (UART) and sent position related data. However, in order to validate the indoor positioning system, encoded navigation data which includes ephemeris and pseudorange measurements are needed. Some special GPS receivers are able to give these raw data. One of these special GPS receivers is LEA-4T from U-blox Company. This receiver is selected because it is a highly sensitive receiver, it communicates both with RS232 ports and USB ports, it is capable of extracting 10 Hz data and lastly it has a well documentation for its functions.

3.3.1 Hardware of the Receiver

A prototype board is designed for the GPS receiver. The schematic and layout of the board are designed with EAGLE. In the prototype board, a USB and RS232 ports are put for communication. Also, board has a 5 volts and 3 volts inputs for

DC supply. The schematic of the board can be seen in Fig. 3.24.

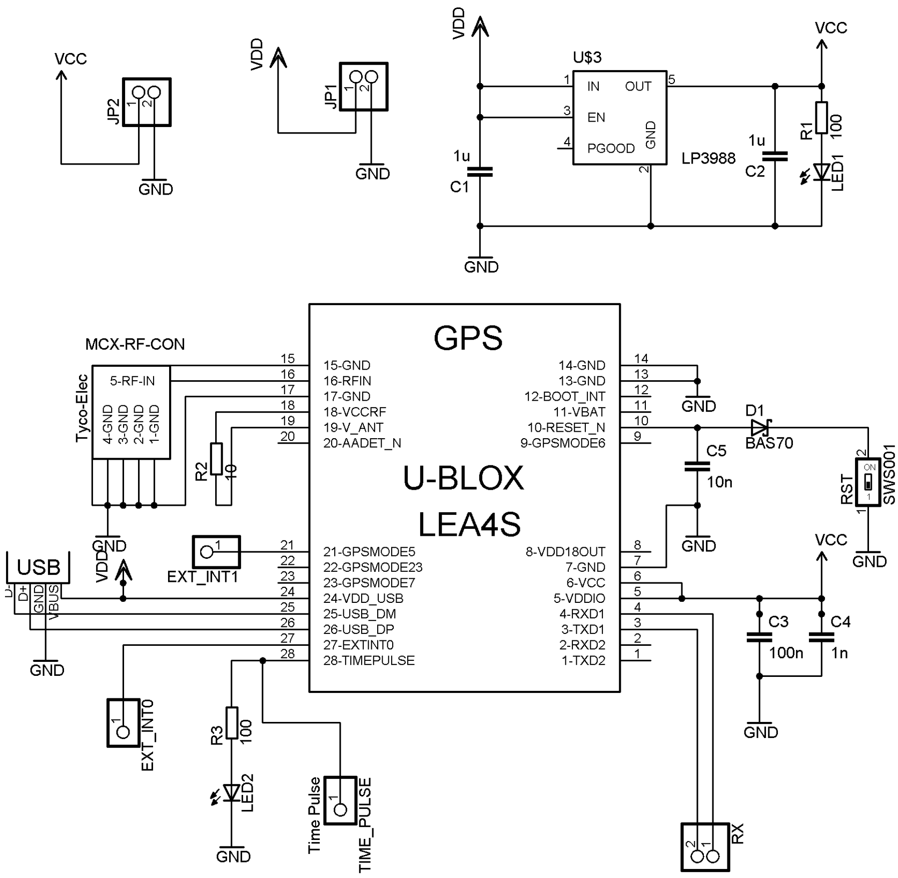


Figure 3.24: Schematic of the GPS receiver circuitry

The mask of the layout and the orientation of components in the board can be seen in Fig. 3.25.

The board is made by lithography and wet etching. After wet etching the components are soldered to the PCB. The prototyped board can be seen in Fig 3.26.

3.3.2 Interface of the receiver and Data acquisition

Data acquisition with GPS receiver is done through Matlab. The data acquisition is created by defining the COM port and the UART properties of the protocol such as baud rate, parity and etc. An example of defining a serial port and getting data

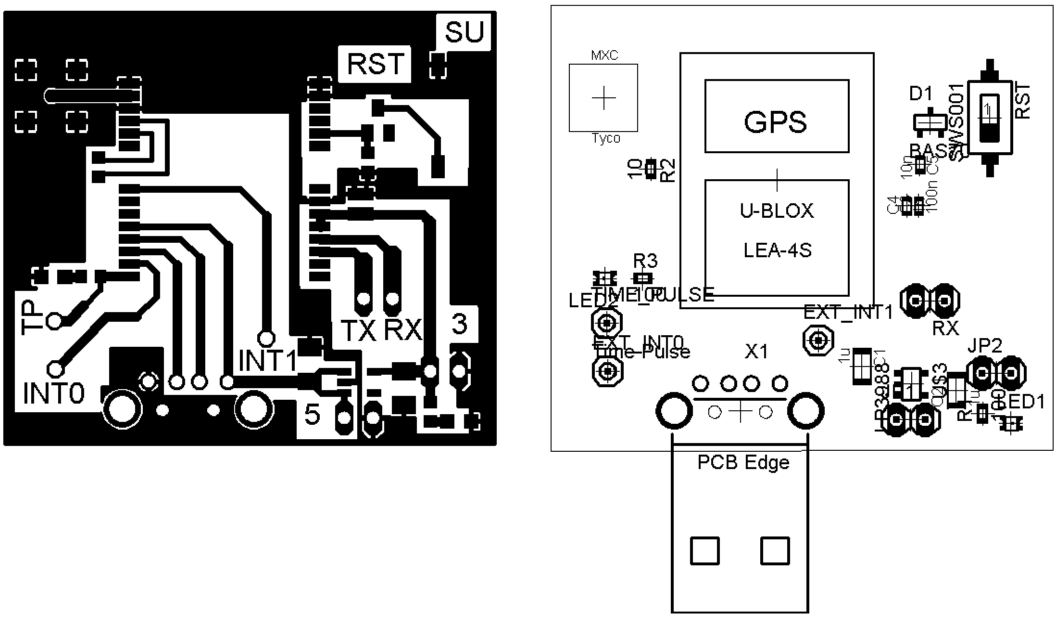


Figure 3.25: Layout of the GPS receiver circuitry and the orientation of the components in the layout

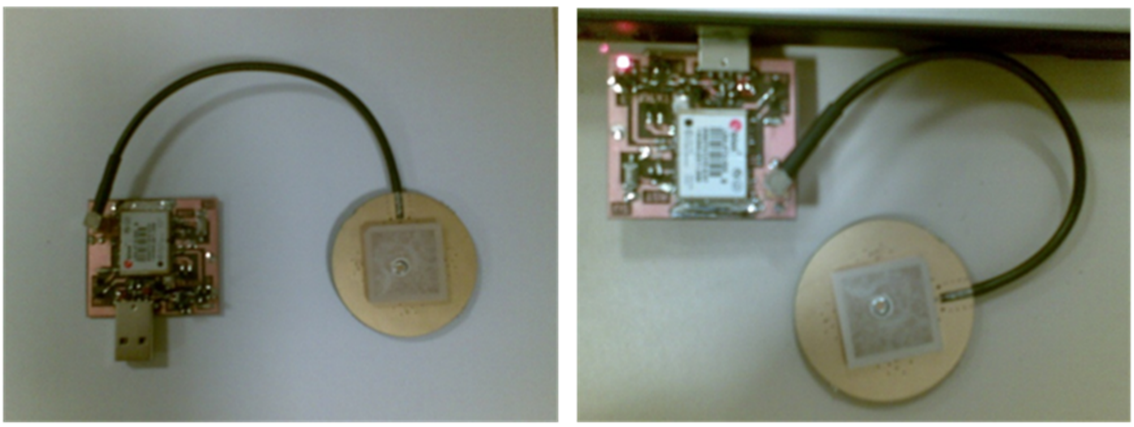


Figure 3.26: Manufactured GPS receiver circuitry

in Matlab can be seen below.

comPortStr='COM3';
SerialPort=serial(comPortStr,'BaudRate',19200,'DataBits',8,...
'FlowControl','none','Parity','none','StopBits',1,'terminator','CR/LF',...
'InputBufferSize',512); fopen(SerialPort);

In this example, the COM port is set to COM3. The USB connection is set through COM3 serial port. Baud Rate, data bits, flow control, parity, stop bits and the termination are set to the default parameters that are used by LEA-4T. Lastly, the size of the input buffer is set. This input buffer is used to keep received data until it is read internally.

3.3.3 Getting Data from GPS Receiver

LEA-4T uses U-blox receiver specific (UBX) binary data. After creating data acquisition between computer and receiver through serial port, binary data in the UBX format can be taken with MATLAB. In order to resolve data from UBX binary data, structure of packets is analyzed and data is resolved with function "fread" respectively to its specific formats such as signed, unsigned integers or floating points. The structure of the packet that is sent from the receiver can be seen in Fig. 3.27.

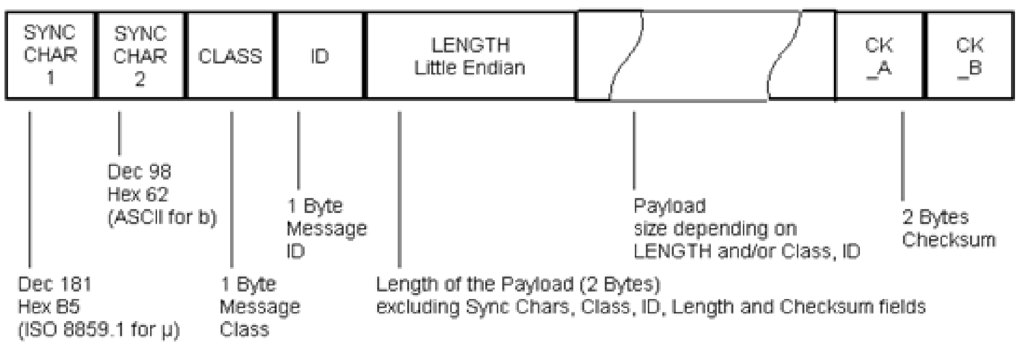


Figure 3.27: Structure of data packet sent by LEA-4T [1]

In order to get data from receiver, special messages are sent which is called polling. Data came serially in the payloads, and it should be resolved according to the binary protocol. The types of the data can be seen in Table. 3.4.

Table 3.4: Types of binary data sent by LEA-4T

Short	Type	Size (Bytes)	Comment	Min/Max	Res
U1	Unsigned Char	1		0 - 255	1
I1	Signed Char	1	2's complement	-128 - 127	1
U2	Unsigned Short	2		0 - 65535	1
I2	Signed Short	2	2's complement	-32768 32767	1
U4	Unsigned Long	4		0 - 4294967295	1
I4	Signed Long	4	2's complement	-2147483648 - 2147483647	1
R4	IEEE 754 Single Precision	4		$2^{+}127$ - $2^{+}127$	$2^{-}24$
R8	IEEE 754 Double Precision	8		$2^{+}1023$ - $2^{+}1023$	$2^{-}53$

RXM RAW data is polled for pseudoranges measurements. Pseudorange measurements of all satellites are gotten with the reception time of the receiver. Also, by polling RXM RAW data, GPS week, number of visible satellites, carrier phase measurements, dopler measurements, message quality and lastly carrier over noise ratio of all the measurements can be gotten. Content of the RXM RAW data can be seen in Appendix A.

By polling the receiver with the code of the RXM-EPH, ephemeris is also taken from the receiver. Content of the RXM-EPH can be seen in Appendix B. The sub frames that are sent by the satellites are directly given by the receiver when it is polled with the code of RXM-EPH. The parameters of the ephemeris must be extracted from these sub frames. The full description of the sub frames are in ICD-GPS-200 document [15]. In addition to the pseudorange and ephemeris, clock solution (NAV-CLOCK) of the receiver, ionospheric correction parameters (AID-HUI) and satellite vehicle information such as the elevation and azimuth angle calculations (NAV-SVINFO) are taken from LEA-4T similarly [16].

3.4 Repeater

Repeaters are combination of two antennas and an amplification unit. The main aim of the repeater is to receive a signal, amplify it and then retransmit it again. In order to transmit GPS signals to an indoor area, repeaters are used. As the receive antenna of the repeater, designed directional antennas are used. As the amplification unit, the designed amplifier and an additional amplifier is used. This additional amplifier has 15 dB gain. It is used to cover a larger indoor area. As this amplifier comes after the designed amplifier, the effect on the noise figure is negligible. Lastly as the transmit antenna standard off the shelf GPS antenna is used. The combined system can be seen in Fig. 3.28. After the design of the repeaters path loss measurements are done to observe the indoor radio propagation of GPS signals.

Indoor radio propagation varies from the conventional outdoor radio propagation. Difference mainly stems from two aspects. Distances between the transmitter and the receiver are too small in indoor areas and secondly indoor environment is highly unpredictable. As in the outdoor radio propagation, scattering, reflection and diffraction are the mechanisms that affect propagation in the indoor areas. However, in indoor areas, the effects of these mechanisms are much higher than the outdoor areas[3]. Therefore, as the indoor environment changes, the propagation pattern of the radio signals also changes. The plan of the area, walls, movement in the area, construction materials and building type highly affect the propagation. However, a path loss measurement is done in specific environments to have an idea of the path loss in the closed areas.

3.4.1 Path Loss Measurements

Path loss measurement is basically the measurement of the power loss between the transmitter and the receiver antennas with respect to the distance between them. There are many methods that are used to measure the path loss. Some of them depend on the measurement instruments and some of them use transmitters and receivers. In here path loss measurements are done with GPS receiver as the U-Blox

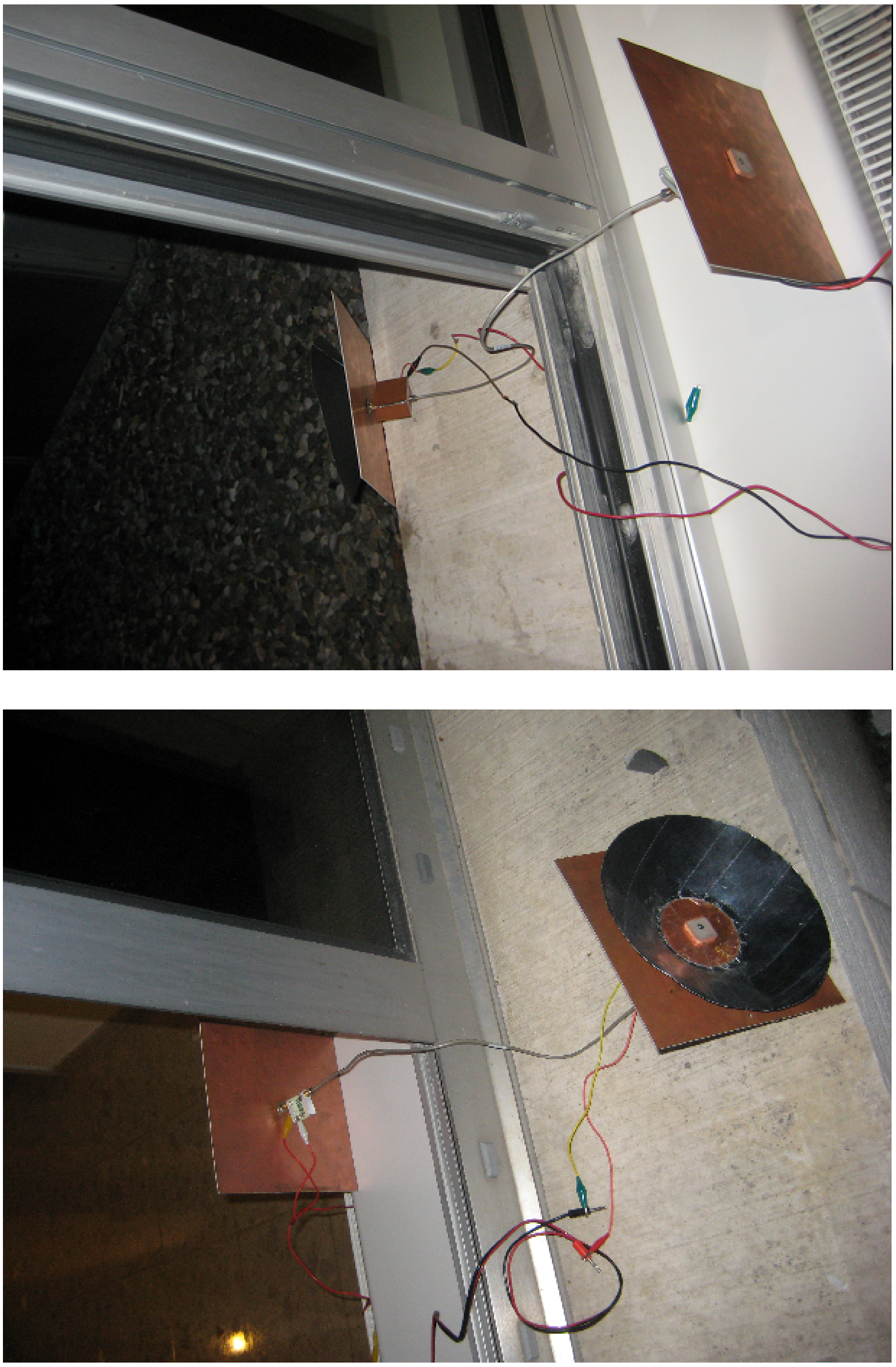


Figure 3.28: Repeater

LEA-4T GPS receiver can give the signal strength of the GPS signals with respect to the satellites.

By using repeaters, GPS signals that are coming from the satellites can be amplified and transmit to the indoor areas and the signal strength can be measured. In order to find the indoor path loss, signal power at the repeater must be known. By measuring the transmitted power at one receiver and the measuring the received power at other receiver, the attenuation can be found. In order to learn reference signal level at the repeater, a second GPS receiver is used. After amplifying the signal that is coming from the satellite, signal is divided into two equal signals with a splitter. Half of the power is send to indoor area by an antenna and the other half is sent to GPS receiver to log the signal strength at the repeater. The signal strength levels at the repeater and the receiver is logged with GPS time stamps so that the path loss between repeater and receiver can be calculated. The measurement setup can be seen in Fig. 3.29.

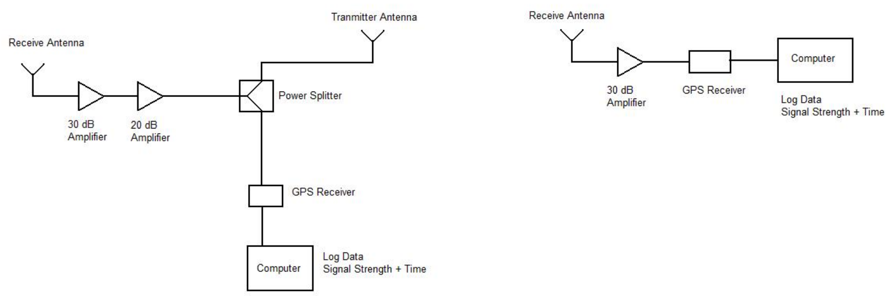


Figure 3.29: Measurement setup for path loss measurements with GPS receiver

As it seen from the figure, the signals that are coming from the satellites are amplified through the amplifiers than the power is divided into two. One of them is sent to a GPS receiver and the signal strength and the time is logged. Other half of the signal is sent to an antenna and transmitted in to the room and then the transmitted signal is received by another GPS receiver and the signal strength and the time is logged. As a result, the transmitted power from the repeater and the received power are known with time stamps so that the path loss can be extracted.

The measurements are done in room FENS 1033. The layout of the room can be seen in fig 3.31. Photo of the setup can be seen in Fig. 3.30.

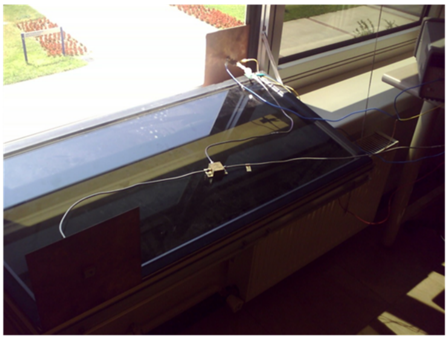



Figure 3.30: Measurement setup for path loss measurements with GPS receiver

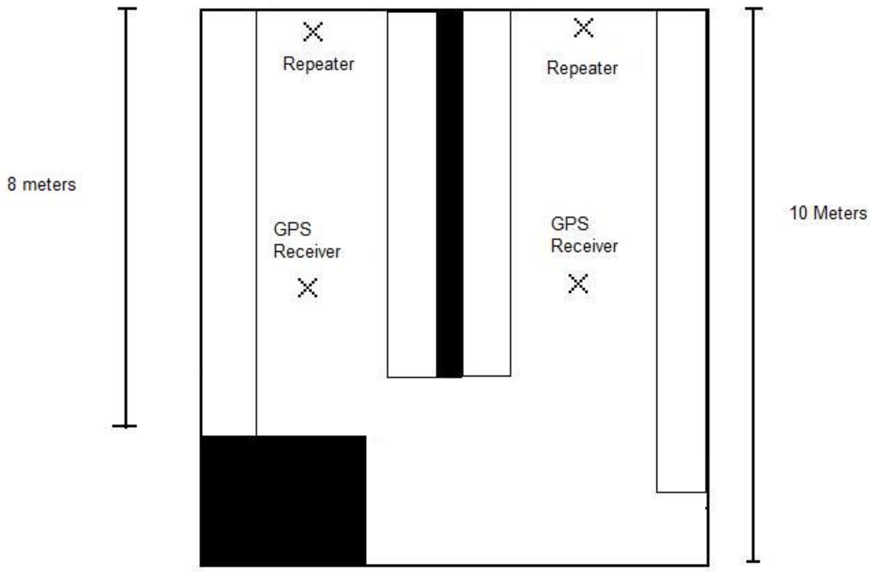


Figure 3.31: Layout of the room for the path loss measurements with repaters and GPS receiver

Measurement are done both for the left and right part of the room. Two antennas firstly separated by 1 meter and then with one meter increment of the distance, measurement are done. In every meter, 100 signal strength measurements are taken. The result of the propagation loss in the left part of the room with respect to distance loss can be seen in Fig. 3.32.

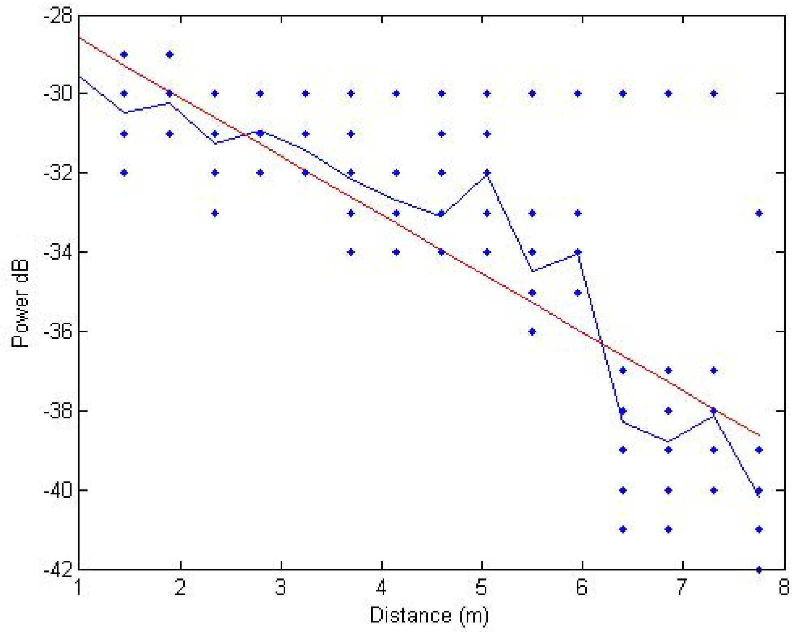


Figure 3.32: Path loss measurement I

Blue dots shows the signal level that is measured at each distances. The blue line shows the mean of the 100 signal strength measurements at each distance. The red line is the linear line fit polynomial with respect to the mean signal strength. Because the indoor environment is open to reflection, diffraction and scattering, the signal strength at each point varies. However, mean of the measured signal strengths decreases as the distance between the repeater and the receiver increases, as it is expected. Second measurement is done at the right part of the room. Again the measurement parameters were the same and at each point again 100 measurements are taken. The result of the propagation loss can be seen in Fig. 3.33.

Again, the blue dots shows the measured signal strengths at each distance, blue line show the mean signal strength at the each distance and the red line shows the linear polynomial that fits the mean signal strength. Again signal level varies a lot at each distance. However, the mean of the signal strength measurements show decay with the distances as it is expected.

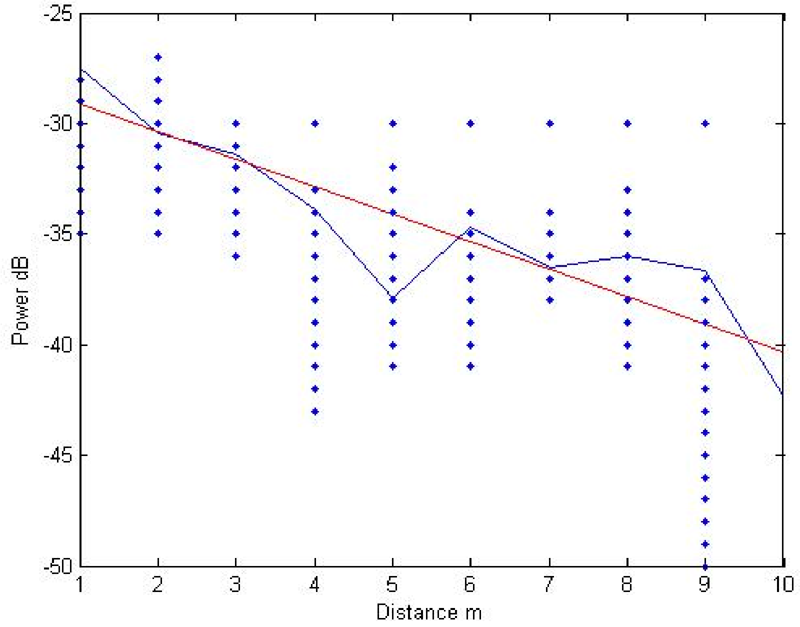


Figure 3.33: Path loss measurement II

3.4.2 Path Loss Model

There are many types of propagation loss models. However, many of these models are made for outdoors such as free space, two ray, Okumura model, Hata model, Extended Hata model etc. As the indoor models, researches shows that the signal path loss obeys the Log distance path loss model [17]. The logarithmic distance path loss model is Eq. 3.2.

$$PL(dB) = PL(d_0) + 10n\log(\frac{d}{d_o}) + X_\sigma \tag{3.2}$$

Where the path loss exponent "n" depends on the building type, surroundings, layout of the indoor area and $X\sigma$ represents a normal random variable in dB having a standard deviation of σ. The calculated path loss exponent and standard deviation can be seen in Table. 3.5.

As it seen from the table, path loss exponent is smaller than the free space path

Table 3.5: Path loss measurement results

Parameter Measurement Type	Path loss Exponent "n"	Standard Deviation X_σ
Measurement at the left of the room	1.15	2,93
Measurement at the right of the room	1.1	4.03

loss component. The reason for this is that the reflected, scattered and diffracted signals add up at the receiver in this experiment so that the signal level becomes higher than it would be.

Chapter 4

Software of the Indoor Positioning System

In the previous chapter, hardware design of the indoor positioning system is explained. With the designed hardware, GPS satellite signals are received by the repeaters and then re-transmitted to indoor areas. Thus, the indoor coverage of the GPS is provided. However, line of sight courses of the GPS signals are curved by retransmitting the signals with repeaters. This curvature results in wrong positioning with standard GPS receivers. In order to remove the effects of the repeaters and find the correct position of the receiver, a set of algorithms is designed and implemented. These algorithms and their implementation will be explained in this chapter.

Proposed indoor positioning system uses triangulation to find the position of the receiver. Triangulation uses line of sight distance measurements from several reference points. After finding line of sight distances from the reference points, by using basic geometry positioning is done. The classical triangulation can be seen in Fig. 4.1, where P1, P2 and P3 are reference points and the R1, R2 and R3 are the measured distances between the reference point and the receiver or the target, by intersecting three circles the position can be found.

In the proposed indoor positioning system, repeaters are used as reference points and the distance of the receiver with respect to several repeaters are found for triangulation. Calculation of the distance between the repeater and the receiver requires several tasks. A block diagram that shows the overall process is shown in Fig. 4.2. First of all, pseudoranges measurements, ephemeris of each satellite, clock

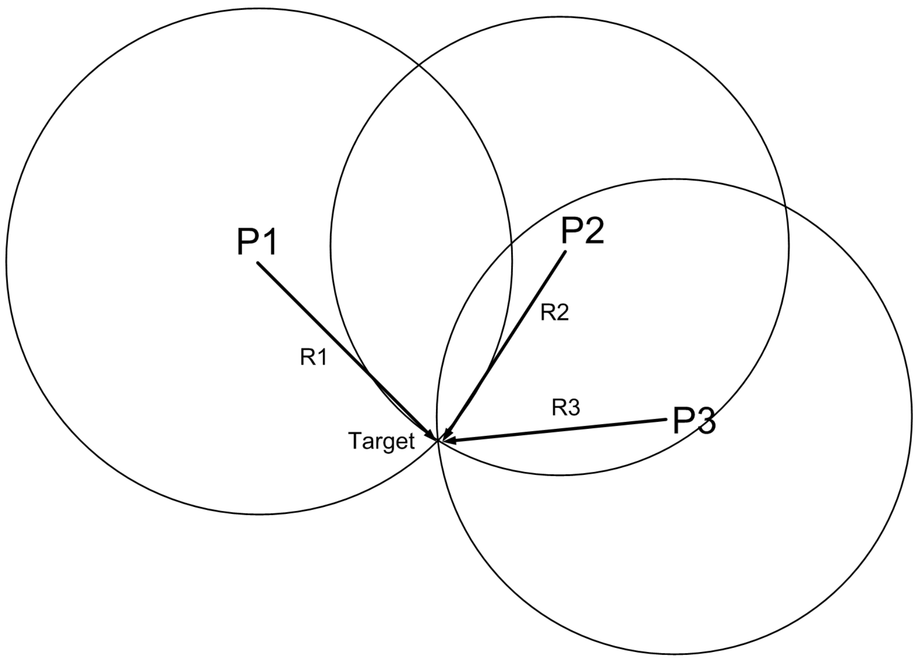


Figure 4.1: Basic triangulation

solution of the receiver and lastly the ionosphere parameters are gotten from GPS receiver. Pseudorange measurements are the distance measurements of the receiver. Ephemeris is used for satellite calculation. Clock solution of the receiver is the clock bias solution that is found by the receiver itself. Lastly, ionosphere parameters are used to decrease the effects of the ionosphere which will be detailed in the next sections.

After getting ephemeris, the satellite positions can be calculated. However, in order to calculate the satellite positions accurately, distance between the receiver and the satellite must be known, clock offset of the receiver must be solved and lastly satellite clock offset must be removed. Satellite clock offset and the receiver clock offset must be removed to create a synchronous system. Actual distance between the satellite and the receiver is needed to calculate the propagation time of the signals so that the satellite position can be found at the emission time of the signal. Therefore, in order to calculate the satellite positions, clock solution of the receiver and the actual distance is needed. However, these parameters are calculated after the calculation of the satellite position. As these parameters are not calculated yet, satellite position is calculated iteratively where the clock solution of the

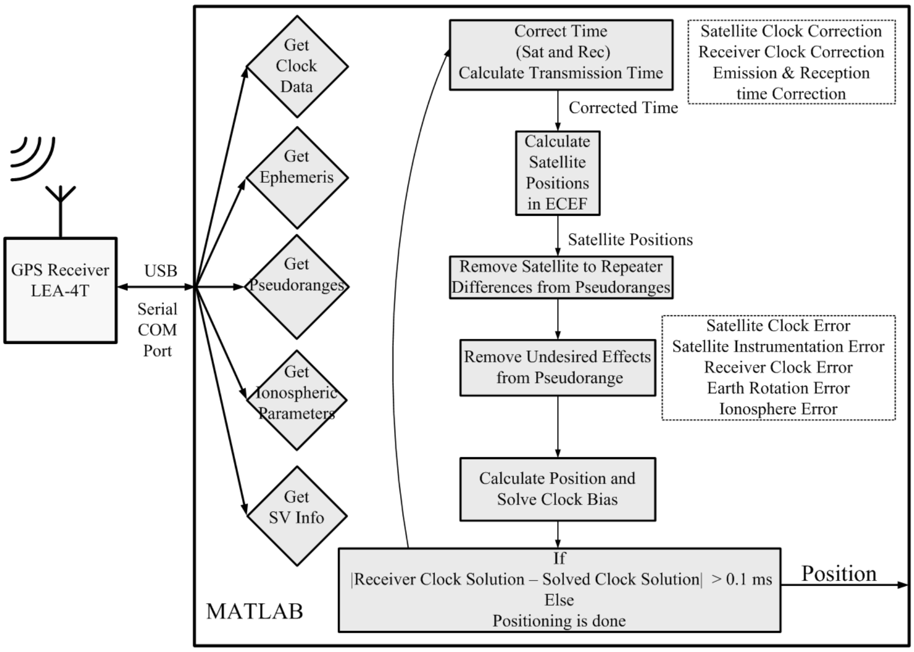


Figure 4.2: Block diagram of the used algorithms

receiver is used as a starting point for clock bias and pseudorange measurement is used as a start point for the actual distance between the satellite and the receiver. By iterating the solution, satellite positions can be calculated. Mathematics behind the calculation of the satellite will be explained in the next sections. After the calculation of satellite position, distance between the satellite and the repeater can be easily calculated. If the total distance between the satellite and a receiver is known, the distance between the repeater and the receiver can be found by subtracting the distance between the satellite and the repeater. Total distance can be found from the pseudorange measurements. However, there are many undesired effects that add up to pseudorange measurements. These undesired effects stem from the wave propagation in the ionosphere and troposphere layer, instrumentation errors of the satellites, satellite clock offset, receiver clock offset, earth rotation during the transmission of the signals, and repeater delay. All the undesired effects can be removed by using models and parameters that are gotten form the GPS receiver except receiver clock offset. Elimination of these effects will be detailed in the next sections. After removing these effects from the pseudorange and subtracting the satellite to repeater distance from the total distance, repeater to receiver distance plus the clock error can be calculated. By applying the same procedure to other satellite signals that are re-transmitted to indoor area from different repeaters triangulation can be made. In this point, it is important to solve the receiver clock offset. Therefore, for 2D positioning 3 repeaters are needed and for 3D positioning 4 repeaters are needed. As the clock offset is same for all measurements, it is a variable that is solved during positioning. One should note that this process is iterative. In the next sections, the calculation of the satellite position and the elimination of the undesired effects will be explained in detail.

4.1 Finding Satellite Positions

Satellite positions are calculated from the ephemeris that is transferred with the navigation message of the GPS. Ephemeris includes Keplerian orbital parameters, correction for Keplerian orbital parameters and satellite clock information. From these parameters the coordinate of the satellite in a given time can be calculated. The list of ephemeris parameters are in Table. 4.1. These, parameters can be gotten by the GPS receiver LEA-4T.

As a coordinate system, Earth Centered Earth Fixed (ECEF) is used. The main reason of using this coordinate system is that the final positioning is done over the world so it is convenient to use an earth centered coordinate system. Basically, this coordinate system is a right handed Cartesian system which is based on x, y and z. The origin of the ECEF coordinate system is the Earth mass center. The z axis is the mean rotation axis of the earth. X axis shows Greenwich meridian and the y axis complete the Cartesian [18]. The ECEF coordinate system and the orbital plane can be seen in Fig. 4.3.

The satellite positions should be calculated in ECEF coordinate system. Finding satellite positions from the ephemeris parameters are trigonometric calculations that are specified in Interface control document of GPS (ICD-GPS-200) [15]. These equations can be found in Appendix D. Kai Borre's Easy Suite is used for the implementation of satellite positioning in MATLAB [19]

Table 4.1: Ephemeris parameters

M_0	Mean Anomaly at Reference Time
Δn	Mean Motion Difference From Computed Value
e	Eccentricity
$\sqrt{A}$	Square Root of the Semi-Major Axis
Ω_0	Longitude of Ascending Node of Orbit Plane at Weekly Epoch
i_0	Inclination Angle at Reference Time
ω	Argument of Perigee
$\Omega\cdot$	Rate of Rigth Ascension
IDOT	Rate of Inclination Angle
C_{uc}	Amplitude of Cosine Harmonic Correction Term to the Argument of Lattitude
C_{us}	Amplitude of Sine Harmonic Correction Term to the Argument of Lattitude
C_{rc}	Amplitude of Cosine Harmonic Correction Term to the Orbit Radius
C_{rs}	Amplitude of Sine Harmonic Correction Term to the Orbit Radius
C_{ic}	Amplitude of Cosine Harmonic Correction Term to the Angle of Inclination
C_{is}	Amplitude of Sine Harmonic Correction Term to the Angle of Inclination
t_{oe}	Reference Time Ephemeris
IODE	Issue of Data

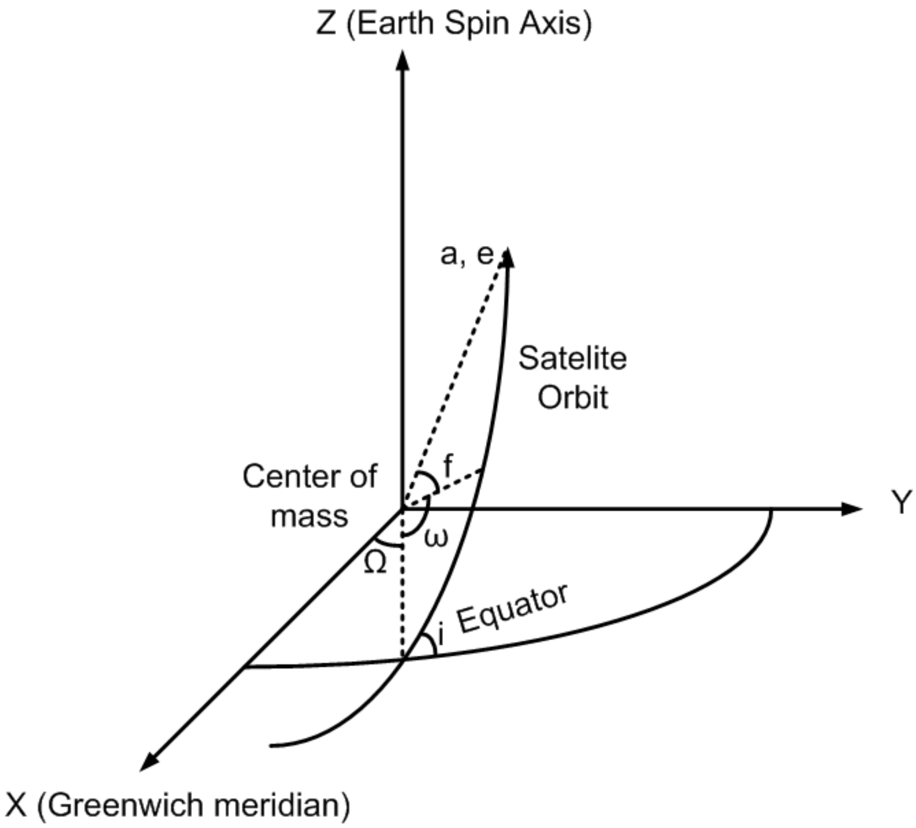


Figure 4.3: Orbit of a GPS satellite in ECEF coordinates

Time is the important point in this calculation. The satellite clock corrections, receiver clock corrections must be done before calculating the satellite positions also the positions of the satellites must be calculated in the transmission time. The propagation delay of the signals should be subtracted from the reception time and the satellite position should be calculated at the time the satellite transmit the signal. Propagation time can be found by dividing the total distance to the speed of waves. However, before finding positions of the receiver, the satellite positions must be calculated, and for finding receiver position, satellite positions must be calculated. In addition to this, clock bias also need be solved to find the satellite position exactly. In order to overcome these problems, an iterative solution is used where the pseudorange and the clock solution of the receiver is used as the first estimations.

4.2 Elimination of Undesired Effects

Distance measurements of the receivers with respect to each satellite contains not only the line of sight distance between them, but also includes some undesired effects. These undesired effects should be eliminated before positioning. These undesired effects stem from the wave propagation in the ionosphere and troposphere layer, instrumentation errors of the satellites, satellite clock offset, earth rotation during the transmission of the signals, receiver clock offset, repeater delay, So, the calculated distances of satellites by the receiver, in other words pseudorange can be defined as;

$$Pseuodorange = R_{sat-rep} + r_{rep-rec} + Repeater_{delay}.c + Iono_{delay}.c + Tropo_{delay}.c + SatInstrument_{delay}.c + SatClock_{offset}.c + RecClock_{offset}.c + EarthRotation.$$

From the pseudorange that is described above, distance between the repeater and the receiver should be found for indoor positioning. Therefore, all of these undesired effects and the distance between the satellite and repeater must be removed. The undesired effects on the pseudorange and their ranges can be seen in Fig. 4.4.

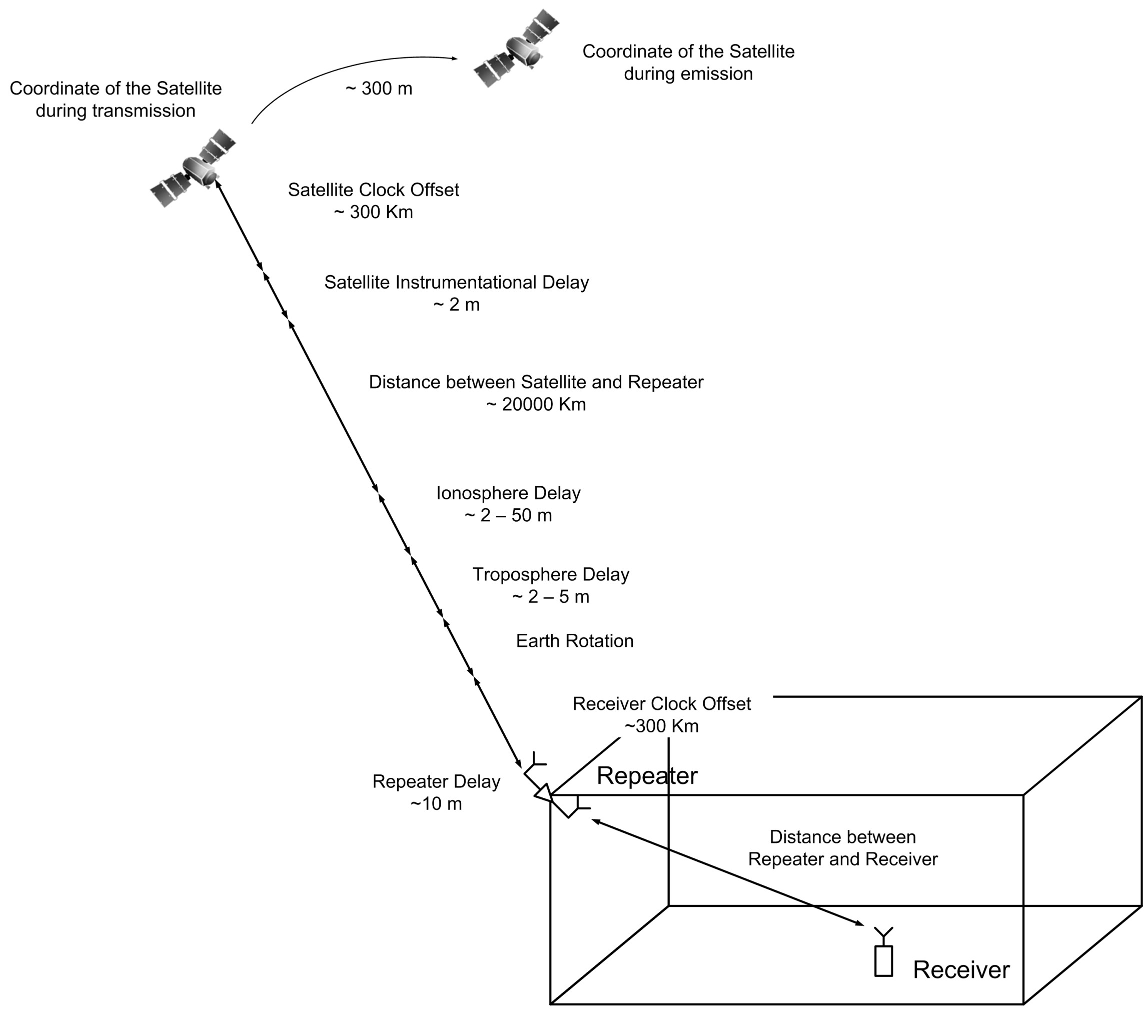


Figure 4.4: Undesired effects on pseudorange

Satellite clock offset:

GPS works in its own time system GPS time. For the measurements all the satellites should be synchronous with this time. In order to accomplish this, every satellite carries four atomic clocks. However, although they carry atomic clocks, offset occurs between. In order to compensate this offset, ground stations send this offsets to the satellites. Satellites send this clock offset parameters to the receivers with the navigation message. Offset of the satellite clock can be found from Eq. 4.1 where a_{fo}, a_{f1}, a_{f2} are polynomial coefficients that are given by ephemeris, t_{oc} is clock data reference time in seconds again given by ephemeris and t is the time of data transmission. Δt_r is the relativistic correction term (seconds) which is calculated in Eq. 4.2 where e, A and E_k are gotten from ephemeris and F is a constant which is $-4.442807633\ 10^{-10}$ sec/meter [15].

$$satclock_{offset} = a_{f0} + a_{f1}(t - t_{oc}) + a_{f2}(t - t_{oc})^2 + \Delta t_r. \tag{4.1}$$

$$\Delta t_r = Fe\sqrt{A}\sin(E_k) \tag{4.2}$$

Earth rotation effects

In the time between the transmission of the GPS signals from the satellites and the reception of the receiver, earth rotates. Therefore, the calculated pseudorange also includes this rotation. The earth rotation correction is in Eq. 4.3 where ω_E and c are the Earth turn rate which is $7.2921151467\ 10^{-5}$ (rad/sec) and speed of light in the vacuum which is 299792458 (m/s) respectively][20].

$$EarthRotation = \frac{\omega_E}{c}(x_{sat}y_{rec} - y_{sat}x_{rec}) \tag{4.3}$$

Ionosphere effects

Ionosphere is a layer of the atmosphere that is between 50 km to 1000 km. Gas molecules in this layer are affected by the solar radiation and they lose electrons. The lost electrons affect the propagation of radio signals that are passing this layer

[11]. GPS signals passes this layer and ionosphere increases the propagation between 2 - 50 meters according to the time of the propagation [12]. The effects of the ionosphere decreases at night where solar radiation is lowest. The effect ionosphere is frequency dependent, therefore its effect could be removed totally by using two different frequencies but civil GPS can only use one frequency - L1band-. Still, there are some algorithms to decrease the effects of this layer. The most used model is the model of Klobuchar. In the navigation message of the GPS, Klobuchar model parameters are included which are α_0, α_1, α_2, α_3, β_0, β_1, β_2 and β_3. By using this model the effects of the ionosphere can be decreased from 2-50 to 1 to 25 meters. Klobuchar model can be seen in Appendix E.

Troposphere effects

Troposphere is the lowest layer of the atmosphere it is only 17 km long however, it contains the % 99 of water vapor. Because of the high density caused by the water vapor, the propagation medium is changed and the radio signals are affected by the refraction. There are many models for troposphere but the effect of the troposphere is low therefore, the models are not implemented.

Satellite Instrumental delays

Each of the satellite has specific instrumentation delays that are stem from differences in the antennas and cables that are used in each satellite. The instrumental delay of each satellite is transmitted in its navigation message as TGD (Total Group Delay) and it should be removed.

Effect of repeaters

As the GPS signals are transmitted to indoor areas by the repeaters, delay of the repeater also adds up to pseudorange. The delay of the repeater results from the components and the antenna. The delay coming from the amplifiers are measured and removed during the implementation. Assuming the antenna delay is same for all the repeaters, the effect of the antennas will be canceled during the positioning as the clock bias because it is same for all satellites.

During the implementation, some of the effects of ionosphere are removed by the klobach model. Troposphere model is not implemented because of its low effect and due to lack of a comprehensive model for troposphere. Delays of the repeaters are measured and their effect is removed. Effects of satellite instrumentation delay and satellite clock offset is totally removed. Lastly, earth rotation is taken into account and its effect is removed. After, removing these effects and neglecting the rest, only undesired effect that is left is the clock offset of the receiver. After removal of some of the undesired effects the pseudoranges become;

$$Pseudorange = R_{sat-rep} + r_{rep-rec} + RecClock_{offset}.c$$

4.3 Indoor Positioning

In the previous sections, removal of undesired effects from pseudorange is explained. In addition to this, satellite position calculation in ECEF coordinates is also explained. After the calculation of the satellites positions, distances between satellite and the repeater is calculated. Subtracting this distance from the pseudorange, left pseudorange became;

$$Pseudorange = r_{rep-rec} + RecClock_{offset}.c$$

which is the searched distances for triangulation plus the receiver clock offset. For triangulation, this clock offset should be removed. As the clock offset is same for all measurements, clock offset can be solved by increasing the number of equations that are used for positioning. GPS receivers are able to measure several pseudoranges from different satellites at the same time. So, applying the same routine to all the pseudoranges and finding the repeater to receiver distance plus the clock offset, a number of equations can be obtained. For a 3D solution four equations are needed because the unknowns are x, y, z and t as seen in Eq. 4.4 where x, y, z are the position of the receiver, x_i, y_i, z_i are the position of the repeaters respectively, and p_i is the cleaned pseudorange measurements respectively.

$$p_i = \sqrt{(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2} - RecClock_{offset}.c, \; i = 1, 2, 3, 4. \quad (4.4)$$

For a 2d solution three equations are needed because the unknowns are x, y and t and the z is a constant. For a 1d solution two equations are needed because the unknowns are now only x and t. A crucial point in here is that the satellite signals that the pseudorange measurements are made must be re-directed to indoor area from different repeaters. Therefore, for a 3D positioning solution needs 4 repeaters, for 2D solution needs 3 repeaters. Pseudoranges must be cleaned from the undesired effects and the satellite to repeater distance should be subtracted. With the remainder pseudoranges, indoor positioning can be done and the clock offset can be solved.

Chapter 5

Measurements of the Indoor Positioning System

In the previous chapters, hardware and software parts of the indoor positioning system are explained and the designs of the used components are detailed. In order to prove the offered indoor positioning solution, 1D indoor positioning setup is established and the designed antenna, amplifier and the positioning algorithm is tested and analyzed. For a 1D indoor positioning 2 repeaters are needed. A replica of the antennas and the repeater is also manufactured for the measurements. The setup of the 1D positioning can be seen in Fig. 5.1.

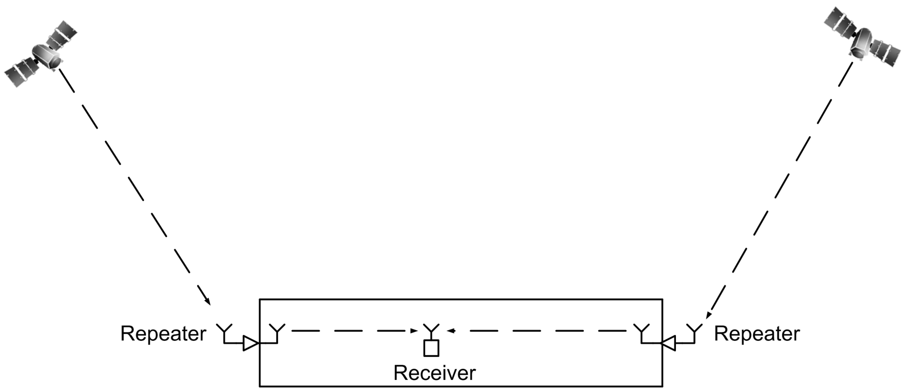


Figure 5.1: 1D indoor positioning scenario

By solving a linear equation that is explained in the previous chapter, the indoor positioning can be done. Measurements are done in Sabancı University in a 60 meter corridor of Faculty of engineering and natural sciences (FENS) building. Repeaters are placed at the two ends of the corridor and several measurements are done. The measurement setup can be seen in Fig. 5.2.

Measurements are done in five different positions. In every position, hundred consecutive positioning is done. In one of the positions, a measurement is done in a different time period. Finally, in one of the points, a measurement is done by selecting different satellites. In addition to the positioning measurements, a zero line test is done to measure the error that stems from GPS. A total of 7 measurements and the zero line test are done and the results are analyzed. These zero line test and seven measurements and their results can be seen in the following sections;

Zero line Measurement

Zero line test is used to detect the error that stems from GPS. In order to measure the error, GPS receiver is fixed to a known position. The undesired effects and the clock bias is solved and distance between the satellite and the receiver is measured from pseudorange. The difference between the actual distance between the satellite and the receiver and the measured distance between the satellite and the receiver is the zero line test. The zero line test of the algorithms and the receiver is shown in the Fig. 5.3. The main reason of the error is that some of the undesired effects can not be removed totally such as ionospheric effects and tropospheric effects.

Measurement I

Actual location is 12 meter away from RF Repeater I. 100 measurements are done at this point. Fig. 5.4 shows the distribution of the calculated positions with respect to distances where the actual position is marked with X. Mean distance of 100 solutions is 11 meters. In Fig. 5.5 one can see the positioning with respect to time.

Measurement II

A second measurement is done at the same location as the Measurement I. However, the measurements are done in a different time. Again the actual location as 12 meter away from the RF Repeater I. 100 measurements are done with a mean result of 9 meters. The results can be seen in Fig. 5.6, 5.7.

Measurement III

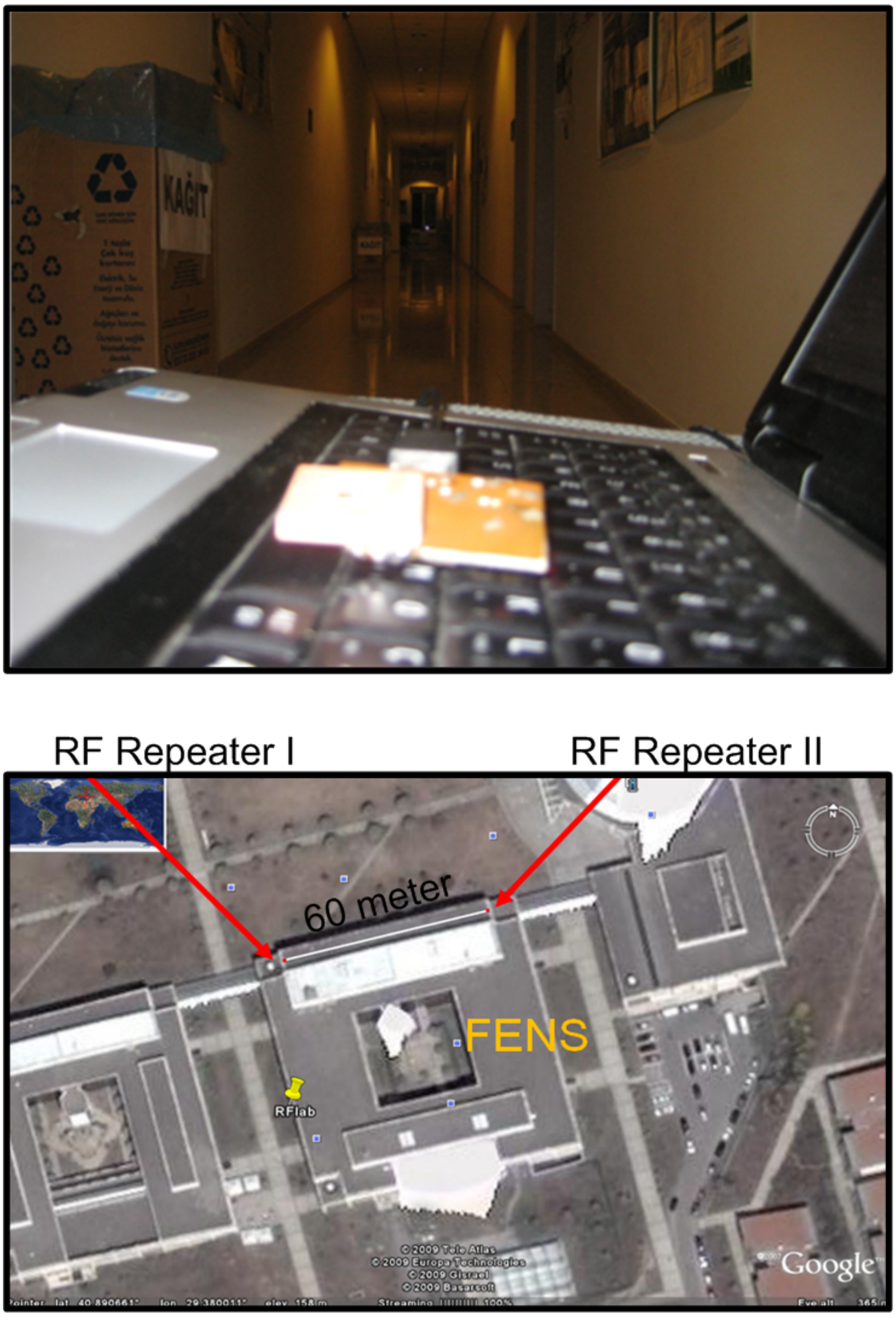


Figure 5.2: Measurement setup of 1D indoor positioning

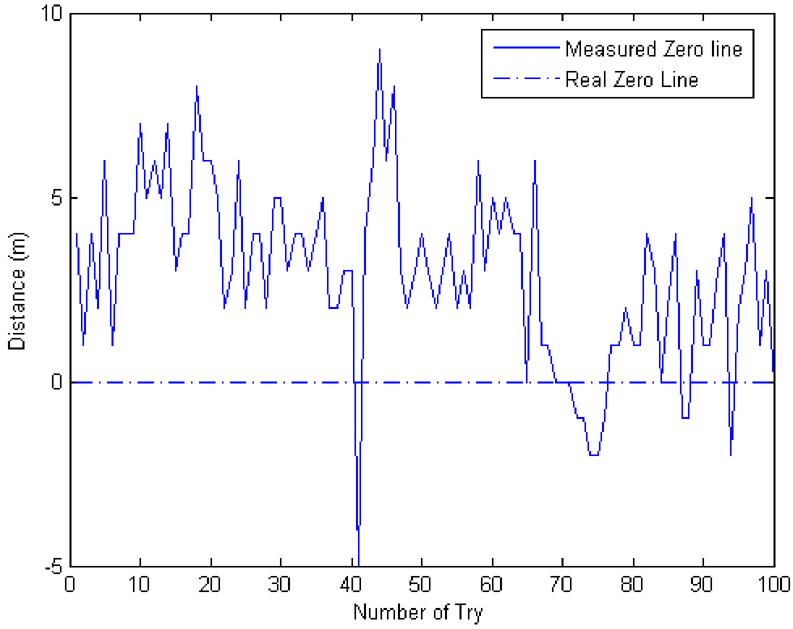


Figure 5.3: Zero line test

Actual distance in this experiment is 18 meter away from the RF Repeater I. Hundred measurements are done sequentially. The result can be seen in Fig. 5.8, 5.11. Again in the figures, the distribution of the found solutions and the found position with respect to time can be found. Mean distance of 100 measurements is 13 meters.

Measurement IV

This measurement is done right after the measurement III. However, for the positioning different satellites are used. Again the actual distance from RF Repeater I is 18 meter. After 100 measurements the mean distance is 15 meters. Results are shown in Fig. 5.10, 5.11

Measurement V

Actual location is 27 meter away from RF Repeater I. Mean distance 31 meters-. Results are shown in Fig. 5.12, 5.13

Measurement VI

Actual location is 33 meter away from RF Repeater I. Hundred measurements are

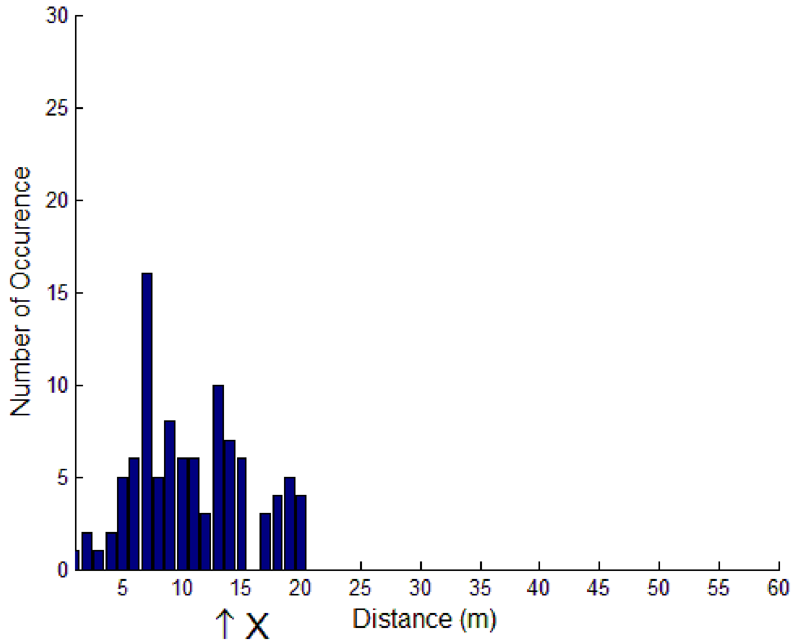


Figure 5.4: Measurement I, distribution of the calculated positions

done where the mean distance is 34 meters. Results are shown in Fig. 5.14, 5.15

Measurement VII

Actual location is 50 meter away from RF Repeater 1. After hundred measurements, mean distance 53 meters. Results are shown in Fig. 5.16, 5.17

The results can be summarized at the Table. 5.1. As it can be seen from the table, the mean error is below 5 meters for all points.

Table 5.1: Summary of the measurements

Distance from RF RepeaterI (m)	Number of Samples	Calculated Position(100 Sample Mean)	Error(m)
12	100	11	1
12	100	9	3
18	100	13	5
18	100	15	3
27	100	31	4
33	100	34	1
50	100	53	3

Results show that offered indoor positioning system works with an accuracy of

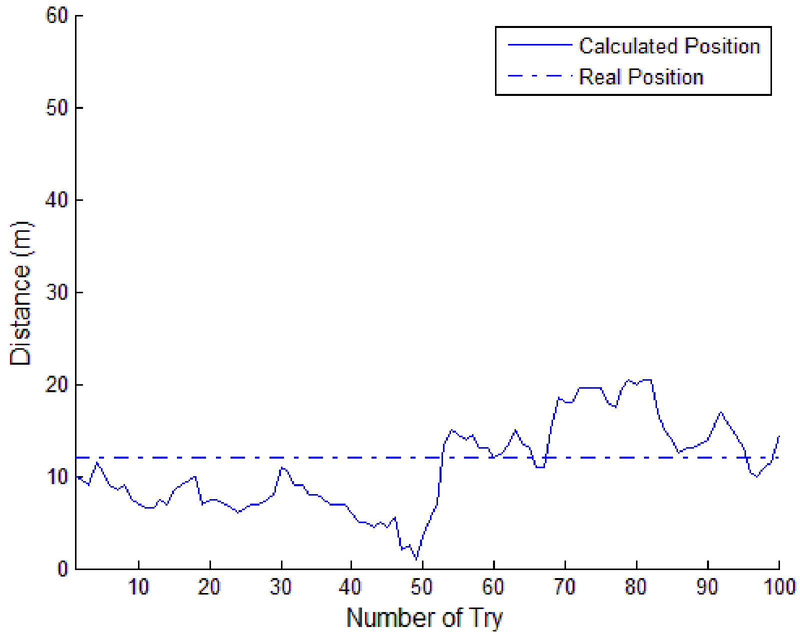


Figure 5.5: Measurement I, calculated positions with respect to time

10 meter with one positioning. However, by increasing the number of measurements and with basic filtering error can be decreased dramatically. In addition to this, as the zero line indicates, GPS itself makes such an error. GPS receiver makes 5 meter error is SEP during positioning [1]. Therefore, the indoor positioning system does not increase the error dramatically during indoor positioning. During these measurements, it is shown that a satellite signal that is repeated is be received by the receiver and encoded properly and also a satellite signal that is used for positioning is repeated to indoor area only from one repeater.

By proving these assumptions and implementing the novel algorithms in 1D indoor positioning, theoretical aspects of the proposed indoor system are proven. 2D and 3D positioning can be constructed upon these basics only by increasing the number of the repeaters and applying positioning algorithm.

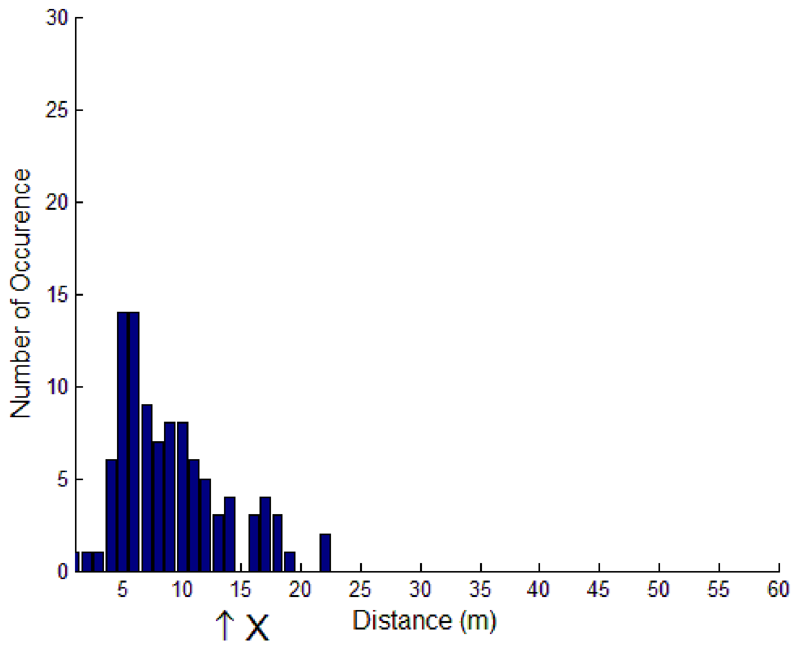


Figure 5.6: Measurement II, distribution of the calculated positions

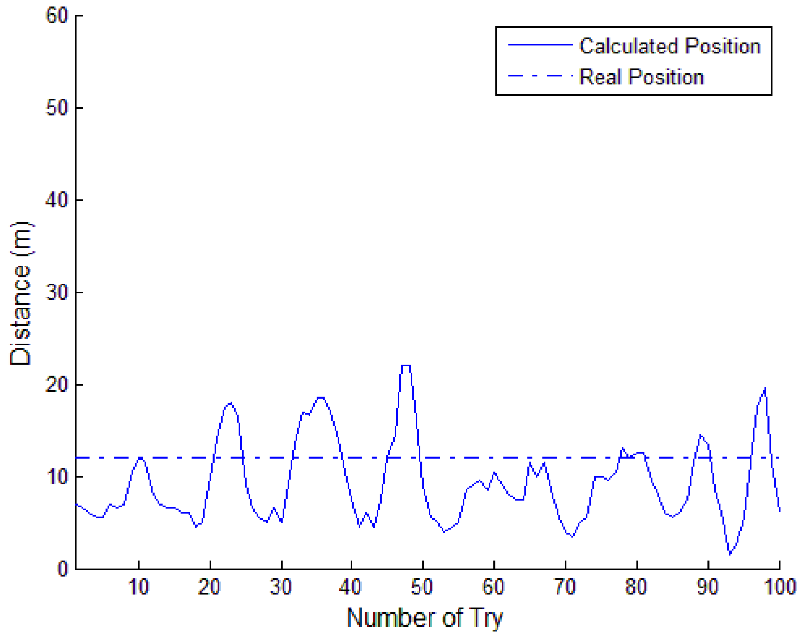


Figure 5.7: Measurement II, calculated positions with respect to time

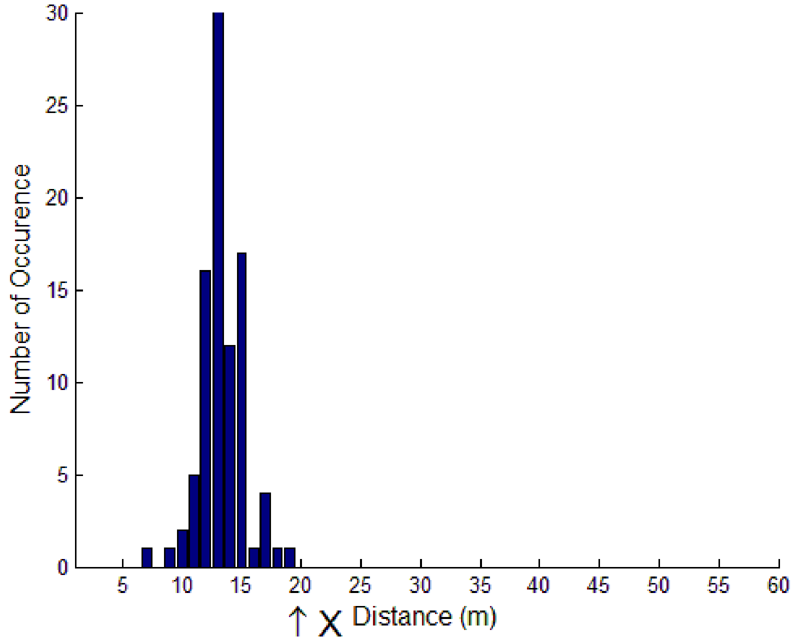


Figure 5.8: Measurement III, distribution of the calculated positions

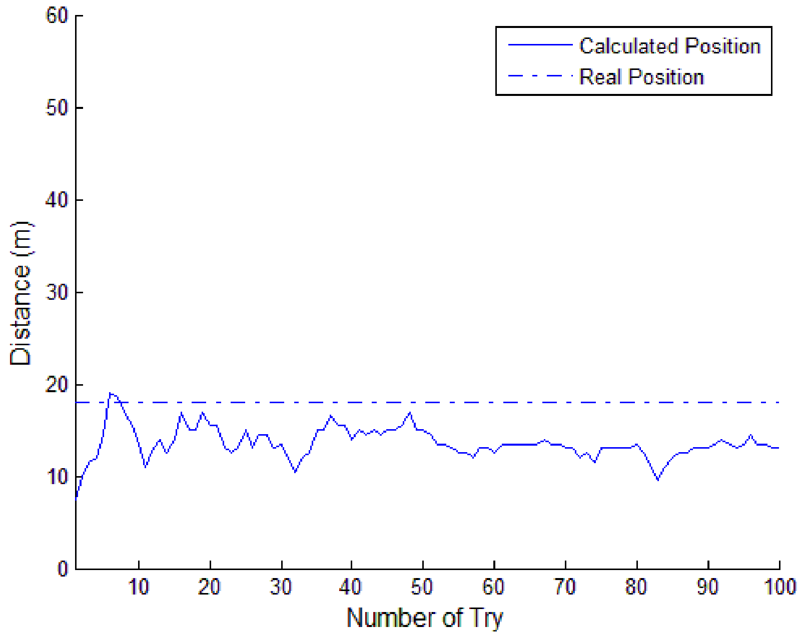


Figure 5.9: Measurement III, calculated positions with respect to time

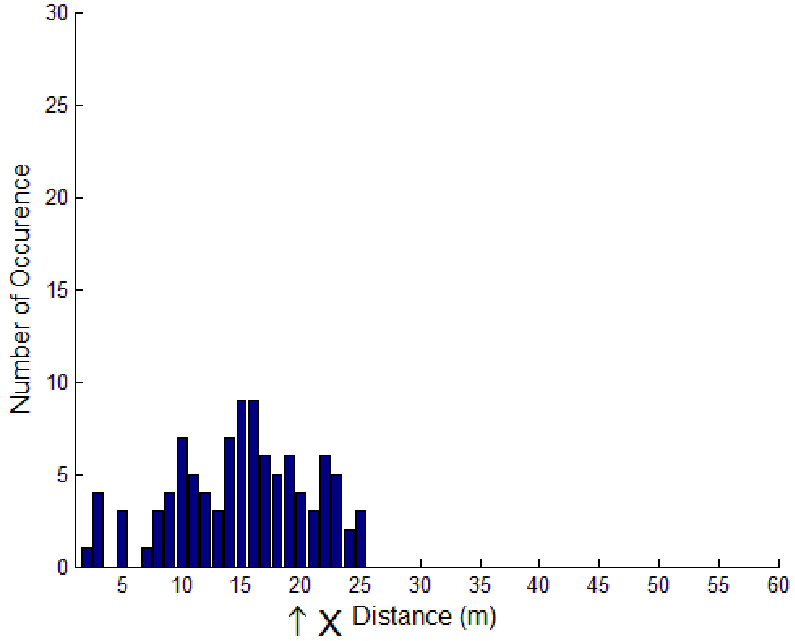


Figure 5.10: Measurement IV, distribution of the calculated positions

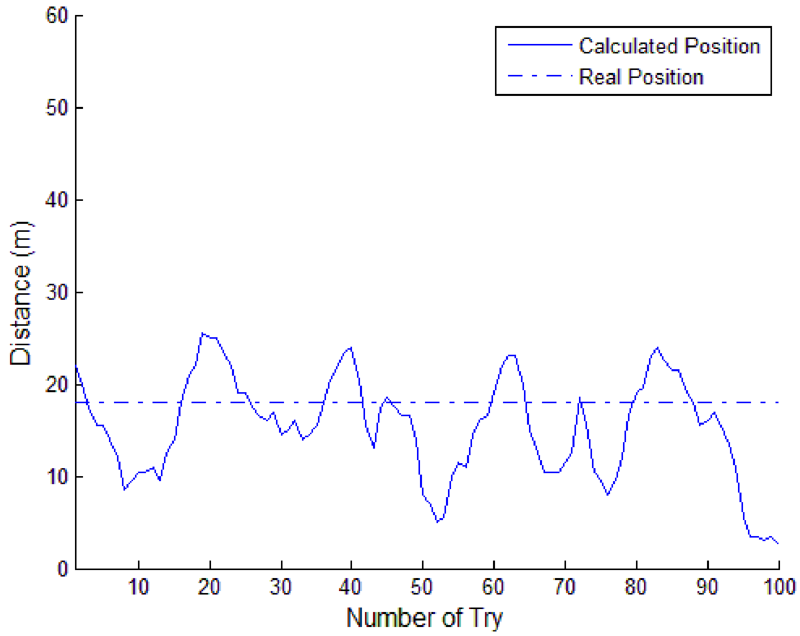


Figure 5.11: Measurement IV, calculated positions with respect to time

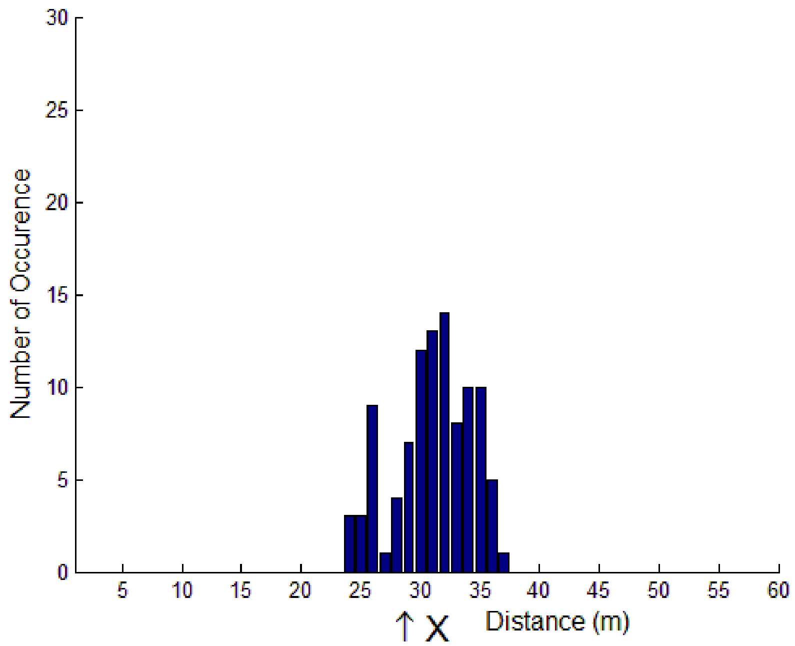


Figure 5.12: Measurement V, distribution of the calculated positions

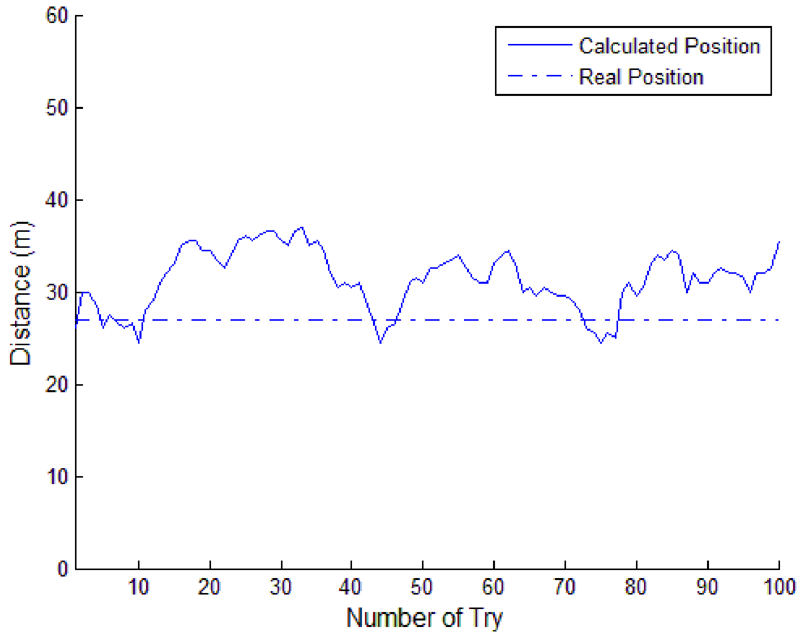


Figure 5.13: Measurement V, calculated positions with respect to time

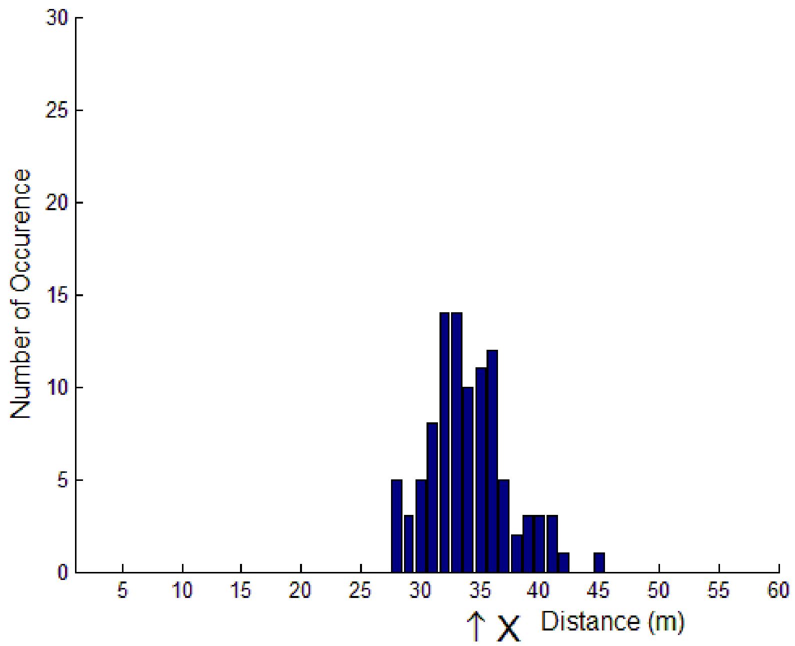


Figure 5.14: Measurement VI, distribution of the calculated positions

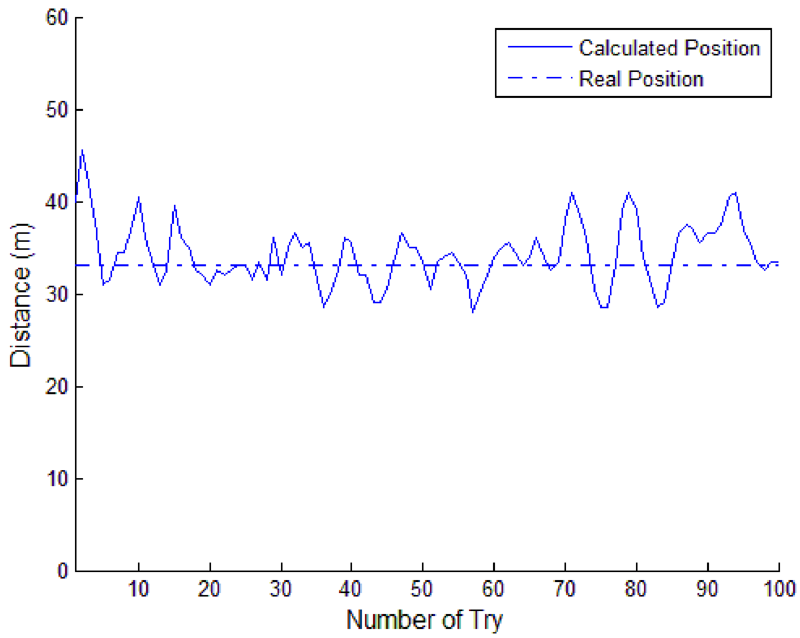


Figure 5.15: Measurement VI, calculated positions with respect to time

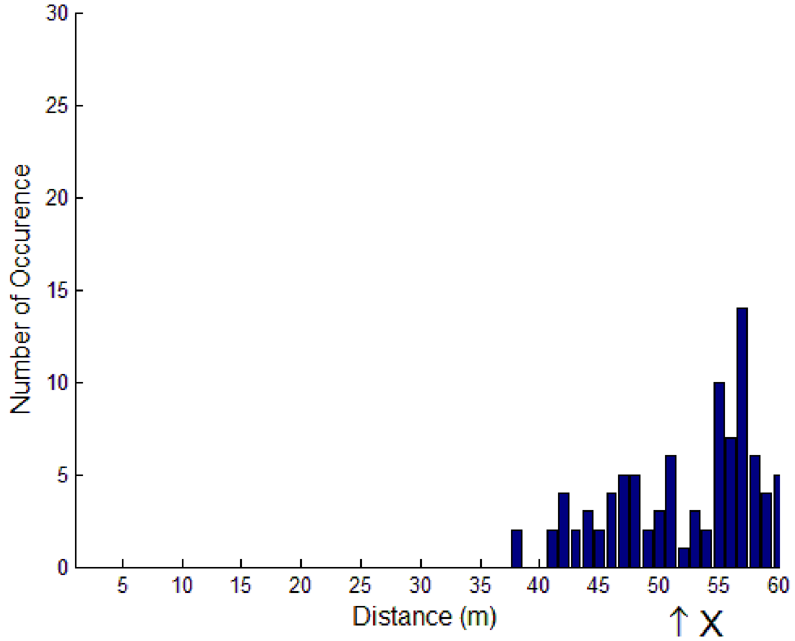


Figure 5.16: Measurement VII, distribution of the calculated positions

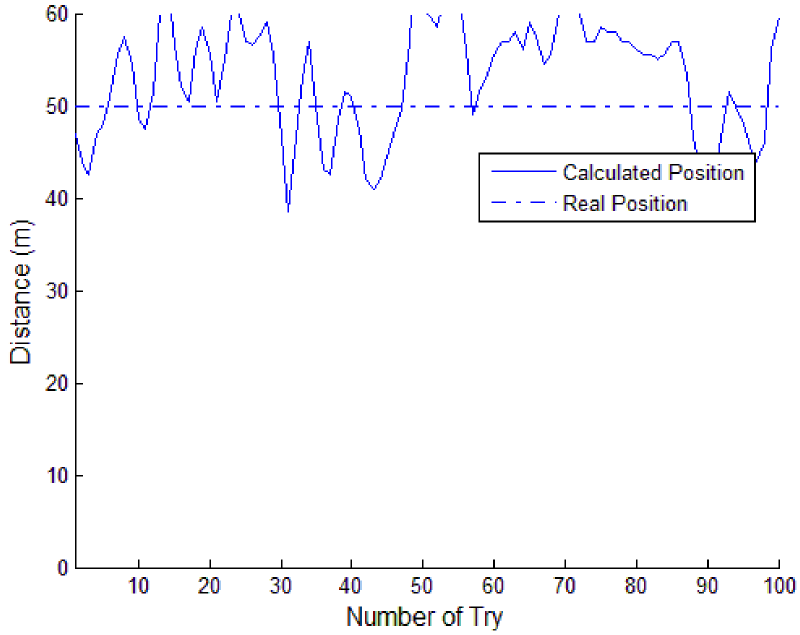


Figure 5.17: Measurement VII, calculated positions with respect to time

Chapter 6

Conclusion

In this work, an indoor positioning system is presented and its performance is evaluated through designing and manufacturing all the components and measuring the overall system. In order to analyze the overall system, directional GPS antenna is designed, manufactured and measured. A low noise amplifier is designed by the discreet components, manufactured and measured. By using antennas and the amplifier, repeater is built. In addition to these, data acquisition with a GPS is provided and novel positioning algorithms are implemented. Indoor positioning by using GPS infrastructure is a simple and low cost indoor positioning solution with promising results. It needs infrastructure addition to a building. However, the additional infrastructure is cheap and simple. In addition to this, standard GPS receivers can be used for positioning with a software update. Therefore the total cost of the system is not high. Moreover, it offers continuation of a GPS service. It does not bring any additional hardware to the users. Most importantly, results of the indoor positioning system are quite impressive and also can be improved.

6.1 Future Work

Theoretical aspects of the indoor positioning are proven in this thesis. However, only 1D positioning is done which is enough to prove the concept. As a future work, same principles can be applied to the 2D and then 3D positioning. In addition to this, as seen in the zero line tests GPS itself has error in the range calculations. It is impossible to remove all undesired effects by using only navigation message and models. However, by differential GPS these errors can be totally removed because this measurement is done in a place with a known position. Therefore, the error can be calculated and transferred to the GPS receiver that is used for indoor positioning. By the help of the differential GPS, all the undesired effects can be eliminated and better results can be gotten during indoor positioning.

Appendix A

Contents of RXM RAW

Raw data measurements can be taken periodically or by polling. The Payload contents can be seen below. [16]

Table A.1: Payload Contents of RXM RAW

Byte Offset	Number Format	Scaling	Name	Unit	Purpose - Comment
0	I4	-	ITOW	ms	Measurement integer millisecond GPS time of week (Receiver Time)
4	I2	-	Week	weeks	Measurement GPS week number (Receiver Time).
6	U1	-	NSV	-	number of satellites following.
7	U1	-	RES1	-	Reserved
8 + N*24	R8	-	CPMes	cycles	Carrier phase measurement [L1 cycles]
16 + N*24	R8	-	PRMes	m	Pseudorange measurement [m]
24 + N*24	R4	-	DOMes	Hz	Doppler measurement [Hz]
28 + N*24	U1	-	SV	-	Space Vehicle Number
29 + N*24	I1	-	MesQI	-	Nav Measurements Quality Indicator
30 + N*24	I1	-	CNO	dbHz	Signal strength C/No. (dbHz)
31 + N*24	U1	-	LLI	-	Loss of lock indicator (RINEX definition)

Appendix B

Contents of RXM EPH

Ephemeris can be taken periodically or by polling. See ICD-GPS-200 [15] for a full description of the contents of the Subframes. In SF1D0 to SF3D7, the parity bits have been removed, and the 24 bits of data are located in Bits 0 to 23. Bits 24 to 31 are the sign-extension of the data. The Payload contents can be seen below. [16]

Table B.1: Payload Contents of RXM EPH

Byte Offset	Number Format	Scaling	Name	Unit	Purpose / Comment
0	U4	-	SVID	-	SV ID for which this ephemeris data is Valid.
4	U4	-	HOW	-	Hand-Over Word of first Subframe
8	U4	-	SF1D0	-	Subframe 1 Word 0
12	U4	-	SF1D1	-	Subframe 1 Word 1
16	U4	-	SF1D2	-	Subframe 1 Word 2
20	U4	-	SF1D3	-	Subframe 1 Word 3
24	U4	-	SF1D4	-	Subframe 1 Word 4
28	U4	-	SF1D5	-	Subframe 1 Word 5
32	U4	-	SF1D6	-	Subframe 1 Word 6
36	U4	-	SF1D7	-	Subframe 1 Word 7
40	U4	-	SF2D0	-	Subframe 2 Word 0
44	U4	-	SF2D1	-	Subframe 2 Word 1
48	U4	-	SF2D2	-	Subframe 2 Word 2
52	U4	-	SF2D3	-	Subframe 2 Word 3
56	U4	-	SF2D4	-	Subframe 2 Word 4
60	U4	-	SF2D5	-	Subframe 2 Word 5
64	U4	-	SF2D6	-	Subframe 2 Word 6
68	U4	-	SF2D7	-	Subframe 2 Word 7
72	U4	-	SF3D0	-	Subframe 3 Word 0
76	U4	-	SF3D1	-	Subframe 3 Word 1
80	U4	-	SF3D2	-	Subframe 3 Word 2
84	U4	-	SF3D3	-	Subframe 3 Word 3
88	U4	-	SF3D4	-	Subframe 3 Word 4
92	U4	-	SF3D5	-	Subframe 3 Word 5
96	U4	-	SF3D6	-	Subframe 3 Word 6
100	U4	-	SF3D7	-	Subframe 3 Word 7

Appendix C

Contents of NAV CLOCK

Clock offset solution can be taken periodically or by polling.

Table C.1: Payload Contents of NAV CLOCK

Byte Offset	Number Format	Scaling	Name	Unit	Purpose / Comment
0	U4	-	ITOW	ms	GPS Millisecond Time of week
4	I4	-	CLKB	ns	clock bias in nanoseconds
8	I4	-	CLKD	ns/s	clock drift in nanoseconds per second
12	U4	-	TAcc	ns	Time Accuracy Estimate
16	U4	-	FAcc	ps/s	Frequency Accuracy Estimate

Appendix D

Calculation of Satellite Positions

Calculation of GPS Satellite Positions are explained in ICD-GPS-200 [15]. The following operations are used to calculate satellite positions by using ephemeris parameters which are listed in Table D.1

t is used for GPS time at the transmission of GPS signals. In addition to this t_k shall be the actual total time difference between the time t and the epoch time t_{oe}, and the week crossovers must be taken into account. If t_k is greater than 302,400 seconds, 604,800 must be subtracted form t_k. If t_k is less than-302,400 seconds, 604,800 seconds must be added to t_k.[15]

Table D.1: Ephemeris Parameters

M_0	Mean Anomaly at Reference Time
Δn	Mean Motion Difference From Computed Value
e	Eccentricity
$\sqrt{A}$	Square Root of the Semi-Major Axis
Ω_0	Longitude of Ascending Node of Orbit Plane at Weekly Epoch
i_0	Inclination Angle at Reference Time
ω	Argument of Perigee
$\Omega\cdot$	Rate of Rigth Ascension
IDOT	Rate of Inclination Angle
C_{uc}	Amplitude of Cosine Harmonic Correction Term to the Argument of Lattitude
C_{us}	Amplitude of Sine Harmonic Correction Term to the Argument of Lattitude
C_{rc}	Amplitude of Cosine Harmonic Correction Term to the Orbit Radius
C_{rs}	Amplitude of Sine Harmonic Correction Term to the Orbit Radius
C_{ic}	Amplitude of Cosine Harmonic Correction Term to the Angle of Inclination
C_{is}	Amplitude of Sine Harmonic Correction Term to the Angle of Inclination
t_{oe}	Reference Time Ephemeris
IODE	Issue of Data

WGS 84 value of the earth's universal gravitational parameter for GPS user;

$$\mu = 3.98600510^{14} \quad meters^3/sec^2 \tag{D.0.1}$$

WGS 84 value of the earth's rotation rate;

$$\dot{\Omega}_e = 7.292115146710^{-5} \quad rad/sec \tag{D.0.2}$$

Semi major axis;

$$A = (\sqrt{A})^2 \tag{D.0.3}$$

Computed mean motion (rad/sec);

$$n_0 = \sqrt{\frac{\mu}{A^3}} \tag{D.0.4}$$

Time from ephemeris reference epoch;

$$t_k = t - t_{oe} \tag{D.0.5}$$

Corrected mean motion;

$$n = n_0 + \Delta n \tag{D.0.6}$$

Mean anomaly;

$$M_k = M_0 + n t_k \tag{D.0.7}$$

Kepler's Equation for Eccentric Anomaly in radians (Solved by iteration);

$$M_k = E_k - e\sin(E_k) \tag{D.0.8}$$

True Anomaly;

$$v_k = \tan^- 1(\frac{\sin(v_k)}{cos(v_k)}) \tag{D.0.9}$$

$$= \tan^- 1(\frac{\sqrt{1-e^2}\sin(E_k)/(1-e\cos(E_k))}{(\cos(E_k)-e)/(1-e\cos(E_k))}) \tag{D.0.10}$$

Eccentric Anomaly;

$$E_k = \cos^- 1(\frac{e + cos(v_k)}{1 + e\cos(v_k)}) \tag{D.0.11}$$

Argument of Latitude;

$$\Phi_k = v_k + \omega \tag{D.0.12}$$

Argument of Latitude Correction (Second Harmonic Perturbations);

$$\delta u_k = c_{us}\sin(2\Phi_k) + c_{uc}\cos(2\Phi_k) \tag{D.0.13}$$

Radius Correction (Second Harmonic Perturbations);

$$\delta r_k = c_{rs}\sin(2\Phi_k) + c_{rc}\cos(2\Phi_k) \tag{D.0.14}$$

Inclination Correction (Second Harmonic Perturbations);

$$\delta i_k = c_{is}\sin(2\Phi_k) + c_{ic}\cos(2\Phi_k) \tag{D.0.15}$$

Corrected Argument of Latitude;

$$u_k = \Phi_k + \delta u_k \tag{D.0.16}$$

Corrected Radius;

$$r_k = A(1 - e\cos(E_k)) + \delta r_k \tag{D.0.17}$$

Corrected Inclination;

$$i_k = i_o + \delta i_k + (IDOT)t_k \tag{D.0.18}$$

Position in Orbital Plane;

$$x'_k = r_k\cos(u_k) \tag{D.0.19}$$

$$y'_k = r_k\sin(u_k) \tag{D.0.20}$$

Corrected Longitude of ascending node;

$$\Omega_k = \Omega_0 + (\Omega^{\cdot} - \Omega^{\cdot}_e)t_k - \Omega^{\cdot}_e t_{oe} \tag{D.0.21}$$

Earth Fixed Coordinates;

$$x_k = x'_k \cos(\Omega_k) - y'_k \cos(i_k) \sin(\Omega_k) \tag{D.0.22}$$

$$y_k = y'_k \sin(\Omega_k) - y'_k \cos(i_k) \cos(\Omega_k) \tag{D.0.23}$$

$$z_k = y'_k \sin(i_k) \tag{D.0.24}$$

Appendix E

Ionospheric Correction

The GPS navigation message includes the parameters of Klobuchar's ionospheric model. Using the model parameters, some of the ionospheric effects can be computed and corrected.

Klobuchar model parameters are included in navigation message are which are α_0,α_1,α_2, α_3, β_0, β_1, β_2 and β_3. In addition to these, geodetic latitude φ and longitude λ of the GPS receiver, time of the measurement and lastly the azimuth A and elevation E of the observed satellite are also needed for ionospheric correction. All four angular arguments φ and λ, A and E are in the units of semicircles where a semi circle is 180 degrees. ϕ is the geomagnetic latitude of the sub-ionospheric point. ψ is the Earths central angle between the GPS receiver and the ionospheric point. F is mapping function that maps the ionospheric effects of the zenith direction into the signal transmitting path. P and Q are the period and amplitude in seconds. The phase is shown by x. c is the speed of light. Frequency of L1 band is denoted by f . The formulas are given below [18]:

$$F = 1 + 16(0.53 - E)^3 \tag{E.0.1}$$

$$\Psi = \frac{0.0137}{E + 0.11} - 0.022 \tag{E.0.2}$$

$$\varphi_i = \varphi + \Psi \cos(A) \tag{E.0.3}$$

$$\varphi_i = \frac{0.416\varphi_i}{|\varphi_i|}, \qquad if|\varphi| > 0.416 \tag{E.0.4}$$

$$\lambda_i = \lambda + \Psi \frac{\sin(s)}{\cos(\varphi_i)} \tag{E.0.5}$$

$$\phi_i = \varphi + 0.064 \cos(\lambda_i - 1.167) \tag{E.0.6}$$

$$t = t - 86400, \qquad if t \geqq 86400 \tag{E.0.7}$$

$$t = t + 86400, if t < 0 \tag{E.0.8}$$

$$P = \sum_{i=0}^{4} \beta_i \phi^i \tag{E.0.9}$$

$$P = 72000, \qquad if P < 72000 \tag{E.0.10}$$

$$x = \frac{2\pi(t - 50400)}{P} \tag{E.0.11}$$

$$Q = \sum_{i=0}^{4} \alpha_i \phi^i \tag{E.0.12}$$

$$Q = 0, if Q < 0 \tag{E.0.13}$$

$$\delta_g(f1_1) = cF5X10^{-9}, \qquad if |x| > 1.57 and \tag{E.0.14}$$

$$\delta_g(f1_1) = cF(5x10^{-9} + Q(1 - \frac{x^2}{2} + \frac{x^4}{4})), if |x| < 1.57 \tag{E.0.15}$$

Bibliography

[1] U-Blox. *LEA-4T Datasheet.* U-Blox, Zrcherstrasse 688800 Thalwil Switzerland, 1 edition, May 2007.

[2] B. Peterson, D. Bruckner, and S. Heye. Measuring GPS signals indoors. *Proc. ION GPS 1997*, pages 615–624.

[3] H. Liu, H. Darabi, P. Banerjee, and J. Liu. Survey of wireless indoor positioning techniques and systems. *IEEE Transactions on Systems, Man, and Cybernetics, Part C: Applications and Reviews*, 37(6):1067–1080, 2007.

[4] Y. Gu, A. Lo, and I. Niemegeers. A survey of indoor positioning systems for wireless personal networks. *IEEE Communications Surveys & Tutorials*, 11(1): 13–32, 2009.

[5] X. Fernando, S. Krishnan, H. Sun, and K. Kazemi-Moud. Adaptive denoising at infrared wireless receivers. In *Proceedings of SPIE*, volume 5074, pages 199–207. Citeseer, 2003.

[6] H. Piontek, M. Seyffer, and J. Kaiser. Improving the accuracy of ultrasound-based localisation systems. *Personal and Ubiquitous Computing*, 11(6):439–449, 2007.

[7] N. Piscataway. Multi-camera multi-person tracking for Easy Living. In *3rd IEEE Intl Workshop on Visual Surveillance*, pages 3–10, 2000.

[8] N. Samama. *Global Positioning: Technologies and Performance.* Wiley-Interscience, 2008.

[9] P. Prasithsangaree, P. Krishnamurthy, and P. Chrysanthis. On indoor position location with wireless LANs. In *The 13th IEEE International Symposium on*

Personal, Indoor, and Mobile Radio Communications (PIMRC 2002), Lisbon, Portugal. Citeseer, 2002.

[10] H. Niwa, K. Kodaka, Y. Sakamoto, M. Otake, S. Kawaguchi, K. Fujii, Y. Kanemori, and S. Sugano. GPS-based Indoor Positioning system with Multi-Channel Pseudolite.

[11] A. El-Rabbany. *Introduction to GPS: the global positioning system*. Artech House Publishers, 2002.

[12] O. Badia Sole. Development of a GPS navigator with Matlab.

[13] C. Balanis. *Antenna theory: analysis and design*. Wiley-Interscience, 2005.

[14] D. Orban and T. Eyerman. Gps antenna lna. Application note, Orban Microwave Products.

[15] G. JPO. ICD-GPS-200, 2004.

[16] U-Blox. *LEA-4T Protocol Specification*. U-Blox, Zrcherstrasse 688800 Thalwil Switzerland, 1 edition, May 2007.

[17] T. Rappaport. *Wireless communications*. Prentice Hall PTR New Jersey, 2002.

[18] G. Xu. *GPS Theory, Algorithms, and Applications*. Springer, 2007.

[19] K. Borre. The GPS Easy Suite–Matlab code for the GPS newcomer. *GPS Solutions*, 7(1):47–51, 2003.

[20] P. Gustavsson. Development of a MatLab based GPS constellation simulation for navigation algorithm developments. *Luleå: Luleå University*, 2005.