FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO

Real Time Locating System Based on active RFID

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Abstract

Nowadays, the efficiency of resources used and the effectiveness of multiple processes in various industrial areas, transport and storage is a constant concern. The company that proposed this MSc (Master Science) thesis, *FoodInTech*, is always concerned in aiding food processing industries in their constant competitive market, aiming to stand out in providing the technology seen as necessary to achieve optimal production, therefore, inventory management is seen as one of the logical steps necessary to help achieving optimal production.

For this, it was necessary to choose the technology that is now developed for large-scale implementation, that fits into the problem and assure that provides the location, but also must have a relatively low cost.

Currently, systems for real-time location are in focus, with new solutions emerging in indoor location which have emphasized Radio Frequency Identification (*RFID*). This technology has evolved dramatically, with the ability to integrate sensors into their tags, which eventually result in the possibility of estimating distances based on signal propagation time. *RFID* is ideal for product management, since it was created for this purpose, where each tag has an unique *Electronic Product Code* (*EPC*).

This dissertation involves the study of the overall accuracy of the position given by the equipment chosen, based on *RFID*, and also by studying how to minimize locating error. At the beginning, tests were conducted outdoor, with the aim of studying the reliability of the equipment in the absence of attenuation and multipath, followed by the inevitable indoor test, since this was the ultimate goal of this study. Measurements were made in this environment to allow the perception of equipment behaviour, on which is subject to errors, mainly caused by multipath and attenuations from surrounding objects, walls and ceiling of the building.

This solution appears to be able to meet the objectives proposed, in which the quality of the result depends only on two conditions, the number of sensors and the geometry of the disposition.

Resumo

Nos dias de hoje, a eficiência dos recursos utilizados assim como a eficácia dos múltiplos processos nas mais diversas áreas industriais, de transporte e de armazenamento são uma eterna preocupação. A empresa que propôs esta tese de mestrado, a *FoodInTech* está preocupada com constante competitividade do mercado, pretendendo se destacar no fornecimento de soluções óptimas na área da gestão de stocks na indústria alimentar que é o seu *core business*. A optimização desses processos passa pela utilização de uma tecnologia que forneça localização em tempo real dentro de edifícios, para realizar uma gestão automática de diferentes processos de actuação na área do armazenamento.

Para isso, foi necessário escolher uma tecnologia que actualmente esteja suficientemente desenvolvida para uma implementação em larga escala, enquadrando-se no problema e que forneça a fiabilidade na localização, mas também que tenha um custo relativamente baixo. Actualmente, os sistemas de localização em tempo real estão de facto em foco, com novas soluções emergentes na localização entre portas (*Indoor*), em que se tem destacado a Identificação Rádio Frequência (Radio Frequency Identification, *RFID*).

RFID tem evoluído de forma extraordinária, com a capacidade de integrar sensores nas suas etiquetas, que acabou por resultar na possibilidade de estimar distâncias baseado no tempo de propagação do sinal. RFID é ideal para a gestão de produtos, uma vez que foi criado com esse propósito, em que cada etiqueta tem um código electrónico do produto (EPC - Electronic Product Code) único.

Esta dissertação passa pelo estudo da precisão global da posição dada pelo equipamento escolhido, baseado em *RFID* e também pelo estudo de como minimizar o erro da localização. Foram realizados testes, inicialmente fora de edifícios com o objectivo de estudar a fiabilidade do equipamento na ausência de atenuação e do efeito multipath. O teste dentro de edifícios foi incontornável, uma vez que é o objectivo final deste estudo. Foram realizadas medições neste ambiente para permitir a percepção do seu comportamento relativamente aos erros que está sujeito, causados essencialmente pelas atenuações e multipath dos objectos circundantes, das paredes e tecto do edifício.

Esta solução mostra-se capaz de preencher os objectivos propostos, em que a qualidade do resultado depende de apenas duas condições: o número de sensores e a geometria da disposição dos mesmos.

Acknowledgement

For all that I am today, for the varied opportunities given, the various options offered by the constant presence, by the endless patience my eternal gratitude to my parents.

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“Believe you can
and
you’re halfway there.”

Theodore Roosevelt

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List of Abbreviations

AIDC	Automatic Identification and Data Capture
AoA	Angle of Arrival
BSs	Base Stations
DGPS	Difference Global Positioning System
DOP	Dilution of Precision
EPC	Electronic Product Code
IR	Infra-Red
ISO	International Organization for Standardization
GDOP	Geometric Dilution of Precision
GPS	Global Positioning System
LoS	Line of Sight
LS	Least Squares
MS	Mobile Station
NNSS	Nearest Neighbour Signal Space
NLoS	Non Line of Sight
OCR	Optical Character Recognition
OS	Operating System
PDoA	Phase Difference of Arrival
PDOP	Position Dilution of Precision
RF	Radio Frequency
RFID	Radio Frequency Identification
RSSI	Received Signal Strength Indicator
RTK	Real Time Kinematic
RTLS	Real Time Locating Systems
SNR	Signal-to-Noise Ratio
TDoA	Time Difference of Arrival
ToA	Time of Arrival
UTM	Universal Transverse Mercator
UWB	Ultra Wide Band
WAF	Walls Attenuation Factor

Chapter 1

Introduction

1.1 Motivation

The need for improving industrial processes is constant, perpetuating the transformation of its work flow, seeking for resources reduction and process optimization, thus rendering more competitive products, both in price and quality.

The benefits of the *RTLS* (*Real Time Location Systems*) in the manufacture are clear, from assembly lines to real time product control. In logistics it is also evident that a low cost deployment of a *RTLS* can optimize a wide range of processes, specially avoiding time waste. Currently, real time tracking systems are gaining vital importance in logistics processes, both outdoor and indoor, from landing queues of the containers naval ports [7], to finding cars among thousands in a parking lot [1].

RTLS have several approaches to obtain the coordinates of the target objects, which are explained later on throughout this MSc thesis.

RFID technology (*Radio Frequency Identification*) has a natural evolutionary path, proving that it is able to gather very useful characteristics with a low implementation cost and reliable location precision. Nowadays, *RFID* tags can implement nodes of environment sensors, such as it temperature or humidity sensors.

1.2 Scope

This *MSc* dissertation fits on the needs of news business segments in processes control of the proponent company *FoodInTech* [8]. This company wants to introduce in their lines of trade, a solution that allows to locate entities in real time, inside buildings. This solution will interact with a production control software, in a way to optimize business processes of client companies.

The goal of this MSc project is to study a technology that enables real time location of entities in an industrial environment. If possible, location determination in all three dimensions is envisaged in order to know, for instance, the altitude of each pallet is in a shelf of the warehouse.

FoodInTech wishes to provide asset location aware services to its customer companies. The work described here is a study on the feasibility of a technology to provide location data in warehouse environments. Companies will benefit from this technology with outflow of the oldest products (FIFO, fist in first out ideology), or eliminate the common problem of forgotten products in warehouse, however the main objective is the automatic stock flow management know as the *Automatic Identification and Data Capture* (*AIDC*), saving time from collaborators of the firm.

The technology to use in the solution must have a low deployment and maintenance cost, optimizing the cost-effectiveness, and be a reliable system. The operating environment can be extreme, with very low temperatures, down to -20 Celsius, high metallic environment as cold stores and with a large number of pieces composed by water (e.g. meat). The *RTLS* should be able to integrate and interact with a management software, since each industrial area (e.g. food industry, drugs, etc) (logically) have different stock management requirements and therefore different management solutions.

1.3 Methodology

Given the presented requirements, the intention is not to create a new technology, but to make use and assess existing technologies in indoor location systems. Therefore, this MSc dissertation describes the study and characterize of distance error measured ranges, understanding how they can be minimized and therefore provide reliable location estimations.

Furthermore, it is also the goal of this work to find out if there is a generic methodology that can be used in the deployment of the proposed technology. The location of the sensing cells of the system can not be located randomly, as it affects the precision directly, according to denominated *GDOP*(*Geometric Dilution of Precision*), described in section 2.3 of chapter 2.

In short, the goal is to obtain know-how to face this new window of opportunity in logistics business.

1.4 Reference Comments

A prior research of studies and technologies in the area of indoor *RTLS* was primordial for the development of the work. The case studies found show different developments in the indoor sensing location. The compilation of results allowed to conclude that, technologies relying on time of travel of radio waves were best candidates when accuracy is relevant. Also the studies are based in low cost implementations, where an expensive solution is not desired. It helped to look for the right development kit; there are other technologies with interesting potential but not reliable.

1.5 Dissertation Structure

This MSc dissertation is divided into six chapters and additional three appendixes. In order to understand the development of used technology , the chapter 2 has a description of the technology and techniques used.

In the third chapter is presented the used development kit, its features and its necessary elements for its operation.

Chapter 4 details the algorithm used and the planing of performed tests. Chapter 5 displays experiments held and its results. Conclusions and future work are presented in chapter 6.

In this document there are three different appendixes, where each one display remaining data, from three experiments (first outdoor test, indoor test and final outdoor test), that was not presented in the results chapter 5.

Chapter 2

State of the Art

In order to face the work in hands, a careful study was made in past developments and approaches in the area of indoor *Real Time Locating Systems* (*RTLS*).

Radio Frequency Identification (*RFID*) was not originally designed with the aim of sensing location, in section 2.1 is presented the evolution and growth of this technology, which it has different applications in the most diverse fields and it is summarized how it proved quite useful in indoor location.

Section 2.2 presents the most reliable approaches found in the area of indoor real time locations sensing, its advantages and limitations. In *RTLS*, techniques to estimate distance are crucial to compute location. Thus in the section 2.2.1 is resumed some of those estimating distances techniques and in the section 2.2.2 is described methods to compute locations, triangulation and trilateration. Nowadays there are several *RTLS* approaches, in the section 2.2.3 is listed the more relevant *RTLS* technologies used.

In *Global Positioning System* (*GPS*) it is used the *Dilution of Precision* (*DOP*) algorithm with the aim to measure base stations geometry sensibility, which is taken into consideration in this MSc thesis, therefore in the section 2.3 is explained how it is calculated.

2.1 RFID - Radio Frequency Identification

Nowadays *RFID* has grown remarkably in the market, due to the range of possible applications and benefits provided to their users. Their use is mostly focused on security threats, with the need to identify goods and people, or on the productivity and efficiency of logistics and transports. Therefore, the anticipated market growth and the selling of units is considerable. It has grown from 1.4 billions dollars in 2009 to 2.3 billions dollars in 2011 [1]. Abreast of the market growth, the average selling price is falling considerable, which means that more and more deployments will take place. It is possible to observe this trend on figure 2.1 that is presented on the page 6.

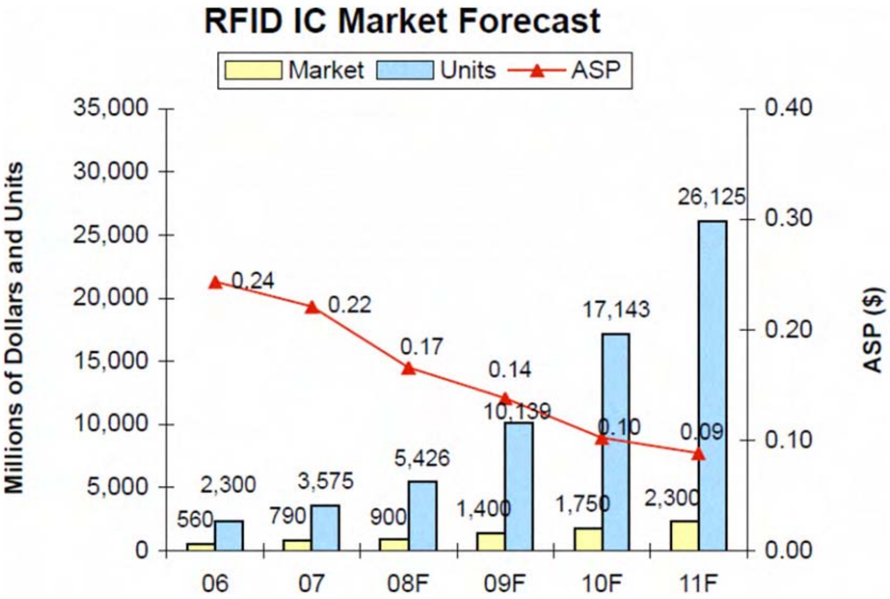


Figure 2.1: Market evolution and forecast for RFID [1]

The evolution on the *RFID* technology was not stimulated by the needs of deployments, but by its normal development that is clear throughout this section.

The early goal of the *RFID* was to identify every object with an assigned tag with its own *EPC (Electronic Product Code)*. Currently, the modern *RFID* systems benefit from the electronics, making it more capable of different applications with smaller integrated circuits and less power consumption. For instance, secondary sensors can be attached to the tag to obtain information of the surrounding environment such as temperature or humidity, both critic measures in the food transportation business. Thus, *RFID* systems emerge as a technology that can determine the location of tagged object, since multiple receivers are used. The use of multiple receivers is essential to compute locations, possible approaches will be better described in the section 2.2.

Other techniques that serve the same purpose, automatic identification systems, are, for instance: the biometric identification, *Optical Character Recognition* (*OCR*) and the barcode tag. Certainly, feasibility and cost of the system to implement has to be reasonable. The barcode tag is an hard to beat competitor, because it is much cheaper and disposable. *RFID* technology has advantages in some applications since each object assigned with a *RFID* tag can be identified with *non line of sight* (*NLoS*), beside the fact that there are low cost and disposable tags or even tags that can be recycled.

There is a wide range of implementations in diverse areas, e.g. in stores and libraries help to avoid stealing products. It is used in the electronic personal identification cards and passports, aiming to increase security identification, thus preventing its counterfeiting. *RFID* is well implemented in the retail and drugs industry, helping to avoid out of stock events.

2.1.1 RFID Components

The *RFID* Systems can be divided by 3 major components to his normal functionality, tags, readers and host application software.

- *RFID tags:* Each tag is associated with an unique *EPC* with the purpose to identify each object assigned with it. *RFID* tags can be differentiated by two types, active and passive tags. Passive tags are not powered, meanwhile it can retrieve the power by rectify the *RF (Radio Frequency)* signal from inductively couple link, or via photo voltaic cells or by thermal energy. This means that tag transmits undetermined way, after get sufficient power to transmit, so it can raise an operation problem in some implementations, due other tag signals collision.

  In the other hand, active tag has its own power source, wherefore there is space for integrate sensors and coordinate communication with readers, avoiding collisions with other tags signals, thus avoid undetected tags. If there is a coordination protocol between the reader and tag, it can maybe extract also the distance that separates them, opening the door to sensing location.

- *RFID readers:* Readers are responsible to interact with tags, to manage communication with tags and avoid signal collisions. Readers can receive data sent by the tag and can be arranged in the most appropriated places, e.g. a gate, where the objects pass through it, in a way that can be identified automatically.

- *Host Application Software:* This is the user interface, where is possible to visualize data flow of *RFID* system. It can manage for instance, the stock of a warehouse, in which can be an intermediary to provide information through internet in real time, enabling to consult it at home.

2.1.2 RFID Standards

The *EPC Electronic Product Code* is the identifying protocol defined by the EPCGlobal organization, which is an unique code assigned to each *RFID* tag.

For a long time there was a lack in *RFID* standard protocols regarding the communication between the reader and the tag. In 2004 EPCGlobal introduced a standard directed to fill the lack of its predecessor, Gen-1 [9]. This standard protocol is today commonly used in the industry.

For air interface protocol there is *ISO* 18000 series and its normal applications are displayed in table 2.1. The two lower band of frequencies are used for inductive tags. The *ISO* 18000-6 protocol was made by *International Organization for Standardization* [10], which encompasses the EPC Gen-2 to simplify the used protocol in *RFID* systems.

Table 2.1: RFID Tag Applications with Corresponding frequency bands [5]

Frequency Band	**Tag type**	**Applications**
Low (9-135 kHz)	Passive	Animal tracking, vehicle immobilizers.
High (13.553-15.567 MHz)	Passive	Access control, luggage control, biometrics
Amateur radio (430-440 MHz)	Active	Container and vehicle identification, proprietary RTLS
Ultra-high (860-930 MHz)	Passive	Supply chain management
Microwave (2.4-2.4835 GHz e 5.8 GHz)	Active e Semi-passive	Open standard RTLS, electronic toll payment

2.2 RTLS - Real Time Location Systems

RTLS are on focus for several companies [7, 11, 12], since its evolution and overgrowth has been tremendous this last decade. It allows implementations with acceptable cost enabling optimizations in logistics processes, therefore encourages an immediate return on investment.

In Market perspective, *RTLS* still have challenges ahead, such as preference of some classical management logistics techniques, which are often outdated and obsolete. Other issue is ignorance or unknowing of such technological benefit from potential customers, or even an offer of solution with inflated costs by some sellers. For this reasons it seems that it is an area to explore. Even so, *RTLS* are expected to have a fast growing market, thus benefits they offer in many areas of application, transport, logistics, hospitals, manufacturing, state services, etc. Furthermore, its implementation will bring benefits that will save resources and time that today are wasted.

2.2.1 Measurements and Observations Types

Real time Location Systems have many approaches to estimate the locations of objects. These techniques rely of different methods, depending on type of read that can be extracted from the technology that is being used. Bellow will be presented some of more used and important practices used in *RTLS*:

- **ToA - Time of Arrival** known also as *Time of Flight* or even *Time Interval of Arriving*, relies on the measurement of time that signal takes on its propagation, between the emitter (t_t) and the receiver (t_r). Through the time of signal propagation the distance can be estimated using the speed of light or the speed of sound (v), depending if is being used a *RF* or an ultrasonic signals respectively, with following relation [13]:

  $$d = v(t_r - t_t) \tag{2.1}$$

  In fact, to measure the signal timing is necessary to know exactly when that was broadcast on the scale of nanoseconds. This requires that the receiver is synchronized with the transmitter, which involves an increased complexity of the system, power consumption and cost. Alternatively, the signal after received, be immediately re-transmitted and the time can be measured by the round trip, taking into account the time it takes to process the received signal until to be effectively re-transmitted.

- **TDoA - Time Difference of Arrival** as the *ToA*, is based on the calculations of the distance through time of signal propagation, knowing its velocity. In turn, seems to be a more reasonable approach since it does not need the receiver be synchronized with the transmitter. On the other hand, receivers must have internal clocks synchronized with each other, that can be periodically synchronize via wireless or wire. When the signal is received in different instants by receivers, is considered that was sent in the same instant by transmitter. It consists in measuring the moment of reception of signals from each receiver, and then estimate differences of instants of reception of each receiver. Is equivalent for instance, to the difference of *ToA* from two receptors, which the signal is transmitted in the unknown instant t_r and received by each receiver in the instants t_{a1} and t_{a2}, receiver 1 and 2 respectively. Results in the difference of the distances from the transmitter to each receiver [13]:

$$d_{\Delta 12} = v(t_{a1} - t_t) - v(t_{a2} - t_t) = v(t_{a1} - t_{a2}) \tag{2.2}$$

- **AoA - Angle of Arrival** is the measuring of the direction of reception of the signal, recording its angles. It is required that receivers be synchronized with each others and aligned in known precise positions. It is possible to obtain the direction and elevation with a single receiver, equipped with 2D array antenna. With angles measures, is used triangulation algorithm to estimate location, enable to compute also positions in three dimensions position using at least three angles.

- **PDoA - Phase Difference of Arrival** consists to note the phase-difference of a received signal on each *BS*, in order to estimate the difference of distances from the transmitter to various receivers, knowing the signal speed. It can be compared with *TDoA*, where differences of instants are taken into account to compute the relation of distance. A recent developed technique *multifrequency-based* Range estimation [14], use at least two basic frequencies, to obtain two phase-difference to further computation of the distance. It has a certain analogy with radar systems, where it uses the phase-difference of the reflected signal wave from objects, to calculate its range. This technique *multifrequency-based*, seems to have potential in *RTLS*, since that if the transmitter allows to emit several signals with varied frequencies, it can theoretically eliminate the environment noise.

- **RSSI - Received Signal Strength Indicator** is the definition in Wi-Fi networks to indicate signal strength. *RSSI* can be used to estimate distance, since *RSSI* decrease throughout the signal propagation. The distance can be estimated by the Euclidean distance used in various studies [15, 16, 17, 2, 12], given by:

$$E_j = \sqrt{\sum_{i=1}^{n} (\theta_i - S_i)^2} \tag{2.3}$$

Where S_i denotes the signal strength of *MS* number i and θ_i the corresponding signal strength for the *BS* number i. This approach is more simple than *time-based* estimation techniques, since to its implementation synchronization between receiver and transmitter, great time reading and great data rating are not needed. It is only necessary a wireless systems as Wi-Fi access point, with few or non hardware changes. Unfortunately, signal propagation model is not linear and is not free of interferences, caused by persons, furniture, walls and surrounding objects, which causes errors on distance estimation based on *RSSI*. Therefore, to improve accuracy rise the need to predict signal attenuation caused mainly by walls and furniture, thus it is made a mapping scan named *Location Fingerprint*, extracting reads in certain points of the deployed area [18]. In short distance prediction is intrinsically linked to errors, thus *time-based* and *angle-based* approaches are in fact more reliable.

2.2.2 Location Estimation Techniques

RTLS technologies can provide *Pseudoranges* or *Pseudoangles* to further compute location. Since the majority of *RTLS* are ranges-based and angles-based, following is explained triangulation algorithm and trilateration algorithm, angles-based and ranges-based algorithms respectively.

2.2.2.1 Triangulation

Triangulation technique is used to estimate the location, needing at least n angles to obtain n coordinates of the location.

Following, in the figure 2.2, is shown a general example of position estimation based on two coordinates [2].

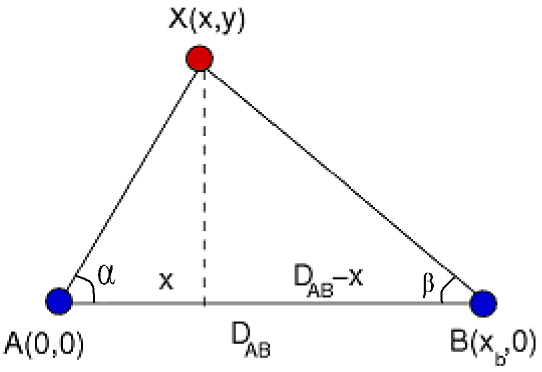


Figure 2.2: Location Estimation using Triangulation [2]

In order to compute each coordinate, is necessary to obtain α and β angles. Using the next equations is possible to compute the position, for x coordinate the equation 2.4 and for y coordinate the equation 2.5.

$$x = D_{AB} \cdot \frac{tan_{\beta}}{tan_{\alpha} + tan_{\beta}} \tag{2.4}$$

$$y = D_{AB} \cdot \frac{tan_{\beta} \cdot tan_{\alpha}}{tan_{\alpha} + tan_{\beta}} \tag{2.5}$$

2.2.2.2 Trilateration

In trilateration method at least n distance measurements from each fixed station are needed, to obtain n coordinates. In the following example shown in the image 2.3, with three fixed positions in order to compute 2D location.

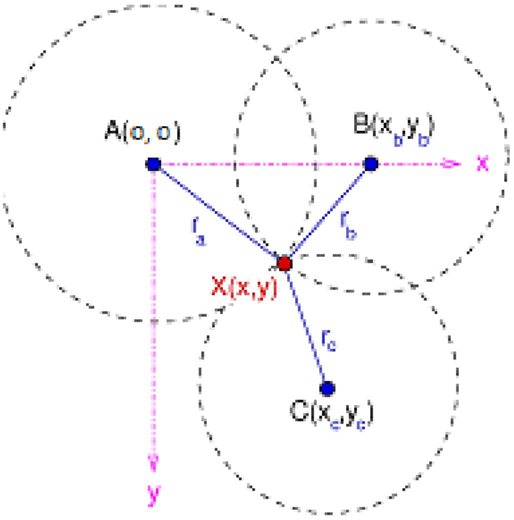


Figure 2.3: Location Estimation using Trilateration [2]

Starting the problem with the XY plan coordinates and knowing the ranges r_a,r_b and r_c:

$$r_a = \sqrt{(x - x_a)^2 + (y - y_a)^2} \tag{2.6}$$

$$r_b = \sqrt{(x - x_b)^2 + (y - y_b)^2} \tag{2.7}$$

$$r_c = \sqrt{(x - x_c)^2 + (y - y_c)^2} \tag{2.8}$$

Simplifying each equation and solving for x and y:

$$r_a^2 = x^2 + y^2 \tag{2.9}$$

$$r_b^2 = (x - x_b)^2 + y^2 \tag{2.10}$$

$$r_c^2 = (x - x_c)^2 + (y - y_c)^2 \tag{2.11}$$

As a result there is:

$$x = \frac{x_b^2 + r_a^2 - r_c^2}{2x_b} \tag{2.12}$$

$$y = \frac{x_c^2 + y_c^2 + r_a^2 - r_c^2 - 2xx_c}{2y_c} \tag{2.13}$$

2.2.3 Technologies

Real time location concept has several implemented technologies, but can be divided by two major characteristics:

- *Indoor*
- *Outdoor*

Nowadays, *outdoor* locating systems are dominated by *GPS* with many purposes, for its good precision and reasonable cost. When transposed to indoor it faces a critical issue: a strong attenuation of the signal that results the method is useless.

Nevertheless, *indoor* environment have space for new approaches and there are varied studies in this area, led by active *RFID* systems. *RFID* systems have some advantages, as *NLoS*, reasonable reading ranges, remarkable reading speed and more important to its proliferation, the cost-effectiveness [15, 16, 17, 7, 11, 2, 19, 14, 12, 18].

- **Infrared -** Location based on infrared is based on, an active badge attached to the object to locate. The badge radiates an infrared beam, with an unique ID number, sent periodically to the receiver. Distance is estimated, assuming that the infrared signal travels at the speed of light. This system is innovative, since it is a wireless location system, with reasonable costs and easy to implement, but it has three major issues:
  1. The short reading distance;
  2. A mandatory requirement: it needs *Line of Sight* (*LoS*);
  3. It can be disturbed easily.
- **Ultrasonic -** There are two main approaches using ultrasonic technology, *The Cricket Location Support System* and *The Bat System*.
  - **Bat System** consists in mounted known locations receivers in extreme points of the area. Each object to locate has a radio transceiver and an ultrasonic transducer that emits an specific ultrasound signal. The radio transceiver is used to coordinate when to emit ultrasound, helping avoid signal collisions. Then, *ToA* is measured and with it is computed ranges between the emitting bat and the receiver. Ultrasound signal travels at the speed of sound (343.2 m/s), therefore this system has a slightly higher margin regarding to time reading error, around microseconds. Comparing systems based on

  Ultrasound with a RF-based system, RF-based systems have signals travelling at the speed of light (3x10^8m/s), therefore it must have precise clocks to the nanosecond scale. Regarding to the erroneous originated in signal reflections, it is rejected by the read ranges average outliers algorithm. The location is then computed knowing the range measurements, using trilateration method. If the user desires to know the direction of the object can deploy one more bat to it. The system is centralized and also enables the power saving mode, by hibernate the bat. The overall accuracy of the system is up to 3 cm with 95% of data read in high dense environment [20]. The principal disadvantage of this system is its high cost implementation.

  - **Cricket Location Support System** as The Bat System use also RF signal and ultrasonic, but in other way. This system use a decentralized transmission, the opposite of *The Bat System*. It uses a randomized algorithm to avoid possible collisions and signal interferences [21]. The listeners are located in the celling known points of the deployed area. It separates the area by smaller sections, where each section needs a reference beacon. It use as well the *ToA*, combine radio frequency and ultrasonic, to measure distances from the beacon to its listeners. Environment interference can be minimized using the difference of the two propagation times (*ToA*) given by the RF signal and the ultrasonic one. The final precision is from 0.15m in a 4m X 4m square area. Once again, this system has an exorbitant cost, turning into inaccessible deployment.

- **Narrowband Radio Frequency -** Narrowband-based systems have the great advantage of their signals pass through objects. There are several technologies using narrowband radio frequency, WLAN, Zigbee, RFID, bluetooth among others. *RTLS* based on Narrowband frequencies normally use *RSSI* to estimate distance, since time-based distance estimation has an increase complexity and power consumption, thus added cost. Nerveless hardware complexity of time-based distance estimation, in order to estimate time of signal propagation, internal clocks must be precise down to nanoseconds, since the signal travels with the speed of light. Another issue that Narrowband frequency-based systems is that signals are expected to have multipath, resulting in a bad time estimation. Therefore, *RTLS* using this band of frequency, normally use *RSSI* to estimate objects location.

  One example of *RTLS* based on WLAN is RADAR, which use Wi-Fi network adapters to measure *RF* signal strength. It models the *RSSI* to distance with Euclidean (equation 2.3), in order to archive real time location awareness. Because of *RSSI* is not linear, caused by *The Walls Attenuation Factor* (*WAF*), objects and people interference, arise the need of optimization techniques. One of the process to improve precision is making a layout of the building floor, known as *fingerprint* [18, 22]. Another used technique is the *NNSS* (*Nearest Neighbour Signal Space*) algorithm. It uses the euclidean distance measure of the neighbour based on its *RSSI*, knowing the fixed location of the neighbour [2]. The RADAR system cannot be deployed for a general solution, wherein the environment is constantly changing (e.g. the furniture, warehouse, etc), thus it becomes a useless approach.

RTLS-based Narrowband frequency have bad accuracy, with several meters of error. RADAR approach can have error around 4.3 meters way of its actual location, with 50% of the measurements, which is considerable high [2].

- **Ultra-Wideband Radio Frequency -** is known as the band of frequency greater then 500 MHz, but is also known as a standard for hight speed data transmission protocol [13]. *UWB*-systems have potential in *RTLS*: they can estimate distance more accurate through signal propagation time (*ToA* or *TDoA*), where *RSSI*-based systems are linked to estimation errors, due its signal strength vulnerability. *UWB* compare with narrowband use higher frequencies, where signals affected by multipath are better identified, since use a shorter propagation. Reflected signal rejection is easier to perform by using nanoseconds precision clocks. For instance, in the case where it is received the original and a reflected signals, the second received signal is discarded, only if the correct signal could reach the receiver.

  Latest *RFID* technology capable of *RTLS* use *UWB* frequencies, which seems to be the most reliable technology to estimate distances. Therefore a open door for a robust indoor locating System based on active *RFID*. Using *ToA* acquired on *RFID* system and knowing the position at least of three receivers, is possible to compute the location with three coordinates of the tag, by classical trilateration technique.

2.3 Dilution of Precision

Global Position System know as *GPS* is widely used in our days, due its feasibility as much as its accuracy.

Dilution of Precision (*DOP*) is a simple method with few formulas, that help to estimate geometry quality of the Base Station (*BSs*) of the *RTLS*, where *GPS* precision is strongly depend of it [23, 24].

DOP analysis can be divided into VDOP, HDOP, PDOP and GDOP, that means vertical, horizontal, position and geometry of *Dilution of Precision*, where the lower its values, the stronger the accuracy of the location. Each individual indicators can be very useful when the goal is to evaluate a certain factor, for instance, common *GPS* is only important for horizontal accuracy to present the road location, thus a good value of HDOP is critic.

In the following table, is presented rating table of *DOP* values 2.2.

In this MSc thesis will be given special attention to obtain the best accuracy as possible, therefore a robust positioning of *BSs* is very important, since it is the only element of *DOP* analysis available to control. Thus, *BSs* location will taken into account to try to minimize the *PDOP* values low as possible, down to the unity.

Table 2.2: An interpretation of Dilution of Precision values [6]

DOP Value	**Rating**	**Description**
1	Ideal	This is the highest possible confidence level to be used for applications demanding the highest possible precision at all times.
2-3	Excellent	At this confidence level, positional measurements are considered accurate enough to meet all but the most sensitive applications.
4-6	Good	Represents a level that marks the minimum appropriate for making business decisions. Positional measurements could be used to make reliable in-route navigation suggestions to the user.
7-8	Moderate	Positional measurements could be used for calculations, but the fix quality could still be improved. A more open view of the sky is recommended.
9-20	Fair	Represents a low confidence level. Positional measurements should be discarded or used only to indicate a very rough estimate of the current location.
21-50	Poor	At this level, measurements are inaccurate by half a football field or more and should be discarded.

As a starting point of *DOP* calculation, the unit vectors must be computed based on each *BS* position to the receiver and at least four satellites are need:

$$\left(\frac{x_i - x}{r_i}, \frac{y_i - y}{r_i}, \frac{z_i - z}{r_i}\right) \tag{2.14}$$

Knowing that, Cartesian coordinates of the spheres are given by:

$$r_i = \sqrt{(x_i - x)^2 + (y_i - y)^2 + (z_i - z)^2} \tag{2.15}$$

Results into the matrix:

$$G = \begin{bmatrix} \frac{x_1 - x}{r_1} & \frac{y_1 - y}{r_1} & \frac{z_1 - z}{r_1} & -1 \\ \frac{x_2 - x}{r_2} & \frac{y_2 - y}{r_2} & \frac{z_2 - z}{r_2} & -1 \\ \vdots & \vdots & \vdots & -1 \\ \frac{x_n - x}{r_n} & \frac{y_n - y}{r_n} & \frac{z_n - z}{r_n} & -1 \end{bmatrix} \tag{2.16}$$

The *GDOP* analysis is usually evaluated by the values contained in the cross matrix given by:

$$\left(G^T G\right)^{-1} = \begin{bmatrix} \sigma_x^2 & \sigma_{xy} & \sigma_{xz} & \sigma_{xt} \\ \sigma_{yx} & \sigma_y^2 & \sigma_{yz} & \sigma_{yt} \\ \sigma_{zx} & \sigma_{zy} & \sigma_z^2 & \sigma_{zt} \\ \sigma_{tx} & \sigma_{ty} & \sigma_{tz} & \sigma_t^2 \end{bmatrix} \tag{2.17}$$

Where:

$$HDOP = \sqrt{\sigma_x^2 + \sigma_y^2} \tag{2.18}$$

$$VDOP = \sqrt{\sigma_z^2} \tag{2.19}$$

$$PDOP = \sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2} \tag{2.20}$$

$$GDOP = \sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2 + \sigma_t^2} \tag{2.21}$$

Chapter 3

RTLS Development Kit by The Convergence Systems Limited

As explained in the chapter 1, the purpose of this MCs Dissertation is the study of a industrial warehouse deployment of a *RTLS*. It was made a research of a development kit available in the market, based on active *RFID* using *ToA* or *TDoA* measurements, in order to obtain ranges to each fixed *BS*. It is known that, systems that use this estimation techniques, seems to have better *trade off* regarding implementation cost and reliability, as it is described in the chapter 2 in the section 2.2.

The basic features of this development kit is described in the section 3.1 and in the section 3.2 some reviews are made about its performance and limitations.

Afterwords, there is only one available found testing equipment, that fill basic requirements of this project and it is *RTLS* Development Kit by *The Convergence Systems Limited* [25].

This Development Kit was acquired by the proponent company, *FoodInTech*, to enable the development of this MSc thesis.

3.1 Development Kit

The Development Kit by *The Convergence Systems Limited*, seems to have the *RTLS* solution desired. It provides the sensing location of the tags with *NLoS* (*Non Line of Sight*), measure the distance with *ToA* of the *RF* (Radio Frequency) signal propagation. The frequency used to the locations estimation in this implementation is *UWB*, between 2400-2483 MHz [26].

3.1.1 RTLS Reader

The CSL development kit consists of six reader antennas: five are slave (CS5111) and one master (CS5111), as reflected in the figure 3.1. Each reader, or anchor is responsible to perform tag ranging and after estimate all ranges, the data is send to the master. Finally the master submits the data into the application software, which computes tag location with two coordinates.

The Master reader coordinates the communication wirelessly with the slave anchors and if the master cannot reach directly one slave anchor, can communicate with it through an intermediate slave.

Figure 3.1: RTLS Reader

3.1.2 Asset Tag

The development kit includes 10 asset tags based on active *RFID* that integrates temperature and motion sensors, powered by 3 AAA batteries, figure 3.2.

Figure 3.2: Active RFID Tag for RTLS

Tag battery depends on its usage: it can be configured to transmit data when it is moved or at predefined intervals of time. Following is an example of battery life [26]:

- For 2 second Update Cycle Time, 6 months battery life (10% motion);
- For 5 second Update Cycle Time, 15 months battery life (10% motion);
- For 10 second Update Cycle Time, 24 months battery life (10% motion).

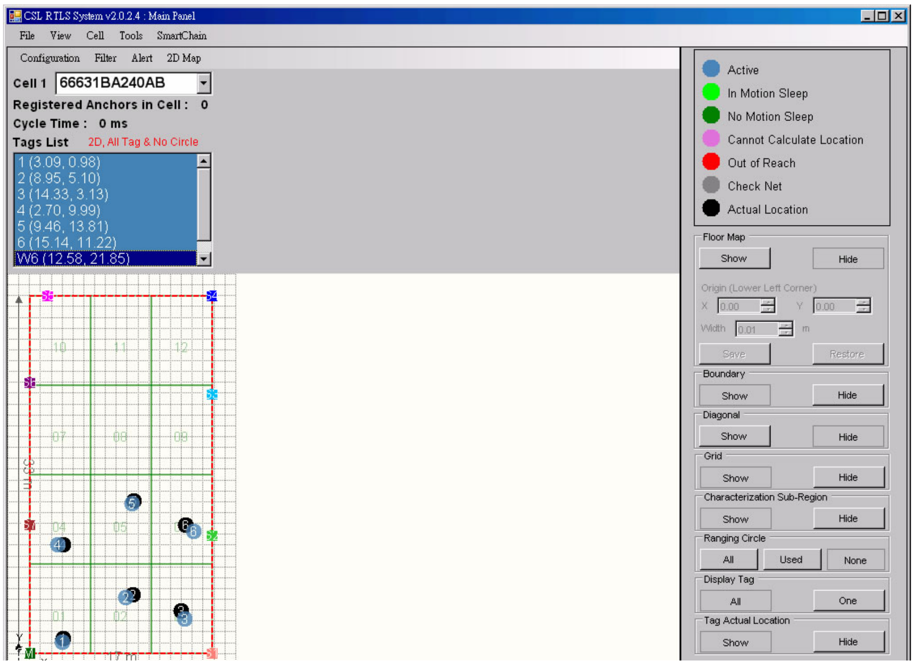
3.1.3 Application Software

The master anchor is connected to a computer over an Ethernet cable, where it is installed the host application server (3.3). To obtain the location in two dimensions, all is needed is to introduce the exact coordinates of anchors and the system will compute location automatically.

The software is written in C# and almost all source code is provided with the development kit. The *RTLS* software is responsible for managing tags information, such its last location, low battery warnings, its state, etc [27]. This application have automated tools to improve efficiency of the location such as:

- Anchor Network Optimization
- Range Accuracy Analysis
- Location Accuracy Analysis
- Multipath characterization
- Anchor Tag Performance Optimization
- Anchor Configuration Optimization

The automatic tools to improve efficiency consists in provide environment data into the application software, i.g. furniture location in the deployed area in order to predict multipath.



Cell 1 66631BA240AB

Registered Anchors in Cell : 0

Cycle Time : 0 ms

Tags List 2D, All Tag & No Circle

1 (3.09, 0.98)
2 (8.95, 5.10)
3 (14.33, 3.13)
4 (2.70, 9.99)
5 (9.46, 13.81)
6 (15.14, 11.22)
W6 (12.58, 21.85)

X 0.00 Y 0.00

Width 0.01 m

Figure 3.3: RTLS Application Software

3.1.4 Covering Angles

The development kit acquired, is the previous version that is available for selling now, with a limited cover angle of 80 degrees horizontally and 30 degrees vertically, as it is depicted in the figure 3.4.

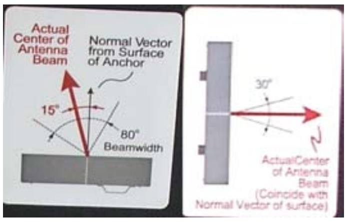


Figure 3.4: Limit Covering Angles - on left side horizontal and on right side vertical

3.2 Resume

In this MSc thesis the main purpose was the assessment of this technology robustness. It was important to ascertain how the application processes information to provide the location of the tag. Unfortunately, is not given access to data, that is used to estimate distances between base stations and mobile station. This means that possible outliers identification, which can lead to further computing location optimization, was not achievable.

The main limitation presented by this specific solution is the fact, in a large-scale implementation, to obtain real-time location of various objects, that would only be done by using tags compatible with this system, i.e. the tags of the same supplier.

The Convergence Systems Limited's RTLS Development Kit is indeed, a device with a great potential, putting an end to the problematic of an expensive and inaccessible indoor real time positioning.

Chapter 4

Algorithm Development and Tests Planing

Throughout this chapter special attention will be given to the study of the reliability of the implementation of the *RTLS* development kit [25] and if possible, what are the important steps to its correct deployment to three dimensional real time location.

4.1 Implementation Requirements

This document started to present the main requirements in the chapter 1, to introduce the scope of this MSc thesis. Like any other product that companies want to introduce in their core business, a wide study is required, in order to evaluate the implementation cost and the potential gain extracted from it. The ambient to install the application can be very adverse, actual the worst case scenario, with metal walls and shelving, organic pieces, in which are consisted essentially by water, e.g. in cold chambers in the food industry. It is likely the multipath and attenuation factors influence the signal that is used to measures ranges.

To acquire the *know how* on the application functionality it is important to test the system in different scenarios, with the intention to understand its core issues to late be deployed in industrial environment. Focus on error forecasting, understand the error behaviour and characterize it is important to the position estimation optimization. Starting with a comfortable environment, the outdoor scenario is more indicated, as the walls and objects in the middle of the area can be avoided. Indoor is the main solicitation of this technology, thus is very important to test it in this environment and understand how the main issues (multipath and attenuation) can affect the final positioning.

A 3D location can be very interesting, giving the location of the object vertically, know how high it is on the shelf, wherefore should be taken measures to facilitate the calculation of a third coordinate.

RTLS have several resources to optimize the location sensing. The *GPS* is one of the technologies that studies the influence of *BSs* position in final location accuracy, using mainly the *DOP* calculation to measure the sensitivity of the coordinates in the final calculation.

Therefore, study of the geometry weight is known as Dilution of Precision and must be taken seriously.

4.2 Development Kit Operational Survey

After choosing the right development kit, the main concern was to understand its *Modus Operandi*, meaning its hardware features and its communication protocols, with the special need to learn how it estimates the distance of the tag to each anchor. Unfortunately, the source code provided by the seller of the development kit, is not totally available to the customer, maybe to escape the plagiarism, what is understandable, since data packet and its protocol is one of the more important elements of the equipment functionality.

It would be important to know every step of the acquirement of the *ToA* given by the equipment, to confirm its accuracy or making improvements. Looking to the available source code, it seems to have a ranges screening, excluding some that are consider unreliable. The exclusion of the bad ranges can be in some cases evaluated by the *Signal-to-noise ratio* (*SNR*), or by identifying reflected signals, which an eventual access to that information through the source code is not reachable.

With the source code, it is possible to look into the code that creates and draws the different windows of the host application. There is one window on the application, where every online tag is displayed with the information regard to it, with special focus of course on its ranges to varied *BSs*. Thus, was possible to catch the most important data: distances to each *"satellites"* of the development kit, where readings time was recorded with the help of *windows* internal clock, which is synchronized by the internet, creating a log data file captured trough the equipment.

4.3 Iterative Least Squares Algorithm

For calculating the position of a given tag was implemented *Least Squares* (*LS*) algorithm. This algorithm is widely used in *Real Time Locating Systems*, wherefore quadratic standard is the best option when, there are more equations than unknowns. It is being used the trilateration technique, which have a prerequisite: it needs at least three *BSs* to obtain three coordinates. With it is possible to minimize the sum of square errors iteratively made by its computation, knowing from the beginning that input values are estimations of real values, in this case range distances.

LS algorithm was implemented in Matlab environment, since it has an easier algorithm development interface and has matrix handling capabilities.

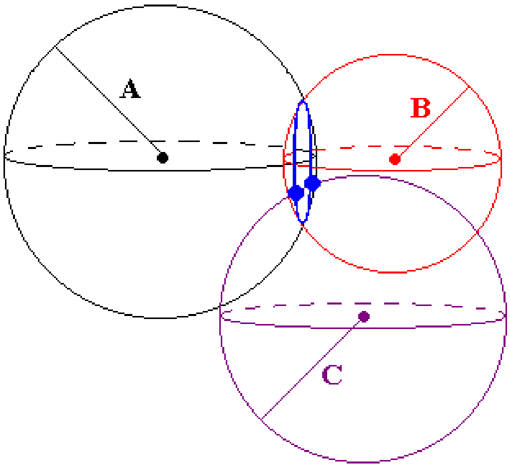


Figure 4.1: GPS - Ranges Spheres Intersection [3]

This problem formulation was based on the paper [28], but differs in the iterative solution. The author introduce the problem with a simplification for 2-D and here it is computed in 3-D. The *MS* coordinates are represented as the following vector:

$$l_0 = \begin{bmatrix} x_0 & y_0 & z_0 \end{bmatrix}^T \tag{4.1}$$

Each *BS* is identified with i, respectively:

$$l_i = \begin{bmatrix} x_i & y_i & z_i \end{bmatrix}^T {}_{,i=1,2,..,N} \tag{4.2}$$

The distance range between each *BS* to the *MS* is the norm of the difference of the two respectively vectors:

$$r_i = \left\| l_0 - l_i \right\| {}_{,i=1,2,..,N} \tag{4.3}$$

The best equation to represent 3D positioning, is the one with the spheres intersection using Cartesian coordinates.

This terminology is indicated to compute location because, imagine that each *BS* have a virtual sphere with radius equal to the respectively range. Predictable, these virtual spheres will intersect and that intersection point is the exact location of the *MS*. Read ranges are expected to be slight larger than the real ones, due to distance error estimation, what will generate not an intersection point but a space where the *MS* can be. It is possible to visualise this even on the example image from the *GPS* (figure 4.1):

Added an error factor to the estimation of the distance, from likely disturbance in the environment, thus:

$$r_i = \sqrt{(x_0 - x_i)^2 + (y_0 - y_i)^2 + (z_0 - z_i)^2}_{,i=1,2,..,N} \tag{4.4}$$

The next equation (4.5) is the vector with the estimated coordinates of the *MS*, which initial coordinates are not important because the solution will naturally converge to its estimation. With the exception that can result in more number of iterations, thus the coordinates of the *MS* are:

$$\hat{l} = (\hat{x}_0, \hat{y}_0, \hat{z}_0) \tag{4.5}$$

The equation 4.6, refers to the difference of the real coordinates and the estimated ones:

$$\Delta l = (x_0 - \hat{x}_0, y_0 - \hat{y}_0, z_0 - \hat{z}_0) \tag{4.6}$$

Afterwords, real position is equal to:

$$x_0 = \hat{x}_0 + \Delta x_0 \tag{4.7}$$

$$y_0 = \hat{y}_0 + \Delta y_0 \tag{4.8}$$

$$z_0 = \hat{z}_0 + \Delta z_0 \tag{4.9}$$

Together 4.7, 4.8, 4.9 to 4.4:

$$\hat{r}_i = \sqrt{(\hat{x}_0 + \Delta x_0 - x_i)^2 + (\hat{y}_0 + \Delta y_0 - y_i)^2 + (\hat{z}_0 + \Delta z_0 - z_i)^2} \tag{4.10}$$

Modelling the problem using the *LS* approximation [29], using the approach to minimize the residual square errors with a sum:

$$g\left(\Delta x_0, \Delta y_0, \Delta z_0\right) = \sum_{i=1}^{N} \left(\|\hat{r}_i\| - r_i\right)^2 \tag{4.11}$$

Without put any restriction to parameters, a linearisation is made and to compute its minimum:

$$\bigtriangledown g = 0 \tag{4.12}$$

Or the equivalent:

$$G_i = \bigtriangledown g \tag{4.13}$$

Partial derivatives of the range with respect to the variable that are intended to be minimized in the equation 4.10, together:

$$G_i = \begin{bmatrix} \frac{\partial r_i}{\partial \Delta x_0} & \frac{\partial r_i}{\partial \Delta y_0} & \frac{\partial r_i}{\partial \Delta z_0} \end{bmatrix}_{\Delta x_0 = \Delta y_0 = \Delta z_0 = 0} \tag{4.14}$$

For each derivative:

$$\frac{\partial r_i}{\partial \Delta x} = \frac{1}{2}\frac{2(\Delta x_0 + \hat{x}_0 - x_i)}{\sqrt{(\Delta x_0 + \hat{x}_0 - x_i)^2 + (\Delta y_0 + \hat{y}_0 - y_i)^2 + (\Delta z_0 + \hat{z}_0 - z_i)^2}}\Bigg|_{\Delta x_0 = \Delta y_0 = \Delta z_0 = 0} \tag{4.15}$$

$$= \frac{\hat{x}_0 - x_i}{\sqrt{(\hat{x}_0 - x_i)^2 + (\hat{y}_0 - y_i)^2 + (\hat{z}_0 - z_i)^2}} \tag{4.16}$$

$$\frac{\partial r_i}{\partial \Delta y} = \frac{1}{2}\frac{2(\Delta y_0 + \hat{y}_0 - y_i)}{\sqrt{(\Delta x_0 + \hat{x}_0 - x_i)^2 + (\Delta y_0 + \hat{y}_0 - y_i)^2 + (\Delta z_0 + \hat{z}_0 - z_i)^2}}\Bigg|_{\Delta x_0 = \Delta y_0 = \Delta z_0 = 0} \tag{4.17}$$

$$= \frac{\hat{y}_0 - y_i}{\sqrt{(\hat{x}_0 - x_i)^2 + (\hat{y}_0 - y_i)^2 + (\hat{z}_0 - z_i)^2}} \tag{4.18}$$

$$\frac{\partial r_i}{\partial \Delta z} = \frac{1}{2}\frac{2(\Delta z_0 + \hat{z}_0 - z_i)}{\sqrt{(\Delta x_0 + \hat{x}_0 - x_i)^2 + (\Delta y_0 + \hat{y}_0 - y_i)^2 + (\Delta z_0 + \hat{z}_0 - z_i)^2}}\Bigg|_{\Delta x_0 = \Delta y_0 = \Delta z_0 = 0} \tag{4.19}$$

$$= \frac{\hat{z}_0 - z_i}{\sqrt{(\hat{x}_0 - x_i)^2 + (\hat{y}_0 - y_i)^2 + (\hat{z}_0 - z_i)^2}} \tag{4.20}$$

Using the partial derivatives, is made a step in the other way around, it is estimated the ranges through the estimated coordinates x, y and z of the *MS*.

The result is an equation that will help to minimize the residual error, approaching the estimation to the best result, trusting on input ranges values, with the following equation:

$$\hat{r}_i = [\hat{x}_0 - x_i, \hat{y}_0 - y_i, \hat{z}_0 - z_i] \tag{4.21}$$

The *LS* residuals are given by the next equation, where it will be used as a condition case to stop the iteration when almost equal to zero, because has null trend as desire, except when the sum errors are to big:

$$\Delta h = r_i - \sqrt{(\hat{x}_0 - x_i)^2 + (\hat{y}_0 - y_i)^2 + (\hat{z}_0 - z_i)^2} = r_i - \|\hat{r}_i\| \tag{4.22}$$

The *LS* approximation consists in the sum of square residual errors. Once that the *LS* approximation use a system of linear equations it can be transposed to a system matrix based form, where each row denotes a *BS*.

On this specific *LS* linearisation the solution of the equation 4.14, arises:

$$\Delta h = G\Delta l \tag{4.23}$$

Not forgetting, the goal is to compute the position residuals, to be able approximate the coordinates to its best guess, depend on range errors. Thus:

$$\Delta l = \left(G^T G\right)^{-1} G^T \Delta h \tag{4.24}$$

Finally, in core iteration step is important to update the location estimation, where the approximating factor used was $k = 0.5$. This used factor intents to approximate the estimation with a little step, since if would be used an unitary factor would might result in an infinite loop because this *LS* quadratic error used has errors associated. Obviously, this $k = 0.5$ factor will result in a larger number of iterations, but this will not be a problem since the iteration is quick enough, therefore:

$$\hat{l} = \hat{l} - 0.5\Delta h \tag{4.25}$$

The computing cycle continues: estimated coordinates trend to converge to its best possible values, clearly conditioned by the quality of read ranges between the *BSs* and the *MS*.

Computation steps repeat the iterations starting from 4.22 until 4.25 after a best guess found.

4.4 Precise Real-Time Kinematic Differential Global Positioning System (DGPS)

This MSc dissertation consists in a study of a *RTLS*, therefore it was necessary to obtain a basis for comparison. Thus, it was need help of a tool that provides real-time location with high accuracy, such as *RTK* (*Real-Time Kinematic*) *GPS*.

Currently, *GPS* is wide used in divers assignments, with reasonable accuracy of few meters. However, there are implementations in which better accuracy is required and this need came from new approaches to improve the *GPS*. The Differential GPS arose with the need of an accurate real time positioning, in coastal or airborne navigation.

The *DGPS* is based at least of two receiving *GPS* stations, a reference station and the mobile station (*MS*) used to perform the location. The reference station must be located in a known fixed position, while the second receiver the *MS*, profits of an improved accuracy. Knowing the exact location of the base station (*BS*) and after receive the ranges of distance to each satellite, becomes possible to estimate the clock offset and therefore compute the deferential correlations of ranges to each satellite, as shown in the figure 4.2.

The *RTK* is an improvement of *DGPS*, where it usually receivers do not line up correctly, resulting in a delay on the compensation given by the *BS* to the *MS*. Therefore, *RTK* kept the received signal, copy it until line the delays of two receivers. This storage of values used by *RTK* will make that signals line up their delays properly and this alignment will provide satellites delays, improving accuracy up to 1 centimeter [30].

4.4.1 Mapping Projection

This specific development kit used, is based on Cartesian coordinates, thus it is needed to transform *World Geodetic System*, more specifically WGS84 given by the *RTK GPS*.

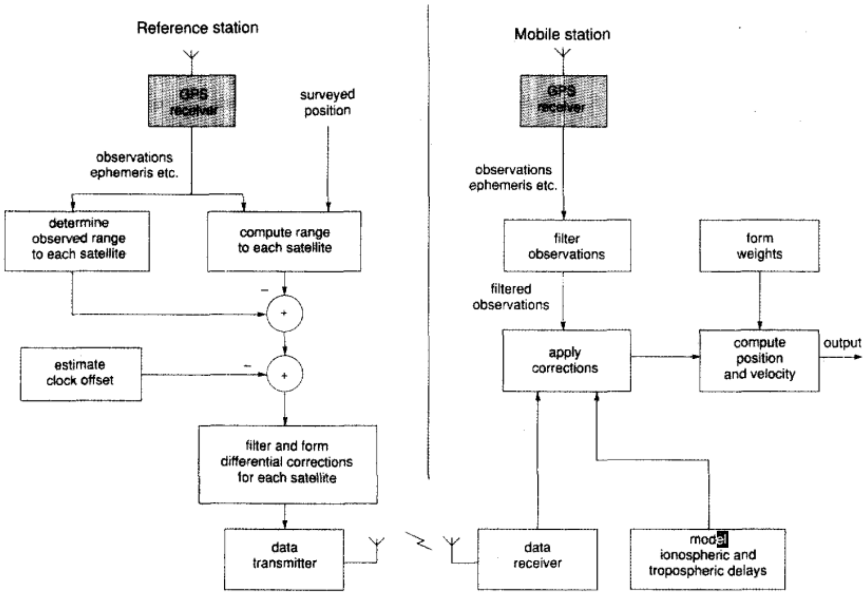


Figure 4.2: Simplified functional diagram of a generic differential GPS system [4]

Projections of the surface of the earth are well studied in the world mapping, in this case it is more advantageous to the *Universal Transverse Mercator projection* (*UTM*). *UTM* is based on the approximation of the surface along the longitude of earth by a cylindrical surface.

The algorithm of *UTM* was already implemented by the Prof. Sérgio Cunha, which helped in the equipment location assessment.

4.5 Tests Planing

The first step of this wide study of the indoor *RTLS* based on active *RFID*, was to understand the exact functionality of the development kit chosen, such as the hardware features related to the communication protocols used between the three elements of the system, reader, tag and application host server as it is referenced in the chapter 3.

Aiming to the development of this MCs thesis, is important to understand how are communication protocols and how technology used can influence the overall accuracy obtained through this *RTLS*. Unfortunately, the piece of the code related with the communication protocol and calculations that gives the distance ranges between the tag and the anchor, is encrypted using *.dll* files. This becomes an obstacle on complete achievement purposed of this study. Howsoever, the source code allows the observation and the creation of a record of distance measurements into a data log file. Using the log file is possible to record ranges of each anchor to each tag and its exact moment, given by the hour provided by the OS, synchronized online.

The tests results and conclusions can be found in the chapter 5. This section aims the presentation of the factors that most likely, are important to the error characterization and thus fall in the test requirements.

4.5.1 First Outdoor Test

In order to test the performance of the development Kit, it is needed to test the equipment in an ideal ambient (absent of multipath, potential attenuation factors, e.g. furniture, persons between the anchor and the tag). The dependency of the direction and angles of the antennas are important to verify, so each anchor was pointed to the center of the area to perform the location sensing. A study like this is possible, extracting the exact location of the area inside of the cell covered, with the *RTK GPS*.

4.5.2 Anechoic Chamber

The vendor of *RTLS* equipment has been careful to inform, that the antenna does not have the ability to read the signal sent by the tag in any direction. Actual, the signal reception direction is in some way restricted, with only 30 degrees vertically and 80 degrees in horizontal directions, as it is explained in the chapter 3. Understanding the variation of the error with the different angles of reception can be crucial in the final precision. Thus, it might be important and interesting to perform a test inside of an anechoic chamber, available at the University, to read phase difference, and direct reception of the signal, without any reflections or multipath.

4.5.3 Indoor Test

Transferring to indoor environment is predictable worst final result, but the final goal is to deploy the system in the same place. Perceptibly this is challenging, but is important to know if it has a reliable implementation and know the limitations. *LoS* requirement is important? The vendor says that is not needed, but does not forget to recommend it, due to objects attenuation.

4.5.4 Outdoor Geometry Test

The final test was planed to be at wide area, trying to have the best *BSs* geometry, that would be the ultimate test to its performance. Test the dynamic location precision, with a tag moving around the deployed area, against the 1cm error of *RTK GPS*.

4.6 Outliers Removal Optimization

Time-based *RTLS* usually have problems caused by multipath effect, which reflected signals interfere directly on accuracy of the measurement. Therefore, high precision clocks are need to distinguish which is original or reflected signal. In the case where it is received original and reflected signals, clearly is easy to identify the reflected signal, which is one with more *ToA* and good estimation is archived by trusting on the first received signal. In the other hand, if the signal cannot reach the receiver through a direct path, a bad or non estimation will occur with a reception of a reflected signal or in worst case non.

A reflected signal also decrease the signal strength, thus *SNR* will be lower. Nevertheless, *SNR* will decrease also with signal passing through objects, meaning that *SNR* should not be alone on outliers identifying. Accessing to data used in the range estimation, i.e. the *SNR*, the phase difference of the signal and the *ToA* would help to identify outliers, unfortunately in this MSc it was not possible to use it, due to lack of access to source code.

Outliers are extremely detrimental in the final solution, if the outlier is so big among other reasonable ranges, it can pull the estimated location to a very bad result. During this MSc, it was implemented the *LS* algorithm, which takes into account the quadratic residuals, used for its convergence. If an outlier happen among several readings, identifying it can lead to its exclusion, therefore an optimization.

Noticeably, its identification is a huge challenge to face, since that *MS* position is not known, thus is hard to conclude if a particular range is an outlier. For instance, the real range is 17 meters and the read range is 26 meters, is clear that is an outlier, with 9 more meters then its real value.

To overcome this obstacle, some attempts were made to identify outliers. The location of each *BS* and the area where *RTLS* is deployment is known, therefore the maximum range read by each *BS* is known. A read range that exceeds its maximum range is considered as an outlier, then it is automatically removed.

Another attempt implemented follows the following steps:

- Compute the location based on ranges given by the equipment using *LS* algorithm;
- Calculate the ranges that affects each *BS*
- Subtract each read ranges (r_i) by the computed ones (r_{im}), subtracting the average of ranges differences, as it is in the following equation:

$$w_i = abs\,(r_i - r_{im}) - \frac{\sum_{j=1}^{n} (r_j - r_{jm})}{n} \tag{4.26}$$

The result is an weight (w_i) given to each range measured in an instant, which the higher absolute value is consider to be the outlier if the difference is evident comparing with others weights.

This attempt to identify outliers is intrinsically wrong, since is based on *pseudoranges* with measurements errors associated. Furthermore, *BSs* geometry will be hardly a *regular hexahedron*, meaning that *BSs* are not separated by the same distance, a fact that is ignored on this calculation. Even so, this calculation can actually, in some cases identify evident and exaggerated outliers, leading to an optimization.

There are cases, wherein a final computed location is located out of the area where *RTLS* operates, due a probable outlier expressly wrong. For instance, the building have a fixed height, but the given result puts it outside. This can be minimized by putting the estimated position in the edge of the area deployed, or simply ignore the read, in which results is ruinous to object tracking.

Chapter 5

Test Evaluation and Results

This chapter describes how tests were developed in different scenarios. In this chapter all the data obtained is not exposed from the experiments carried out. The remaining data not presented on this chapter can be consulted in appendix, that is distributed as follows:

- *Outdoor First Test* is on appendix A
- *Indoor Test* is on appendix B
- *Outdoor Final Test* is on appendix C

5.1 Outdoor First Test

The first outdoor test had the main objective to test the equipment correct hardware functioning and ranging log into the data file, enabling a subsequent location calculation using the developed algorithms. The site was chosen due to the availability of a laboratory with easy access to *RTK GPS* server and equipment, where still filled the requirements of outdoor location, allowing to discard scenarios with multipath and attenuation.

Multiple *BSs* were set in the best possible geometry, covering the area in each corner of the chosen area. In order to compute vertical coordinate, two sensing cells were deployed in the top of the building.

In the outdoor experiments, a very useful *RTK GPS* tool was used, which enables to converted to a map projection using *UTM*, giving coordinates in three dimensions *(x,y,z)*. With *RTK* a real time positioning with an accuracy of 1 cm in the best case. The consider exact locations given by the *RTK* , were used to measure the exact locations of *BSs* and trajectory made by the tag. The path obtained through the *RTK* data can be compared with the computed location based on ranges acquired and the location given by the *RTLS*.

5.1.1 Experience Held

In the figure 5.1 is presented *BSs* location and the exact path given by *RTK* of the experiment held.

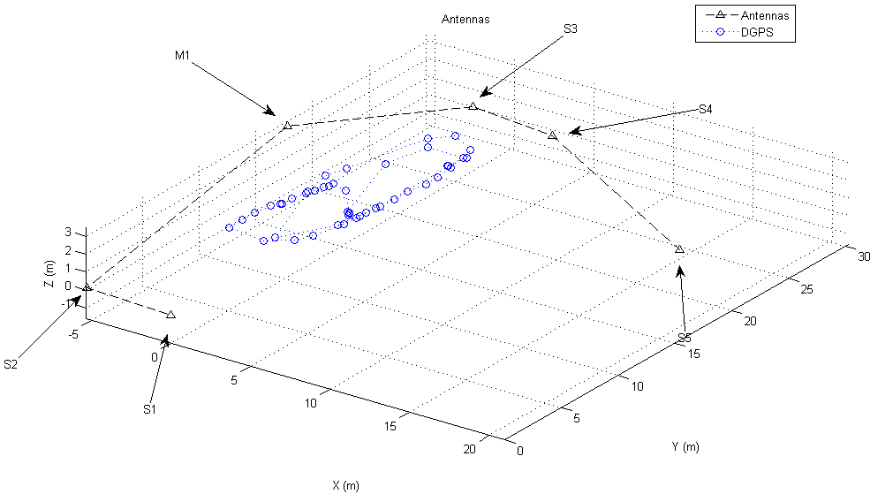


Figure 5.1: Base Stations location and *RTK* trajectory

5.1.2 RTLS 2D Location

The following figure 5.2, has the *RTLS* computed location versus *RTK*. This location with only two coordinates is provide by the application that manages the equipment.

5.1.3 LS 3D Location

Using data stored in the log file, it was possible to compute the position of the *MS* with the algorithm implemented. The location computed by *LS* algorithm is presented in the figure 5.3 (Top View) and in 5.4 (Side View), which is also possible to compare with the actual position.

In the presented figures it can be observed, for most of computed locations, that in the XY plan the positioning is somewhat accurate, around two meters error. It seems that X-coordinate weaker regarding Y-coordinate. In height, Z-coordinate is extremely vague, with an error up to 9 meters. Therefore, a *DOP* analysis is made ahead to see if it can be explained by the geometry of the *BSs*.

5.1.4 LS 3D Location Optimization

Optimization was not achieved, noting in the figures 5.5 top view and 5.6 side view.

The reason for this is that, there are not enough *BSs* to carry out the removal of a worst measure, because they all have similar error. So removing measures, will likely degrade the computed positioning.

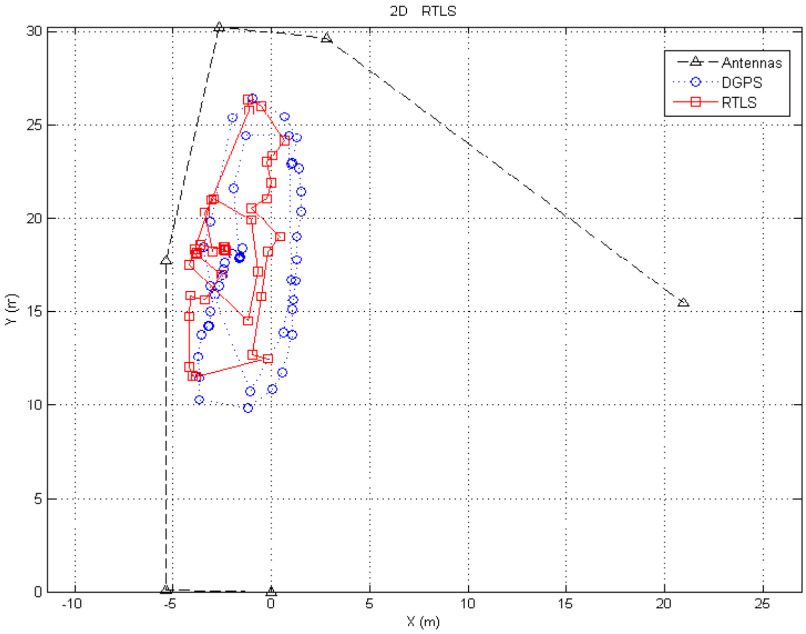


Figure 5.2: RTLS vs RTK

5.1.5 DOP Analysis

The imprecision of these data may be partly explained by *DOP*. The position of *BSs* clearly imposes a bad influence on the final location, which the height is more evident, with only two meters between the lower and the higher *BSs*. It is demonstrated in the *PDOP* calculation:

$$DOP = \begin{bmatrix} \sigma_x^2 & \sigma_{xy} & \sigma_{xz} \\ \sigma_{yx} & \sigma_y^2 & \sigma_{yz} \\ \sigma_{zx} & \sigma_{zy} & \sigma_z^2 \end{bmatrix} \tag{5.1}$$

In this case is:

$$DOP = \begin{bmatrix} 0.67 & -0.03 & 0.53 \\ -0.03 & 0.26 & -0.29 \\ 0.52 & -0.29 & 4.70 \end{bmatrix} \tag{5.2}$$

Where PDOP is given by:

$$PDOP = \sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2} = 2.37m \tag{5.3}$$

Analysing the *PDOP* calculations, it appears that the error introduced is associated with *BSs* geometry. The Z-coordinate is actually the weakest compared to the other two coordinates, reflected in the figure 5.4. Also the X-coordinate seems to be weaker relatively to Y.

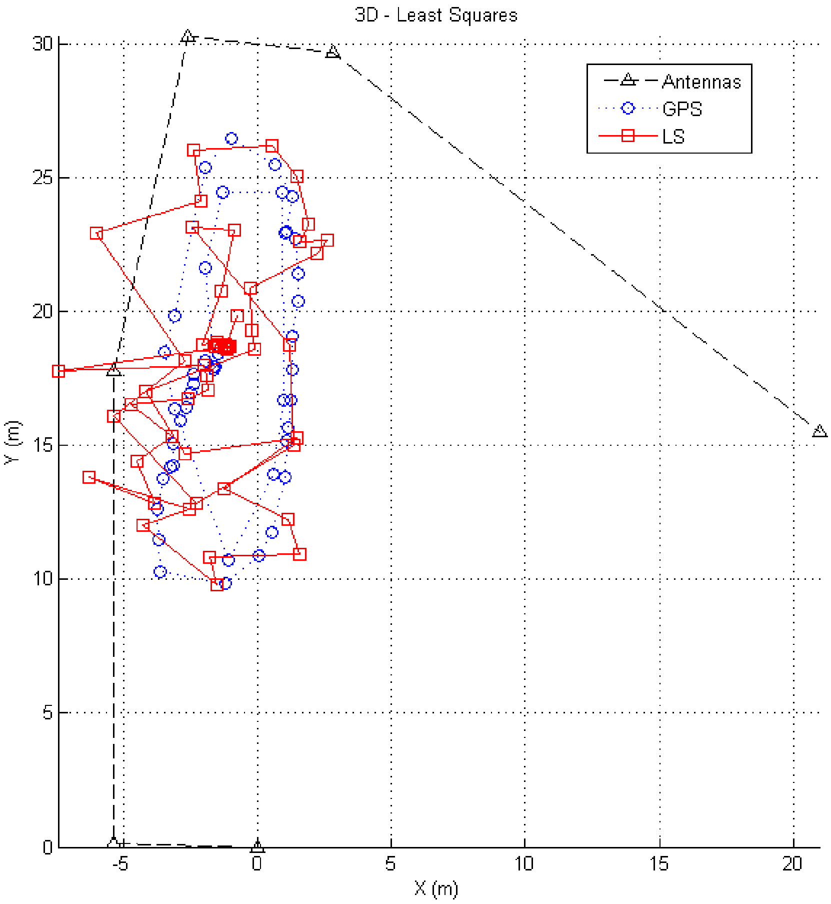


Figure 5.3: LS vs RTK - Top View

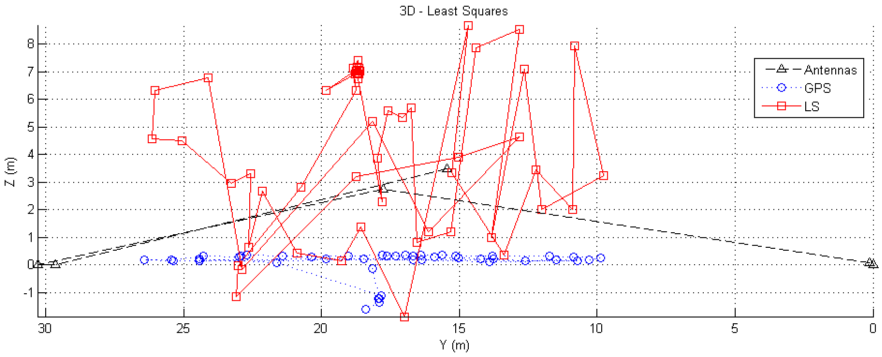


Figure 5.4: LS vs RTK - Side View

Observing the quality of geometry relative to *BSs* position (*PDOP*), results in 2.37, which is considered a good grade in *DOP* scale. *GPS* is certainly more robust, thus a small value of *PDOP* in *GPS* configuration will result in a worst rate when transposed to this *RTLS*.

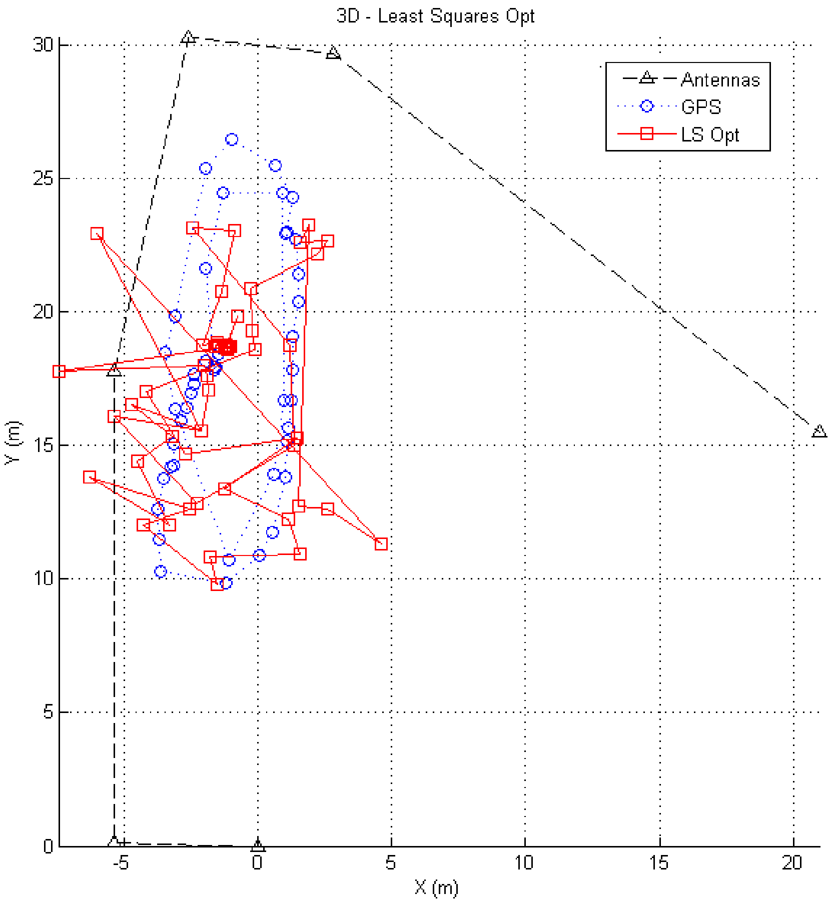


Figure 5.5: LS Optimized vs RTK - Top View

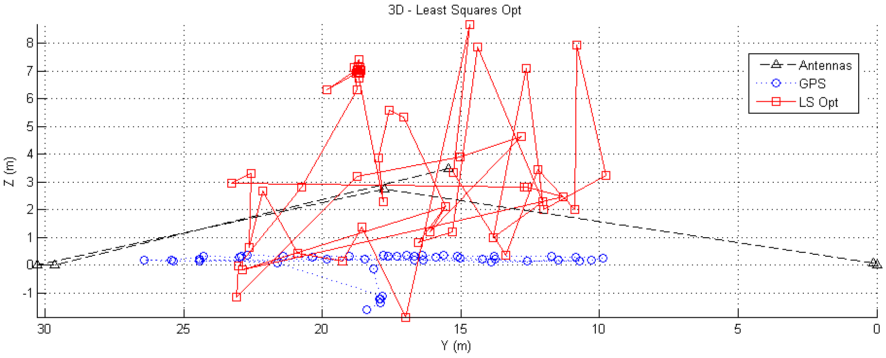


Figure 5.6: LS Optimized vs RTK - Side View

5.1.6 RTLS versus LS

Comparing the errors of coordinates given by the application of the development kit and the *LS* algorithm, for instance the X-coordinate in the figure 5.7, in the most of its values the *RTLS* application has less error then *LS*. The same occurs with the Y-coordinate represented in the appendix A.6.

One explanation could be that *RTLS* application has access to time estimation data and *SNR* of the signal to measure distances. Thereby, identifying outliers ranges and from there optimize the accuracy of the computed location.

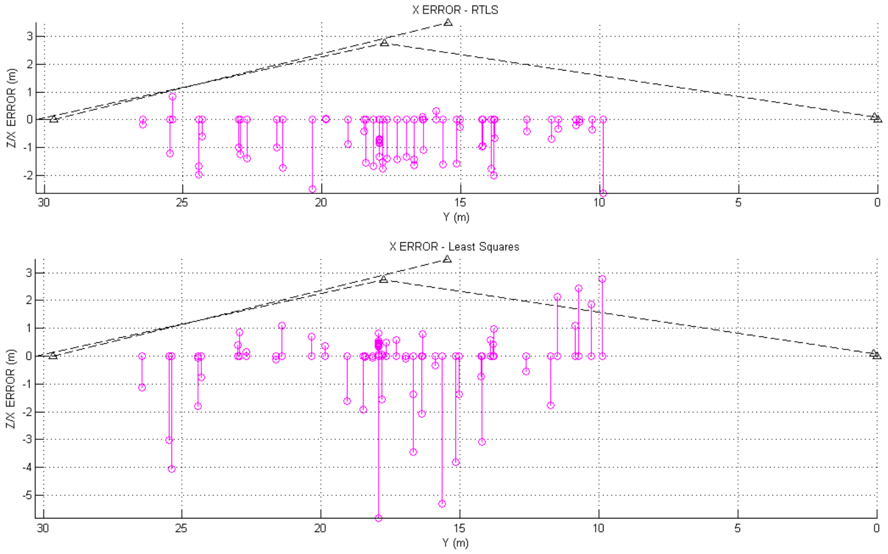


Figure 5.7: X Error - RTLS vs LS

5.1.7 Error Compared with Actual Range Distance

Furthermore, analysing each *BS* range error trough the actual distance of the *MS*, was not possible to identify any correlation between them, as is clear observing the cell named *S4* in the figure 5.8. There are sensing cells, which is evident an offset to most of the values, as the *S4* seems to have 1 meter more, which could be explained by inaccurate internal clocks or defect of the antenna.

5.1.8 Error Compared with Angle of Reception

Recalling the advise of the seller, the sensing cells have limited angle measurement, 80 degrees horizontal and 30 degrees vertical. Therefore, an assessment was made to learn, if the error varies with the angle of reception of the signal used to estimate the distance from the *MS*.

The angle was calculated using the arc cosine of the inner vector given by the two vectors. Assuming that the antennas were directed toward to the center of the deployed area, one of the vectors was estimated by the central point of the deployed area and the *BS*. The second vector, was computed between the actual position of the tag and the fixed location of the reader.

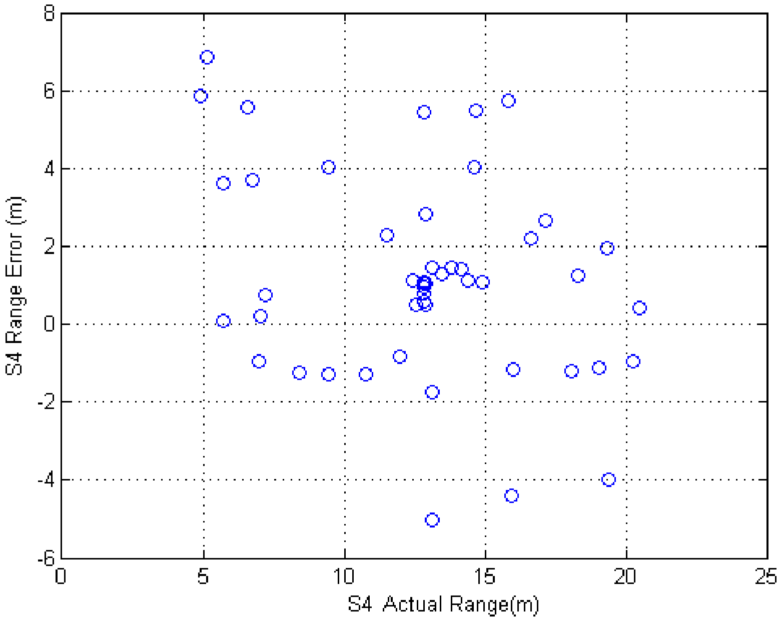


Figure 5.8: S4 Range Error

Looking at the representation of the error versus angles, does not seem that the error increases beyond the limits of the angles refereed by the vendor. E.g. *M1* reader in the figure 5.9 horizontal angle and figure 5.10 vertical angles.

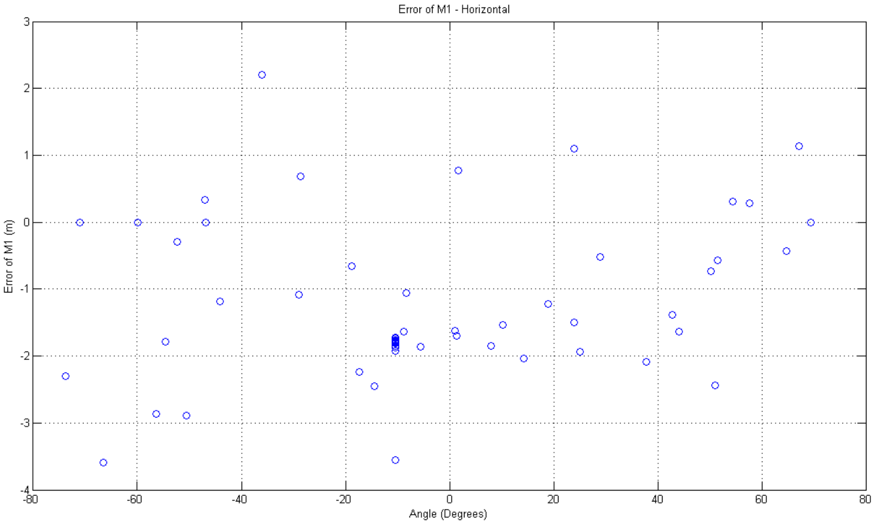


Figure 5.9: M1 Error in perspective with horizontal angles

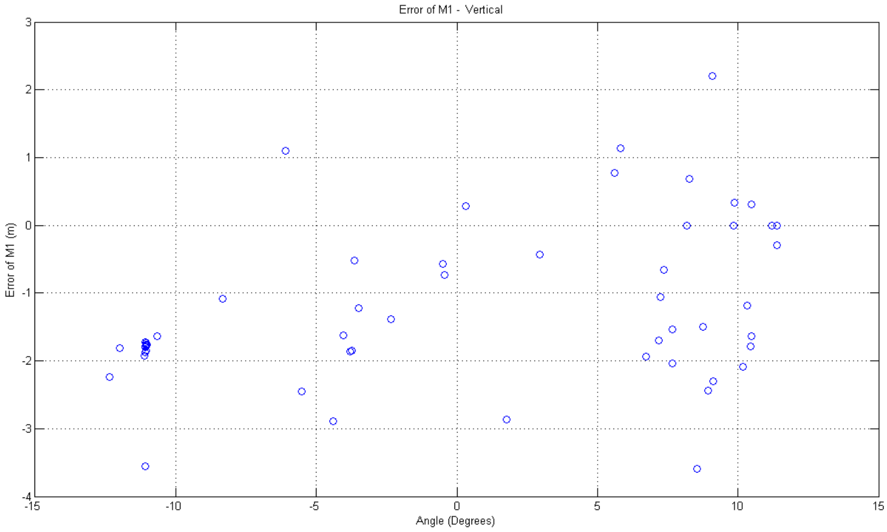


Figure 5.10: M1 Error in perspective with vertical angles

5.2 Anechoic Chamber Test

5.2.1 Description

The manufacturer informs that the reader antenna has a limited angles of the radiation pattern. Therefore the anechoic chamber test was used mainly to verify the influence of reception angles in ranges accuracy. The reader was placed on a rotating base, which had a pointer to the angle it was in, represented in the photo 5.11. The distance between the reader and the tag was exactly 4 meters.

Figure 5.11: Anechoic Chamber (on left the reader and on the right the tag)

Carried out the experiment, samples were extracted in range of -90 to 90 degrees with a step of 10 degrees, horizontally and vertically. Enough to to draw a curve of the weight average error in each step measured, results can be checked for horizontal side in the figure 5.12 and vertical side in 5.13.

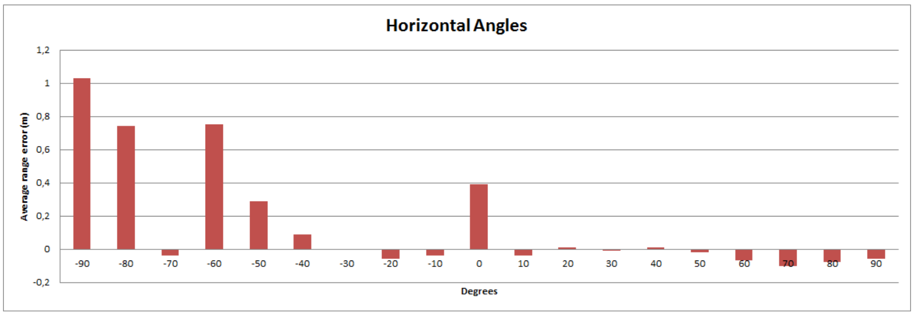


Figure 5.12: Anechoic Chamber Horizontal Average Range Error

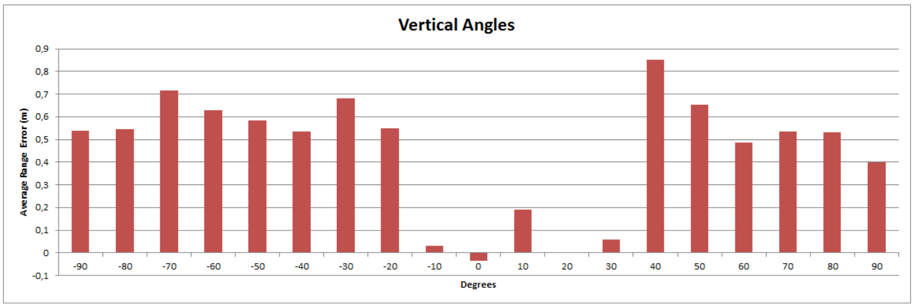


Figure 5.13: Anechoic Chamber Vertical Average Range Error

5.2.2 Results

After making the averages for the cases of vertical and horizontal angles, it appears that the limit angles are like the vendor specify.

The actual center of antenna beam, in the horizontal angles referred by the manufacturer is 15 degrees to the left of the center angle (0 degrees), meaning -15 degrees in the figure, what seems to agree. In the case of vertical angles of the actual center of antenna beam, seems to have a little offset of 10 degrees upper, but still limited to 30 degrees.

Generally the error is minimum in angles advised by the manufacturer, but it appears that the horizontal angles are a little bit more wide than the limits specified.

5.3 Indoor Test

The indoor implementation is the ultimate goal of this study, therefore is compelling the test in such environment, to evaluate the technology behaviour.

5.3.1 Experience Held

The test was performed in a industrial warehouse, with its major business is the food industry. Thus attenuations and multipath caused by metal shelving, celling and walls of the building are expected to happen. The area is based on shelving around 3.5 metes high. The equipment was assembled between two halls, with shelf in the middle of the area, shown in the photo 5.14.

Figure 5.14: Warehouse Deployment

A good location is critical, thus this test was to understand how much bad influence the computed position have by multipath and attenuations.

5.3.2 DOP Analysis

To evaluate the geometry of positions of the readers, the *DOP* was calculated. As a result shown below:

$$DOP = \begin{bmatrix} 2.06 & 0.28 & 1.19 \\ 0.28 & 0.21 & 0.04 \\ 1.19 & 0.04 & 6.16 \end{bmatrix} \tag{5.4}$$

Where PDOP is given by:

$$PDOP = \sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2} = 2.90m \tag{5.5}$$

With this data is already possible to anticipate that the X and Z coordinates precision will not be very good. Therefore, it is expected much different values of X and Z coordinates from their actual values.

5.3.3 Tests

Furthermore, four different experiments were made:

- The first experiment was performed only with the tag in the reference point *"tag1"* shown in figure 5.15, 1 meter high.
- The second experiment was to walk through the reference path, stop in each point for 10 seconds, with the tag about 2 meters high.

- The third experiment is exactly the same as the second experiment, except the tag was 3 meters high.

- Finally the fourth experiment, was to make the path in the same conditions as the second experiment, but with a second tag, placed in the reference point, 1 meter high presented in the figure 5.15, as *tag2*.

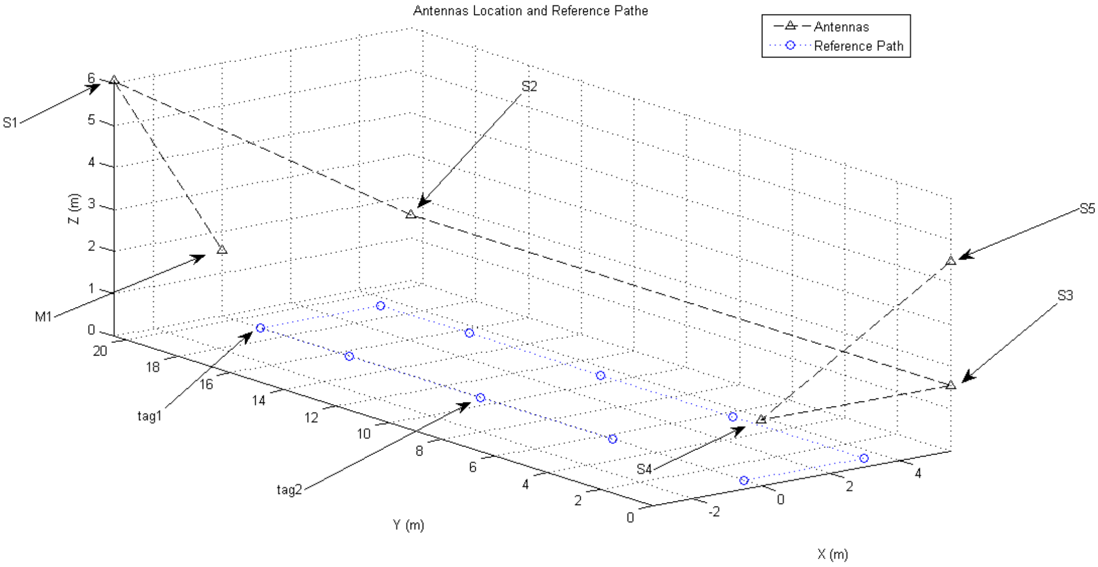


Figure 5.15: Reader Positions and Reference Path Points

BSs were placed by the warehouse to cover the corridors between the shelves, trying to maximize the robustness of its geometry. The most interesting result, which may be able to summarize all the conclusions of the varied measurements made, was the fourth experience. Wherefore, the overall accuracy of the locations in four experiments are around the same values. With primary attention, to poor quality of the X and Z coordinates in all the experiments, which are referred to be likely bad estimation, due to poor *BSs* geometry.

The reference tag named *tag2* used in the fourth experiment a fairly good accuracy that is undoubtedly remarkable. The reason for this may be the fact that, the tag incorporate a motion sensor, which can optimize the location, based on storing only the most accurate distances over time, approaching to their exact location. Even so this information can not be confirmed, wherefore the code is partially not accessible.

In the figure 5.16 is represented the *RTLS* locations estimation, the *LS* in the figure 5.18 side view and 5.17 top view.

Looking into the figure 5.19 (top view) and 5.20 (side view), the optimization of the location based on exclusion of the worst range measure, did not improve the computed positions, in any of

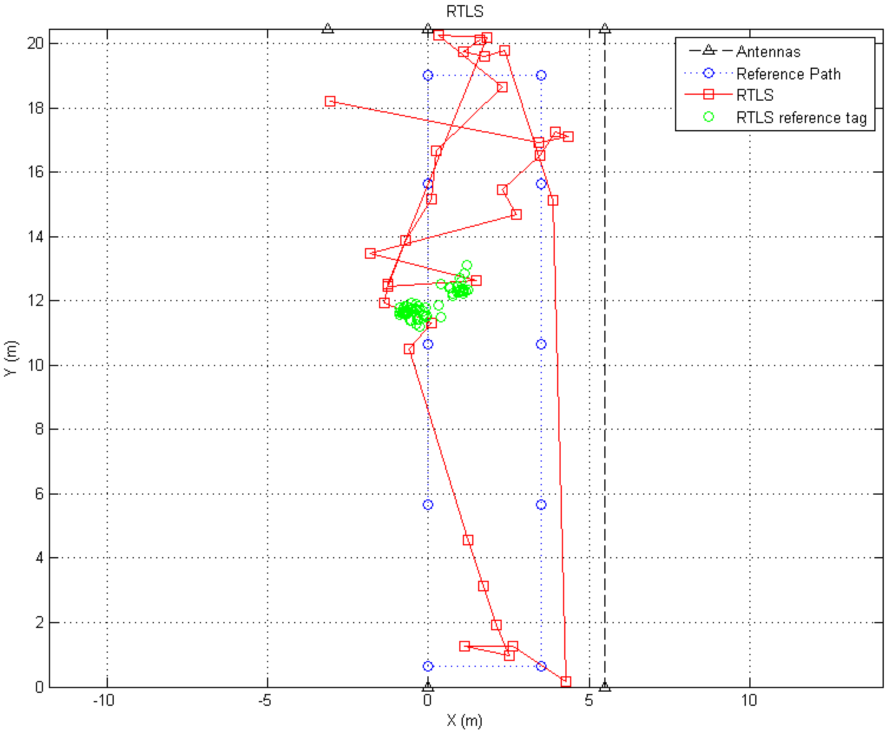


Figure 5.16: RTLS Positions - 4th experiment

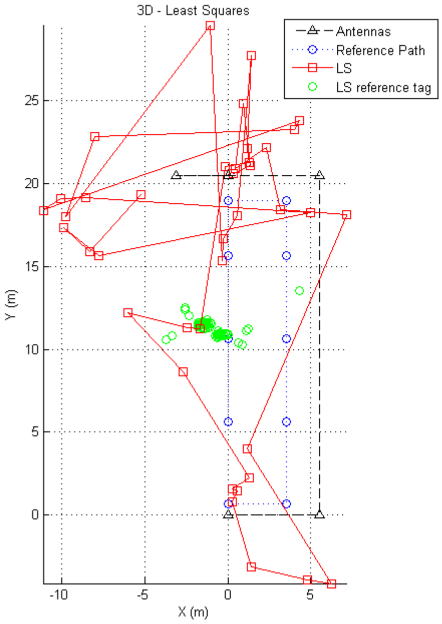


Figure 5.17: LS Positions - 4th experiment - Top View

the four experiments. The explanation is on the basis that, there are few readers to estimate the position, removing one of these measures will directly damage the final result.

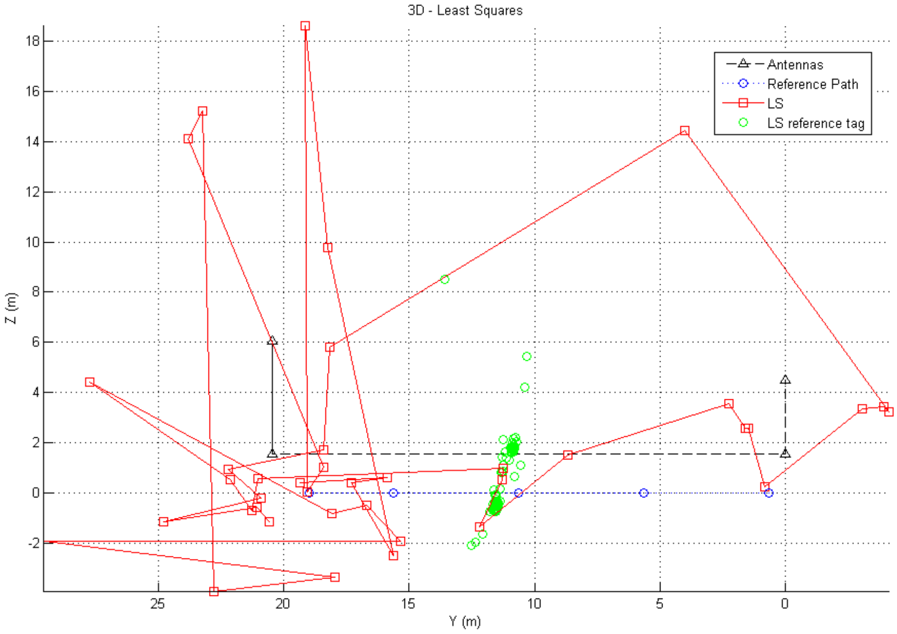


Figure 5.18: LS Positions - 4th experiment - Side View

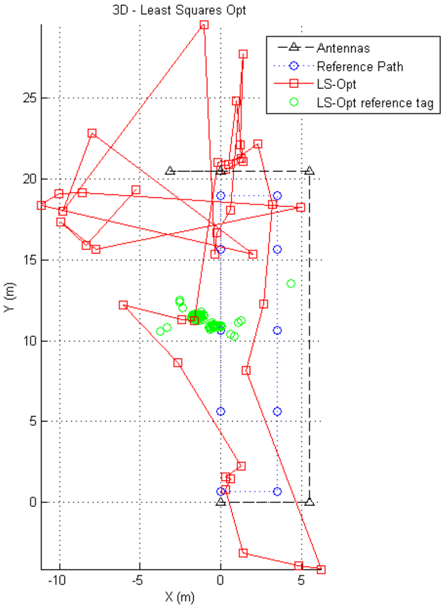


Figure 5.19: LS Optimized Positions - 4th experiment - Top View

5.4 Outdoor Final Test

Through the earlier tests, the major issue seems that was the geometry of the *BSs*. Therefore, this final test had the main concern the positioning of readers, to install them with more robust geometry as possible and in a wide space of the faculty 5.21.

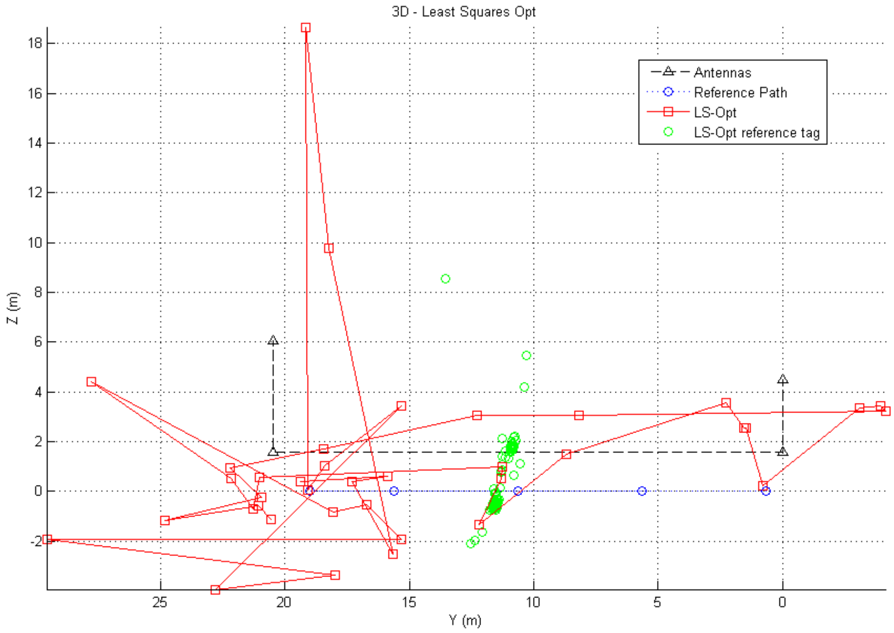


Figure 5.20: LS Optimized Positions - 4th experiment - Side View

Unfortunately, due to a lapse in specifying the exact location of a reader in the *RTLS* host application, resulted in a wrong location, which led to their exclusion in this section.

Figure 5.21: Outdoor Final Experiment Area

5.4.1 Experience Held

The development kit as had already been said in the chapter 3, had only six readers, but two extra readers become available.

From the previously tests, the worst coordinate always was the coordinate in height, thus was deployed four *BSs* higher then the experimented level (*S1, S2, S3, S6* and *S7*). The image 5.22 show the *BSs* locations and also the exact path made, given by *RTK*.

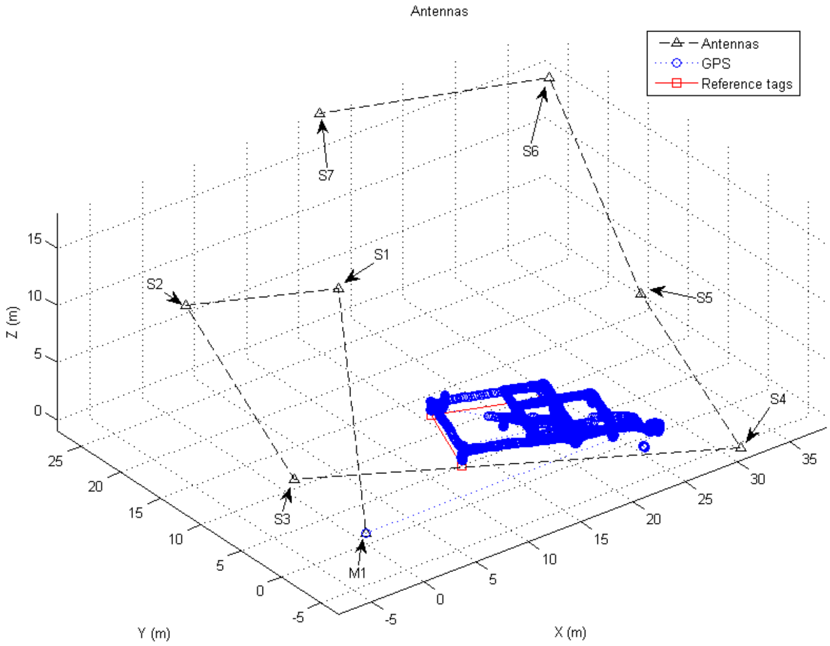


Figure 5.22: *BSs* and Path made

5.4.2 LS 3D Location

Computed the locations based on *LS* algorithm and knowing the location given by the *RTK*, the result is shown in the figure 5.23 (top view) and 5.24 (side view).

With the computation of locations using *LS* can be seen that, for the most of its values, accuracy is quite reasonable. A closer look, seems that the height coordinate have more error then the XY plane.

5.4.3 LS 3D Optimization

Also in this test, an optimization of the location was performed based on the exclusion of the worst estimated distance, in order to obtain a more precise positioning.

The result in this case was actually more satisfying than in previously experiments (side view fig. 5.25 and top view fig. 5.26), but it only helped to minimize outliers positions and did not put them in the actual location.

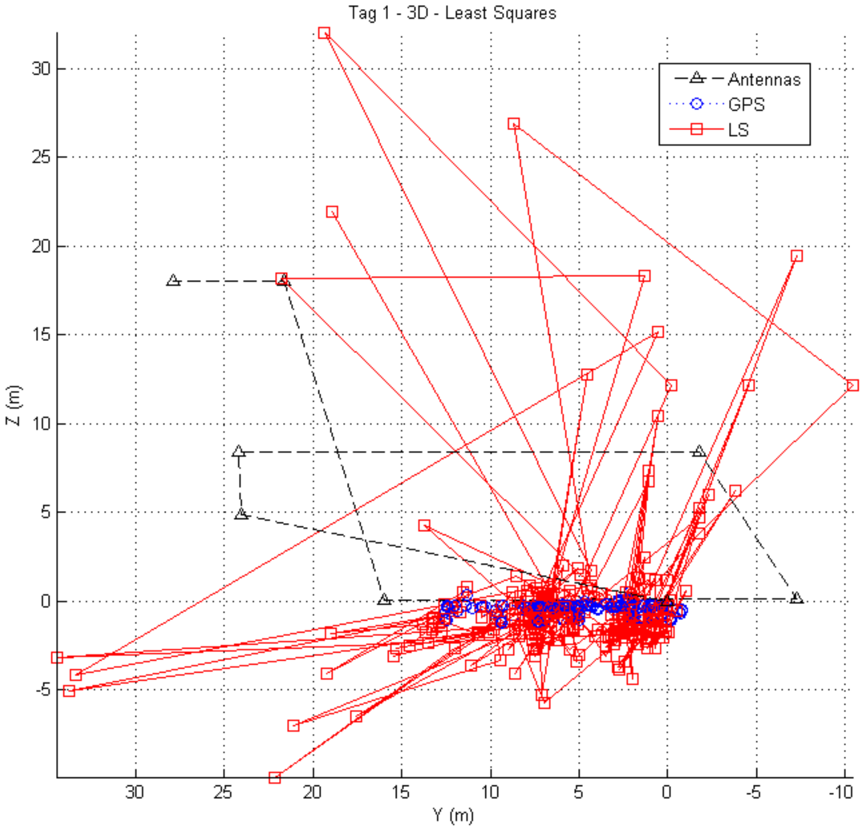


Figure 5.23: *LS* vs *RTK* - Side View

5.4.4 DOP Analysis

Performing the *DOP* calculations to check how strong is the geometry disposition:

$$DOP = \begin{bmatrix} 0.29 & -0.12 & 0.10 \\ -0.12 & 0.57 & -0.59 \\ 0.10 & 0.59 & 1.55 \end{bmatrix} \tag{5.6}$$

Where *PDOP* is given by:

$$PDOP = \sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2} = 1.55m \tag{5.7}$$

No doubt that this distribution of *BSs* is the best of previously experiments and this justify the good location estimation for most values, using the *LS* algorithm. The poor coordinate is the Z-coordinate and that agrees with the obtained data.

5.4.5 Reference Tags

The test was implemented using three reference tags, with the objective to compare static location data and the dynamic location in the above image 5.23.

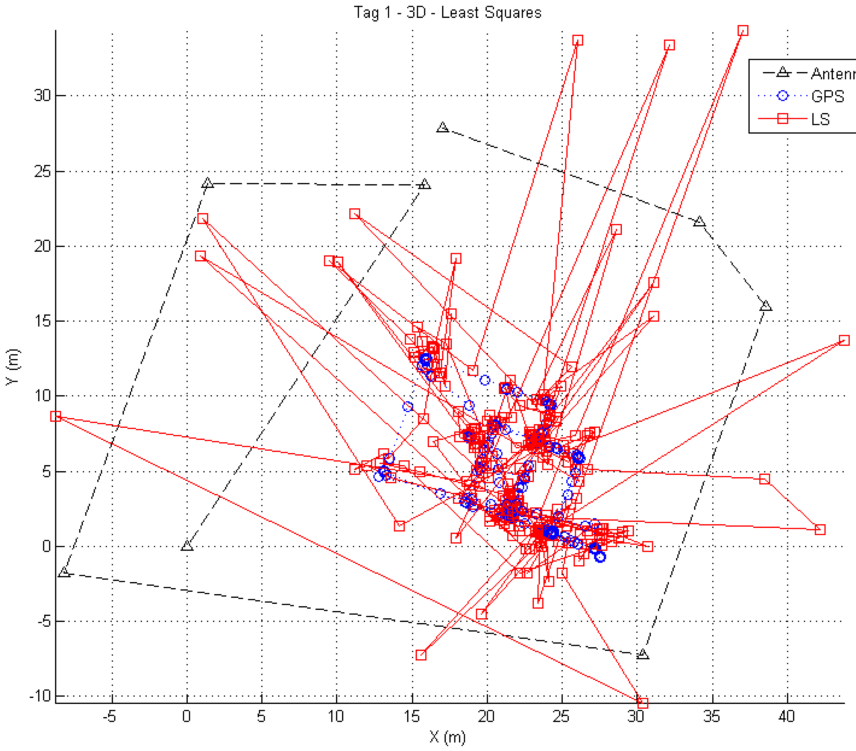


Figure 5.24: *LS* vs *RTK* - Top View

The result of locations of three reference tags were slight different, with better precision on the reference *tag1* and *tag3* than *tag2*. In the warehouse experiment the same effect happened: the accuracy of the reference tag seems to improve along the time due to the likely optimization caused by the motion sensor, where is possible to verify in the figure 5.27 and 5.28 for the reference tag *tag1*.

5.4.6 Error Compared with Actual Range Distance

Concerning the error compared to the actual distance, the conclusion is the same as the first experiment, the error does not vary with the distance from the *MS* concerning the *BS*. As example shown in the figure 5.29 for the reader *S4*.

5.4.7 Error Compared with Angle of Reception

The conclusion here is the same as the first experiment, the range error does not seems to be influenced by the angle of reception, in the *BS S5* is similar with the others, in the figure 5.30 for vertical angles and 5.31 for horizontal angles.

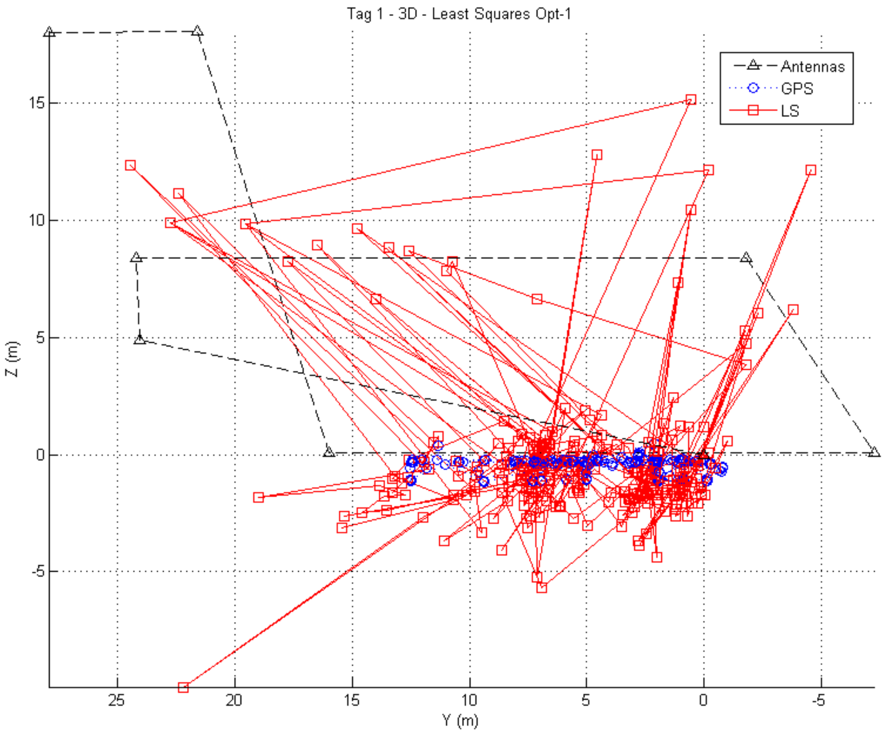


Figure 5.25: *LS* Optimization vs *RTK* - Side View

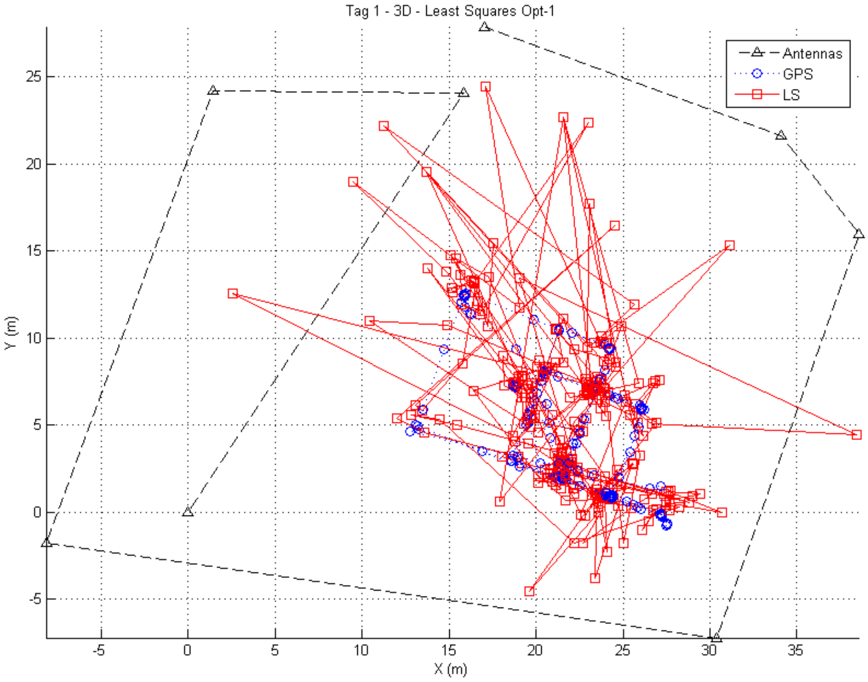


Figure 5.26: *LS* Optimization vs *RTK* - Top View

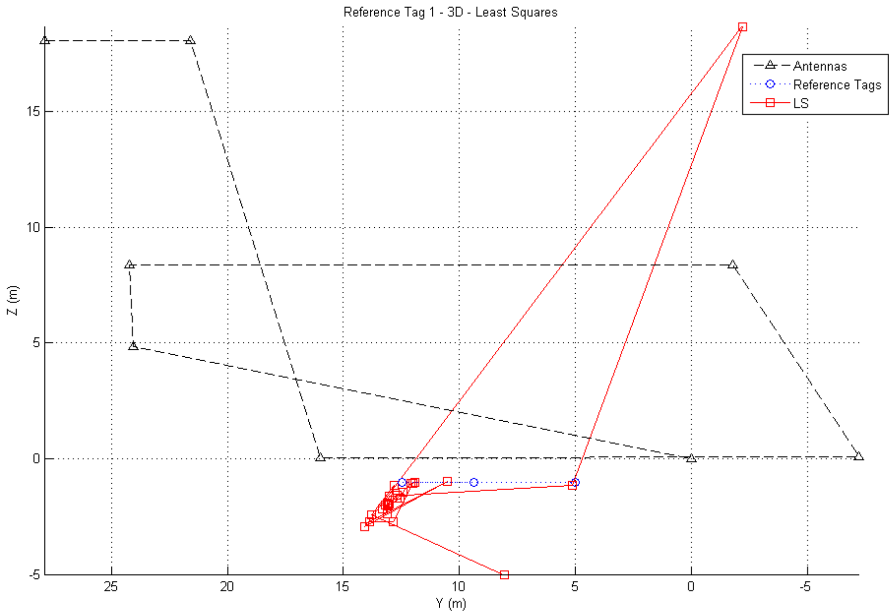


Figure 5.27: Reference *tag1* - Side View

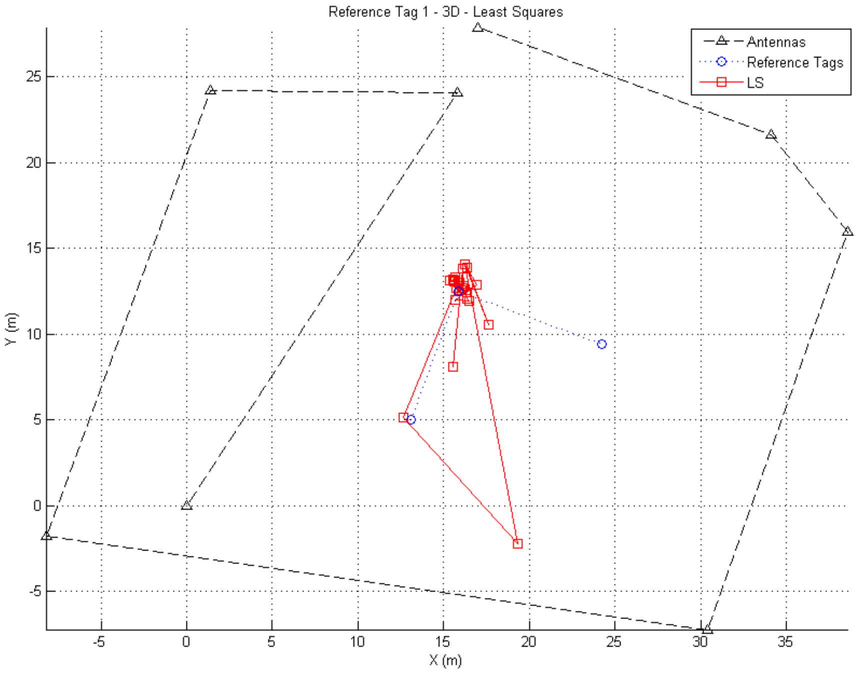


Figure 5.28: Reference *tag1* - Top View

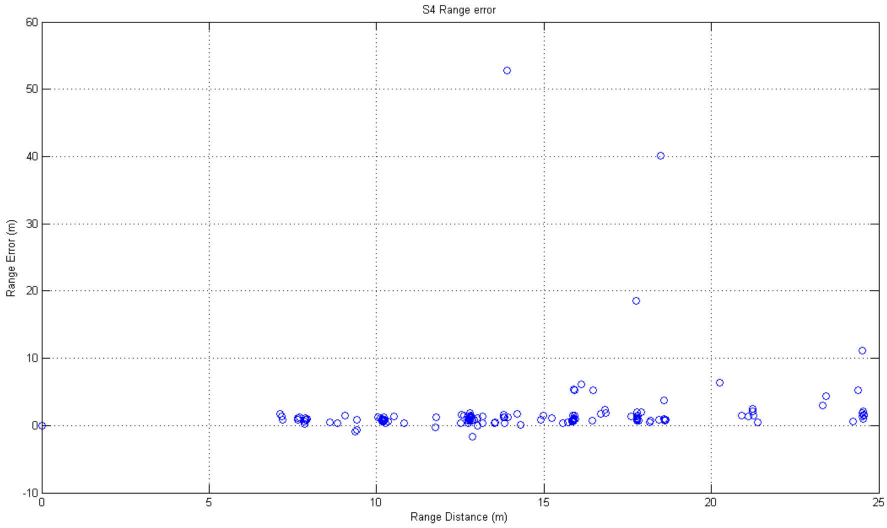


Figure 5.29: S4 Range Error

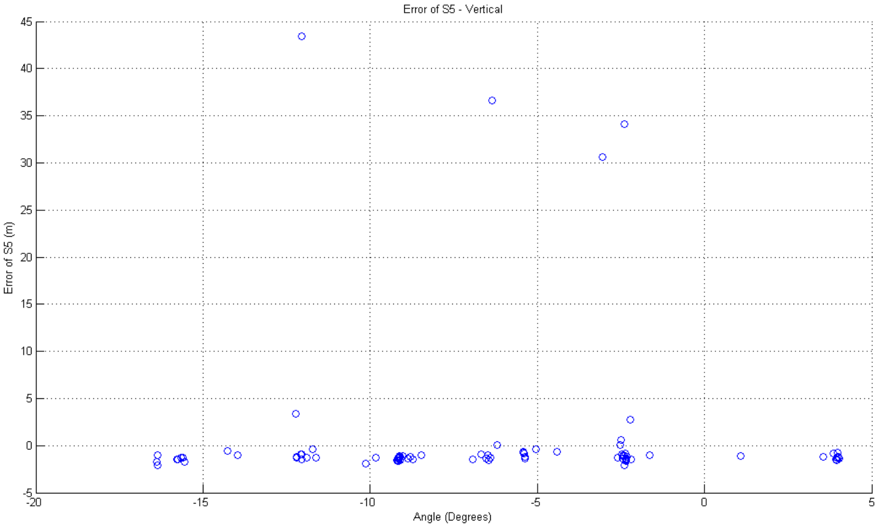


Figure 5.30: S5 Error in perspective with vertical angles

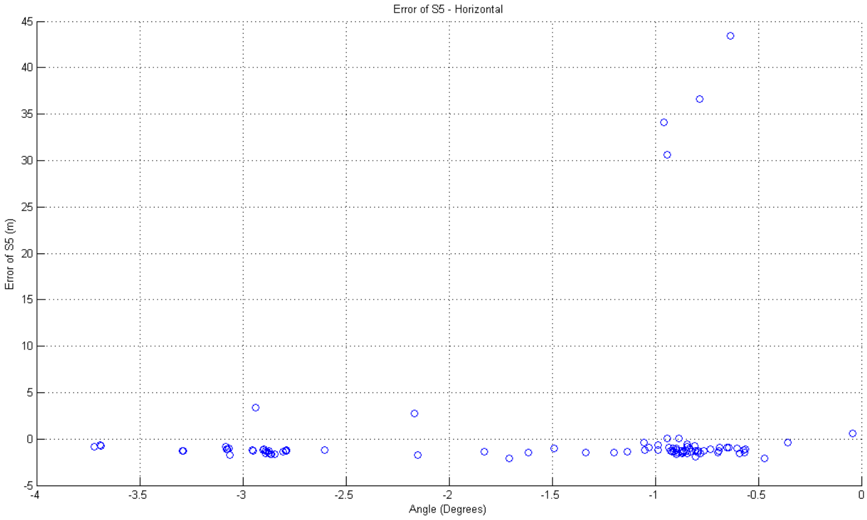


Figure 5.31: S5 Error in perspective with horizontal angles

Chapter 6

Conclusions and Future work

Throughout this MSc dissertation, with the aim of assessing the reliability of a tracking system in real time, based on *RFID* have been possible to draw conclusions on an industrial implementation.

After tests conducted in different environments, which were described in Chapter 5, this chapter are presented conclusive arguments about the developed work and as well future work to proceed to a reliable implementation.

6.1 Objectives Assessment

During the early stage of this MSc, the main concern was to choose a potential technology to the implementation of indoor sensing location. The development kit available in the market seems to have all the requirements to carry out different scenarios tests and to understand how well can locate the *MS*. The technology used seems to have a reliable location awareness with a low cost implementation, using RFID-based system through *ToA* to estimate distances.

Outdoor scenario was extremely important to understand how the locating system can improve precision and two major conclusions were obtained. The accuracy of the system strongly depends on *BSs* positioning, *DOP* analysis were made and the error seems to increase where values of the *DOP* are weaker, meaning each of three Cartesian coordinates were evaluated. The second conclusion is that this specific technological solution is sensitive to disturbance to its *RF* signal, in other words, interferences may occur due objects between *MS* and its *BSs*, as multipath effect and attenuations of the signal. Therefore, it is critical the deployment of a reasonable number of anchors around the space to locate, attempting to have *LoS* with at least three anchors in all indoor area. The manufacture claims that the system operates with *NLoS*, which in fact is true, but strongly suggest that *LoS* should be achieved, due to signals interference. Nevertheless, a good number of *BSs* will greatly enhance the accuracy of the system. Wherefore, location is more robust, since it is based on more ranges. Furthermore, outliers can be easily identified, resulting on its removal improving overall precision. The Least Squares algorithm is based on more equations then unknowns, thus if the position is based on more ranges will certainly have more equations to estimate the same unknowns, that in this case are x, y and z spatial coordinates.

In the development of this MSc dissertation, the biggest issue faced was the limitation on accessing to the source code. An accessing would enable to understand exactly how ranges are estimated and perform optimization, due the possibility to identify outliers based data used to estimate *ToA*, phase-difference and maybe *SNR*.

6.2 Future Work

The proponent company *FoodInTech* wants to provide an automatic management solution for warehouses in the food industry, using indoor *RTLS*. Knowing their final goal that is a large scale implementation, more tests should be performed with more anchors deployed taking into account *DOP* values minimal as possible. The algorithm should be implemented in development kit source code with access to ranges data, in order to identify outliers ranges to optimize positioning computing.

A large scale implementation require a large number of tags compatible with this system, which could be very important in the cost of this industrial deployment, thus a study of cost-effectiveness should be given proper attention.

Appendix A

Appendix - Outdoor First Test Analysis Figures

In this appendix remaining data will be presented, part of these in the chapter 5 in the section 5.1 of the *Outdoor First Test*.

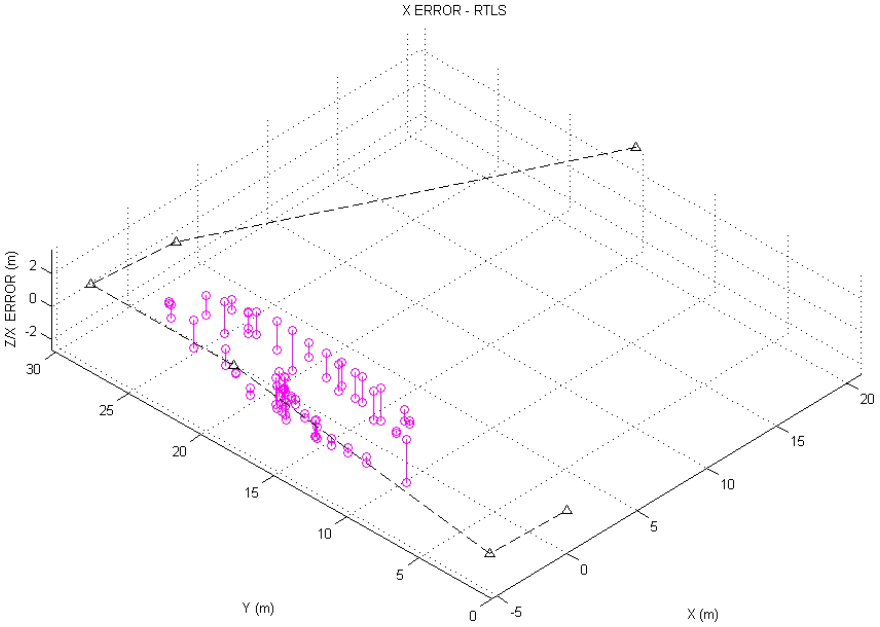


Figure A.1: X Error relative to the location given by RTLS

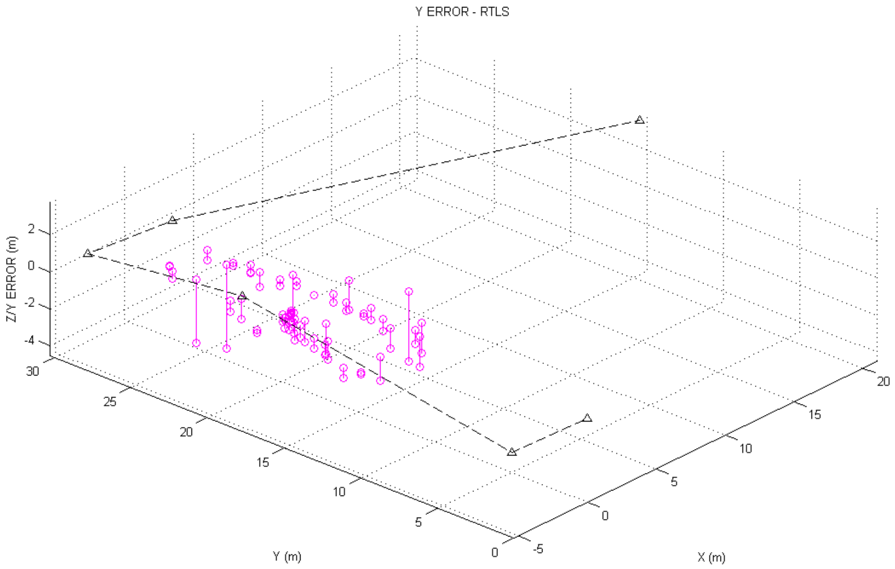


Figure A.2: Y Error relative to the location given by RTLS

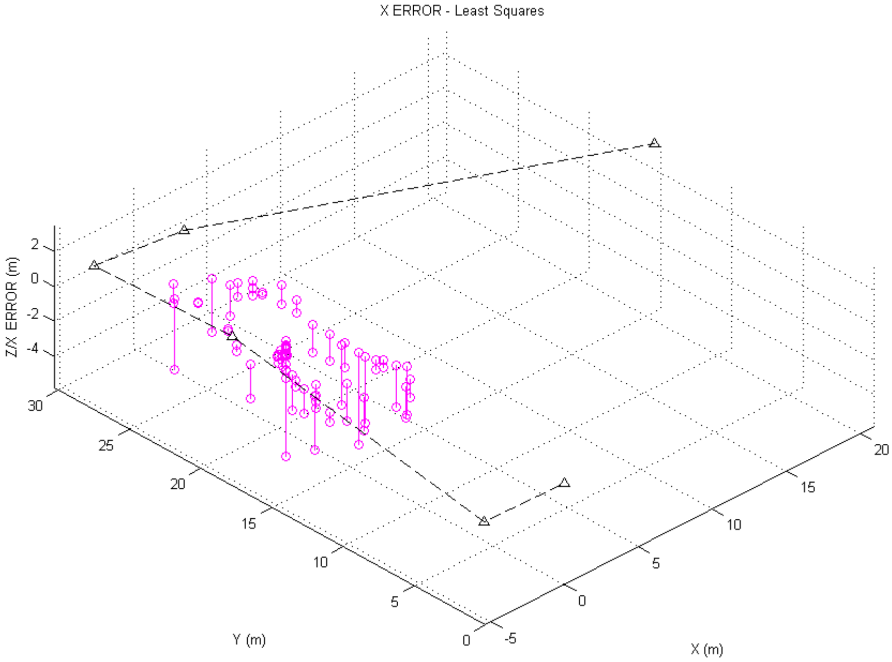


Figure A.3: X Error relative to the location given by LS

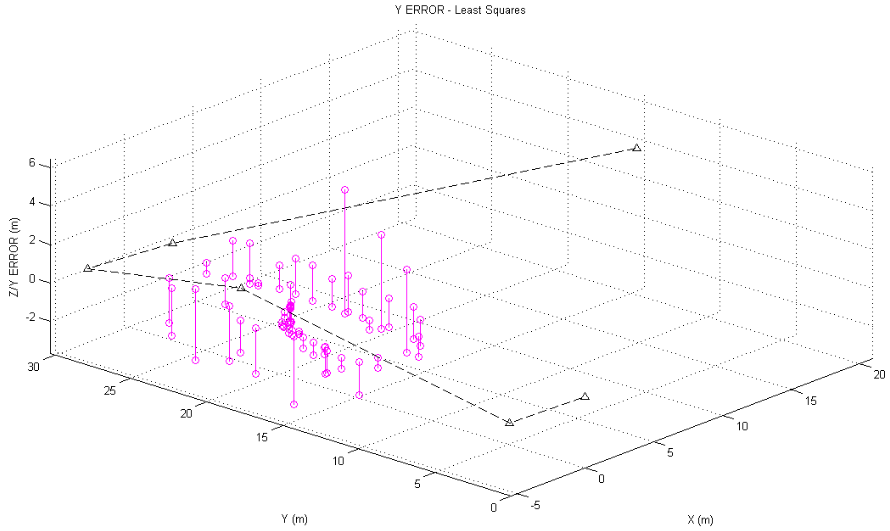


Figure A.4: Y Error relative to the location given by LS

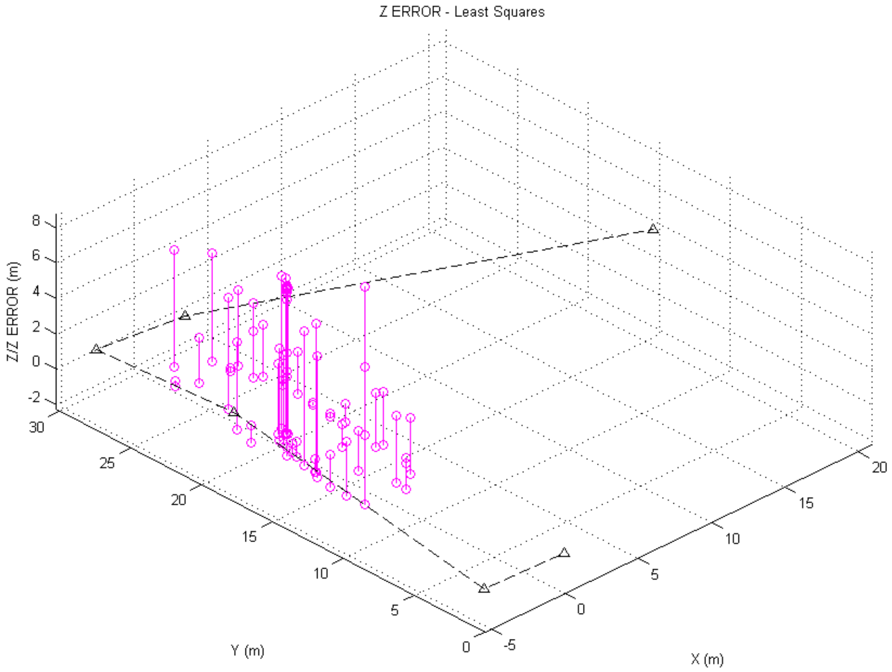


Figure A.5: Z Error relative to the location given by LS

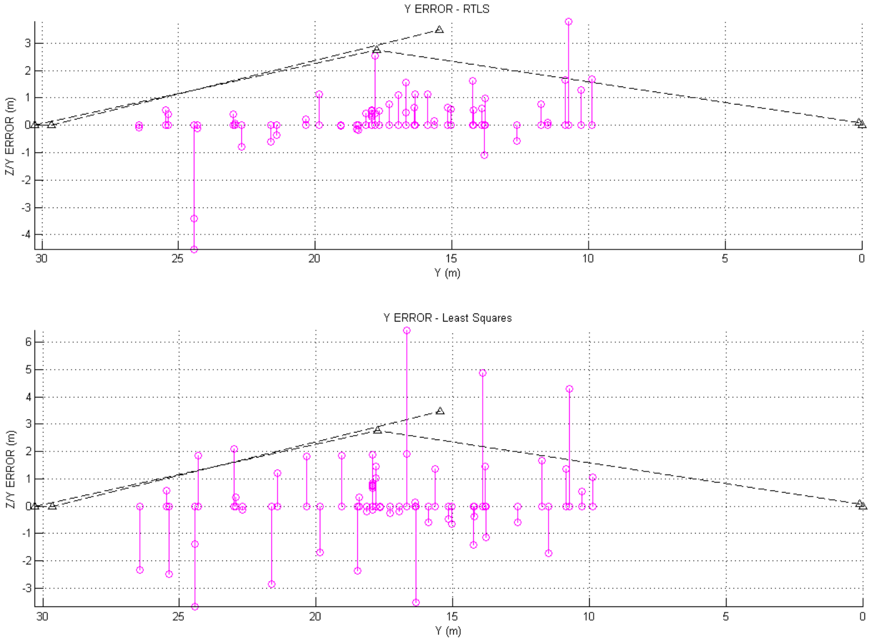


Figure A.6: Y Error - RTLS vs LS

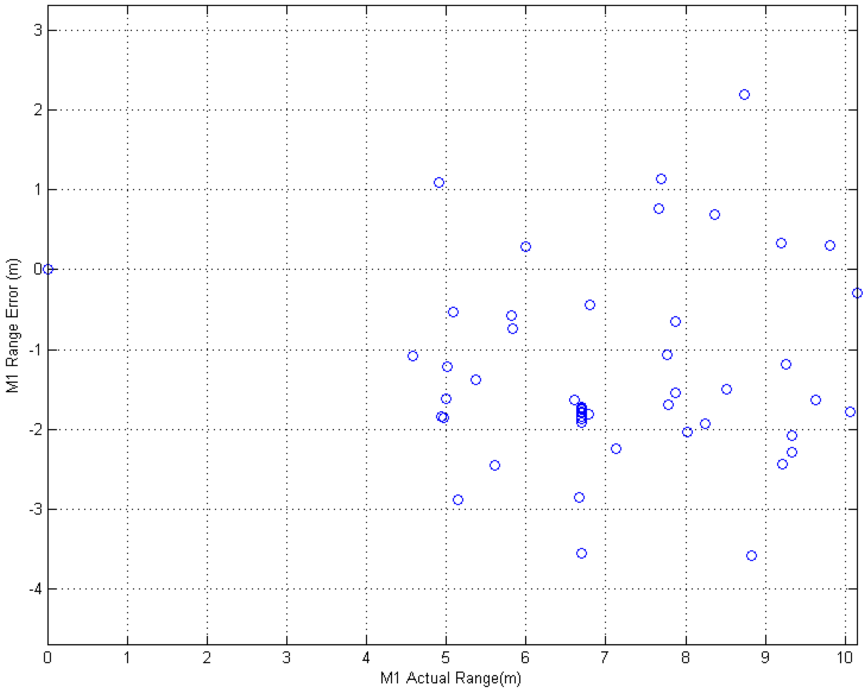


Figure A.7: M1 Range Error

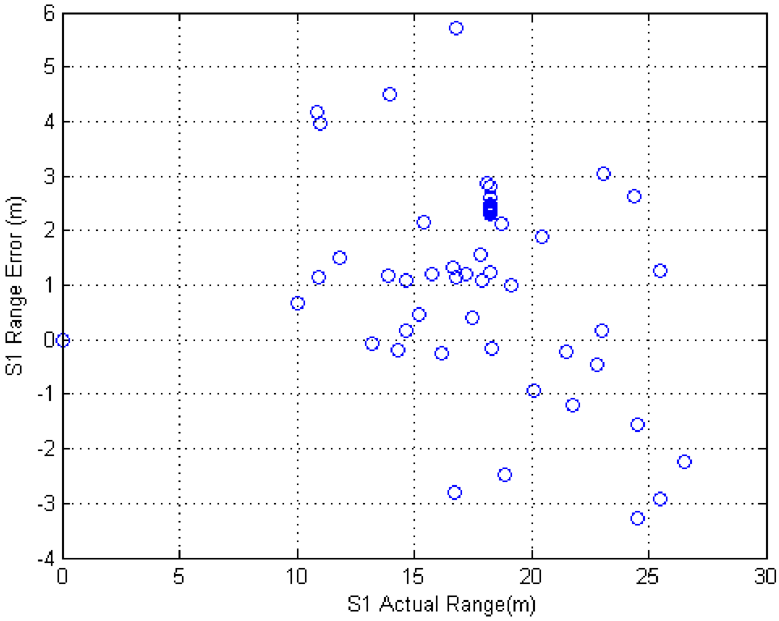


Figure A.8: S1 Range Error

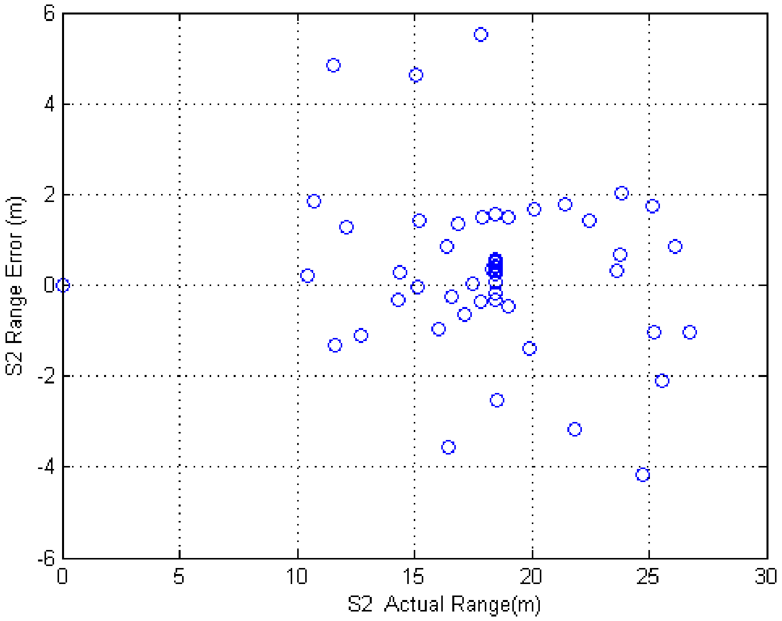


Figure A.9: S2 Range Error

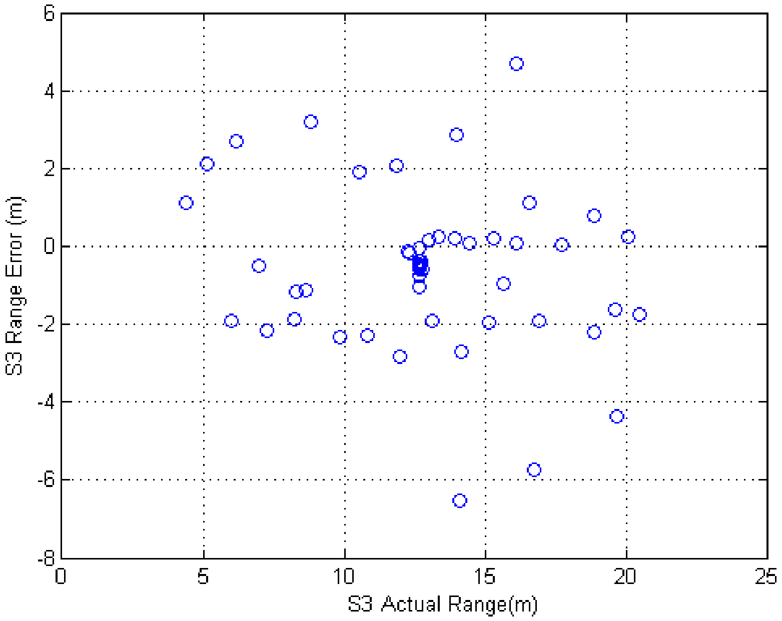


Figure A.10: S3 Range Error

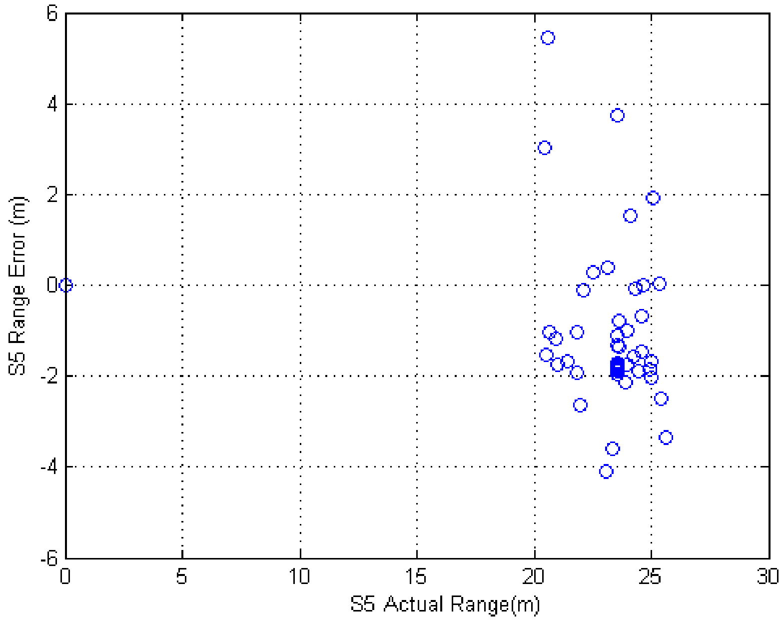


Figure A.11: S5 Range Error

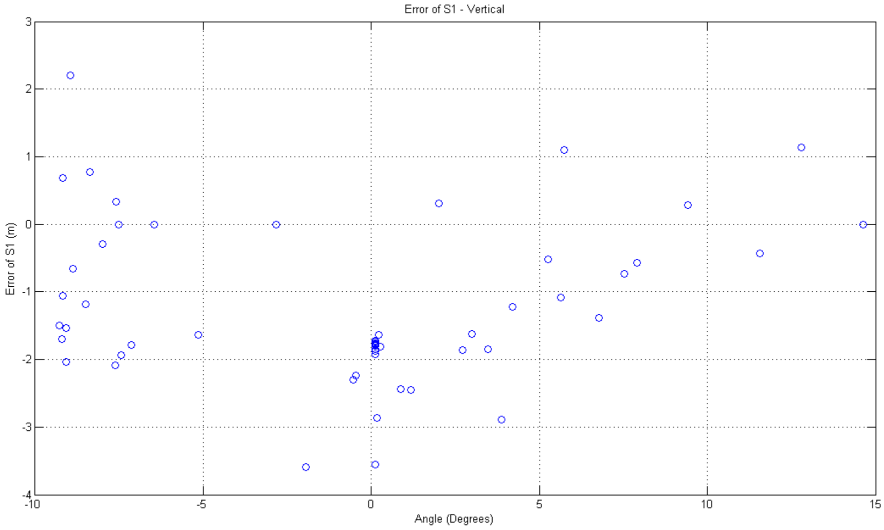


Figure A.12: S1 Range Error in perspective with vertical angles

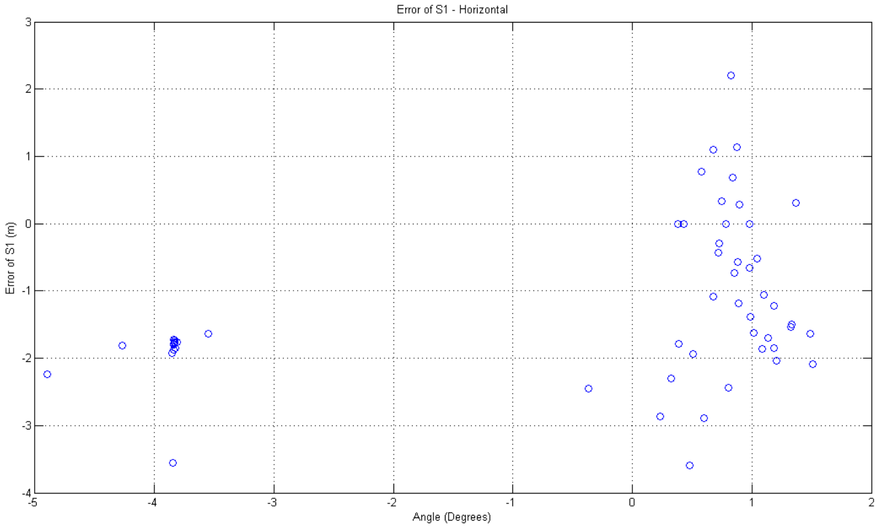


Figure A.13: S1 Range Error in perspective with horizontal angles

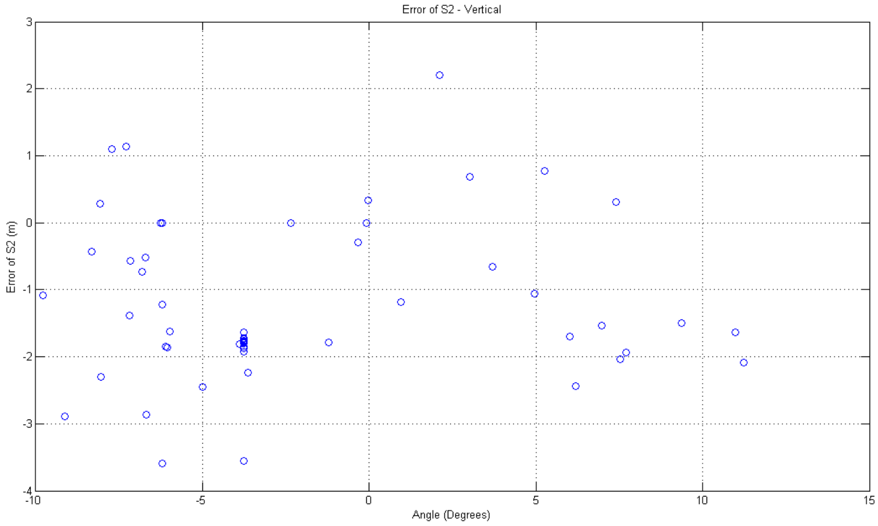


Figure A.14: S2 Range Error in perspective with vertical angles

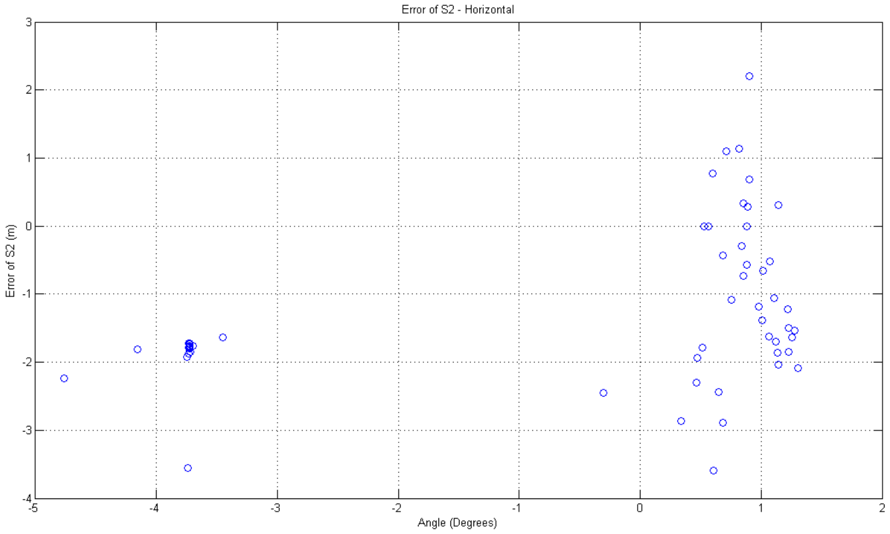


Figure A.15: S2 Range Error in perspective with horizontal angles

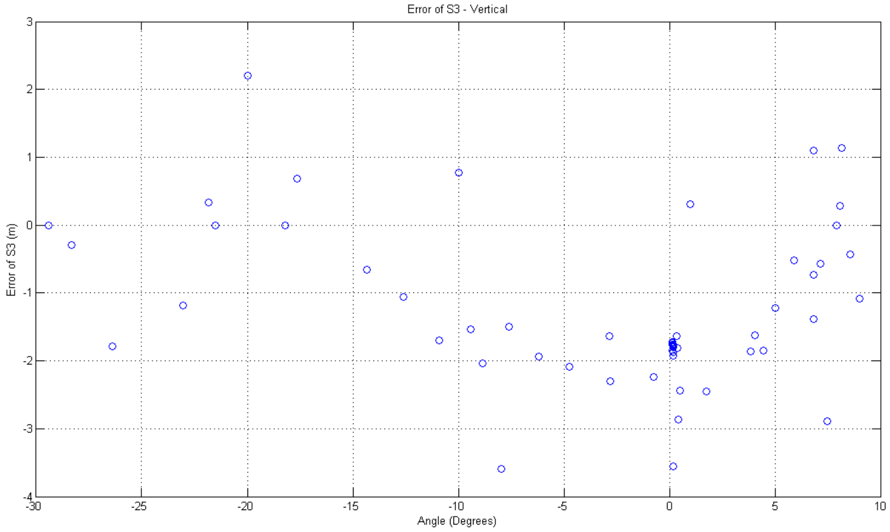


Figure A.16: S3 Range Error in perspective with vertical angles

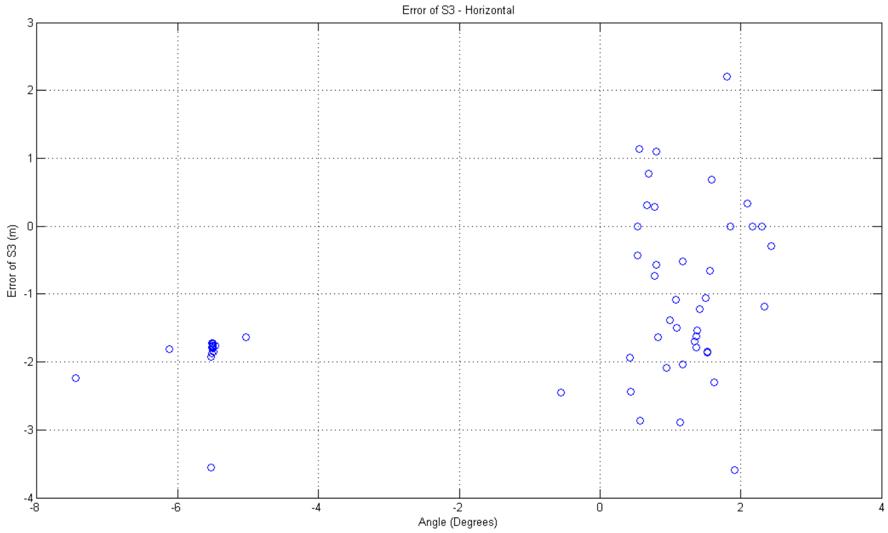


Figure A.17: S3 Range Error in perspective with horizontal angles

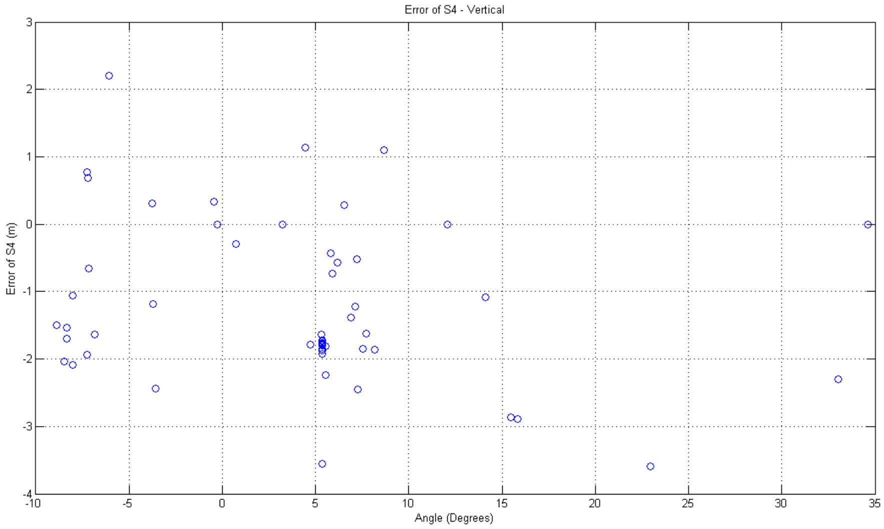


Figure A.18: S4 Range Error in perspective with vertical angles

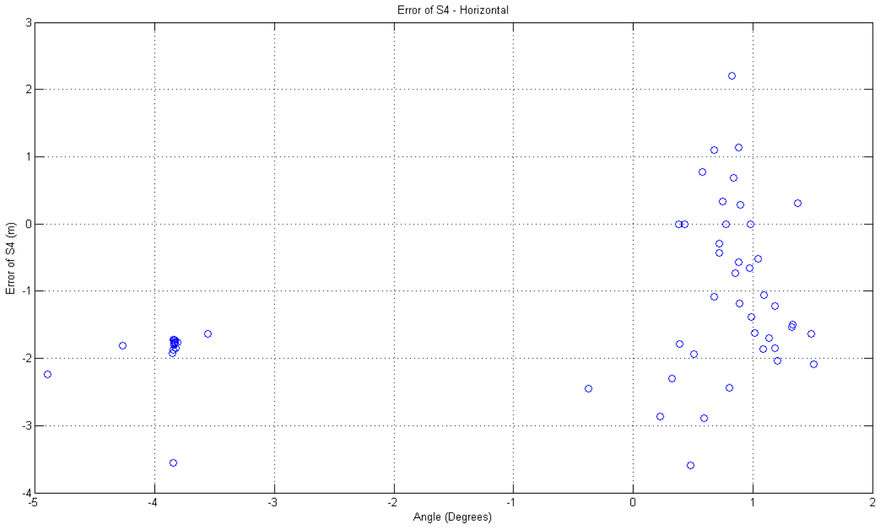


Figure A.19: S4 Range Error in perspective with horizontal angles

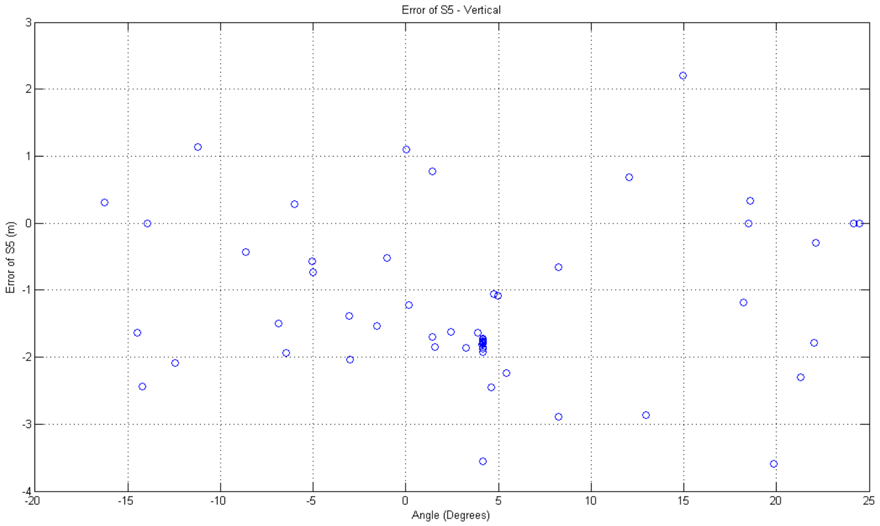


Figure A.20: S5 Range Error in perspective with vertical angles

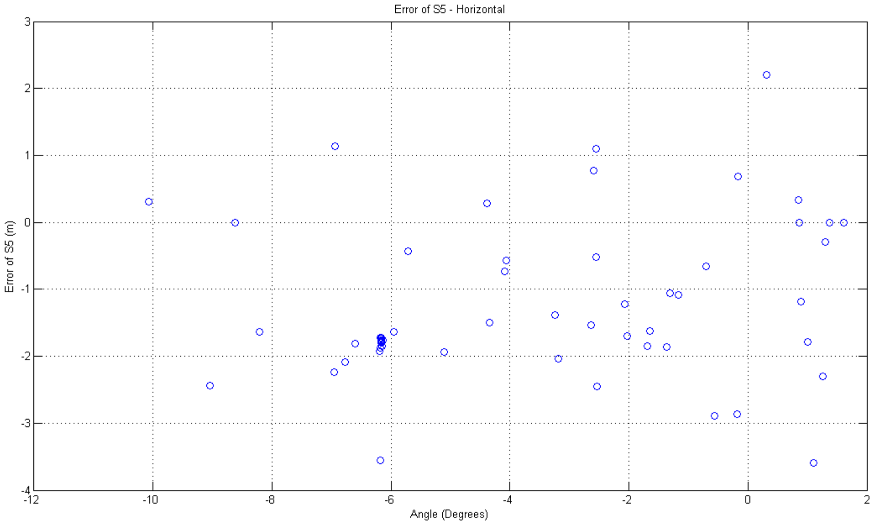


Figure A.21: S5 Range Error in perspective with horizontal angles

Appendix B

Appendix - Indoor Test

In this appendix remaining data will be presented, part of these in the chapter 5 in the section 5.3 of the *Indoor Test*.

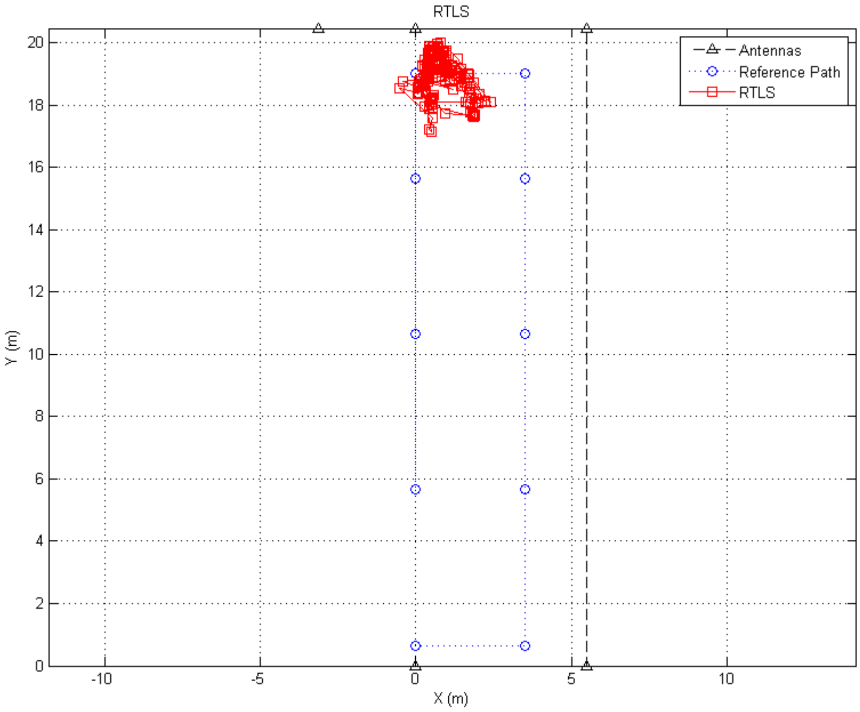


Figure B.1: RTLS Positions - 1st experiment

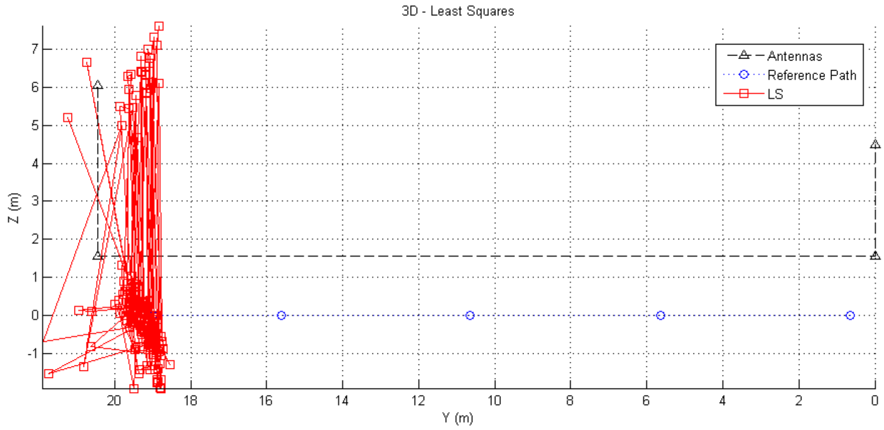


Figure B.2: LS Positions - 1st experiment - Side View

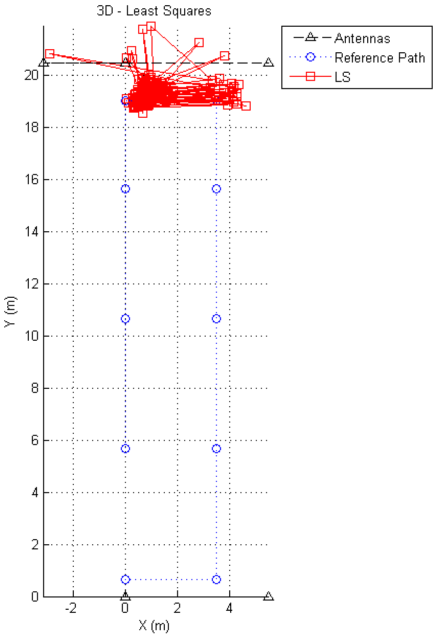


Figure B.3: LS Positions - 1st experiment - Top View

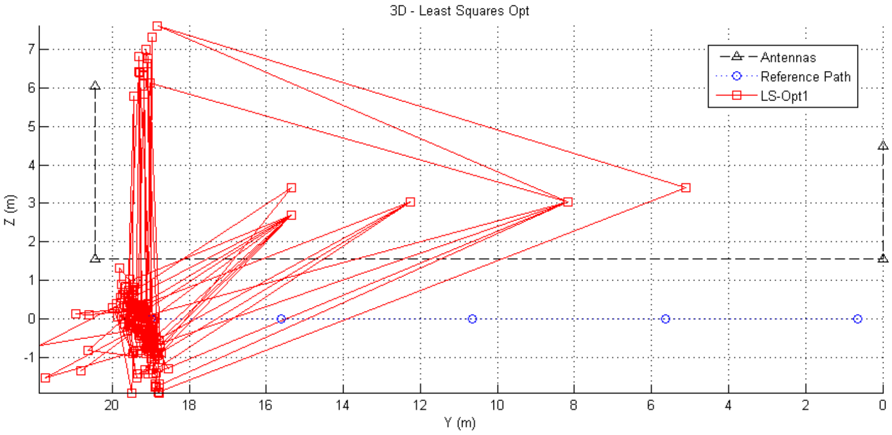


Figure B.4: LS Optimized Positions - 1st experiment - Side View

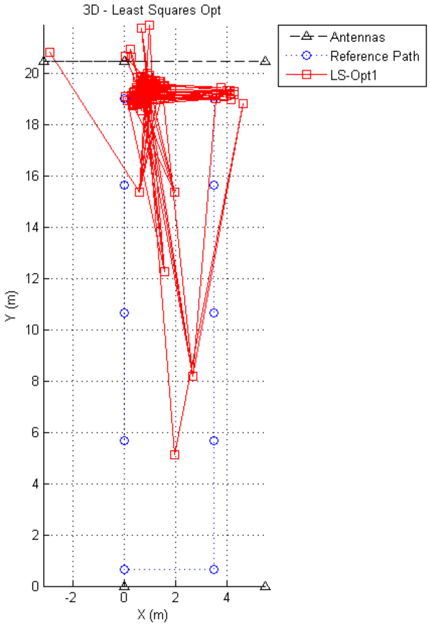


Figure B.5: LS Optimized Positions - 1st experiment - Top View

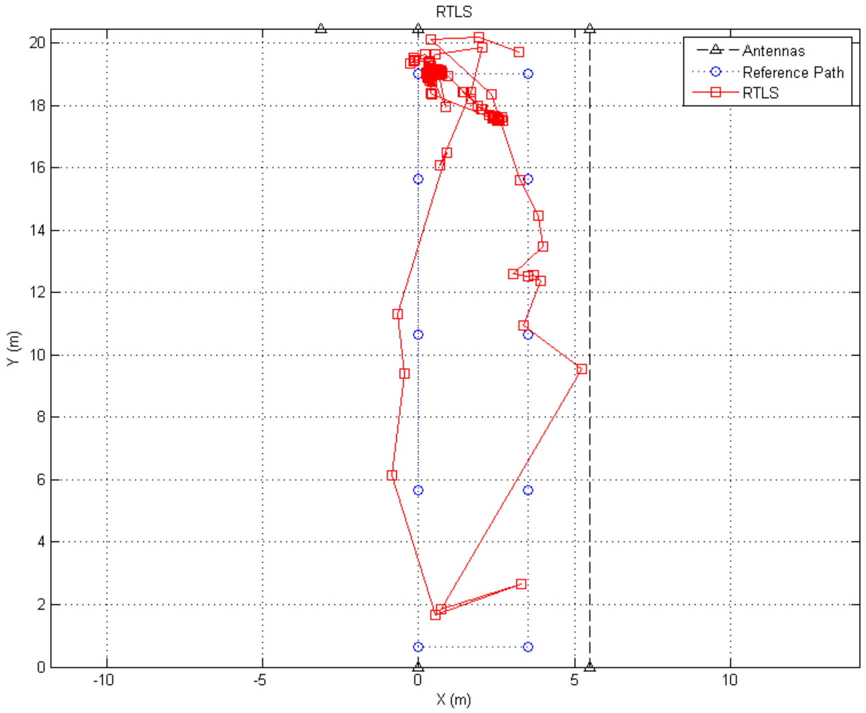


Figure B.6: RTLS Positions - 2nd experiment

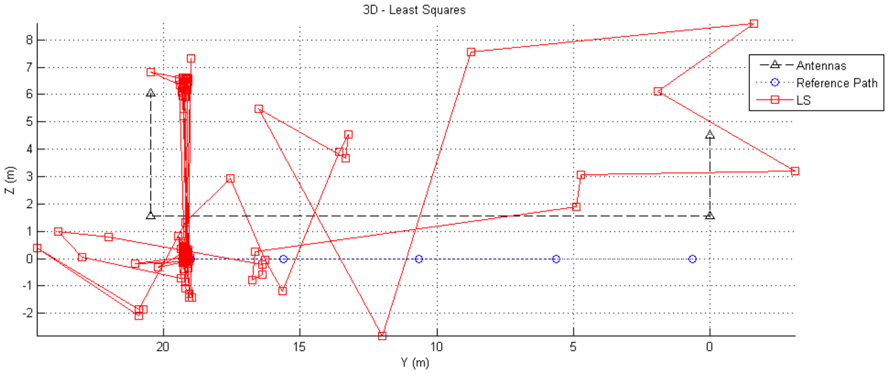


Figure B.7: LS Positions - 2nd experiment - Side View

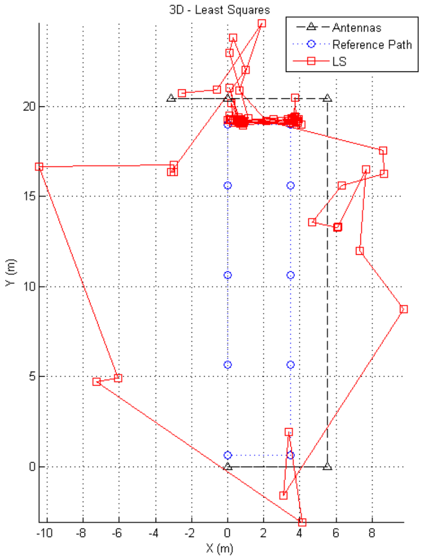


Figure B.8: LS Positions - 2nd experiment - Top View

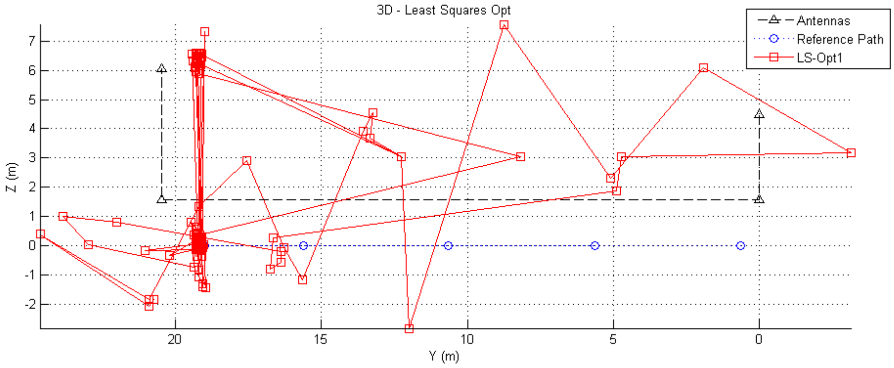


Figure B.9: LS Optimized Positions - 2nd experiment - Side View

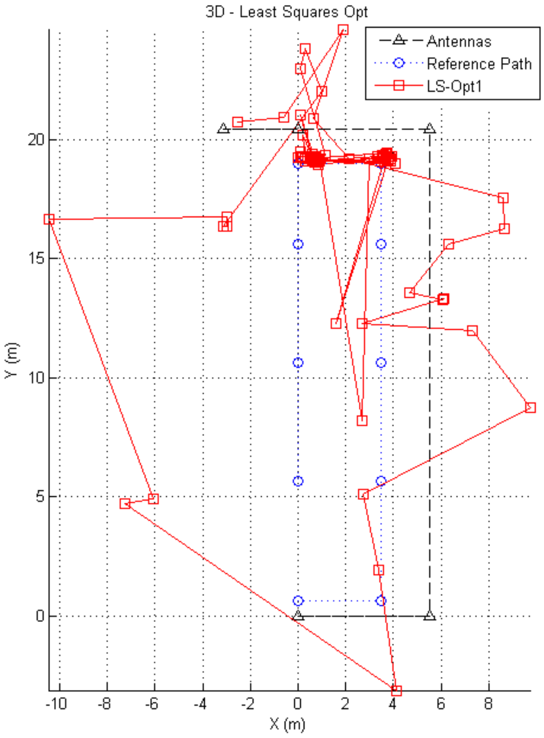


Figure B.10: LS Optimized Positions - 2nd experiment - Top View

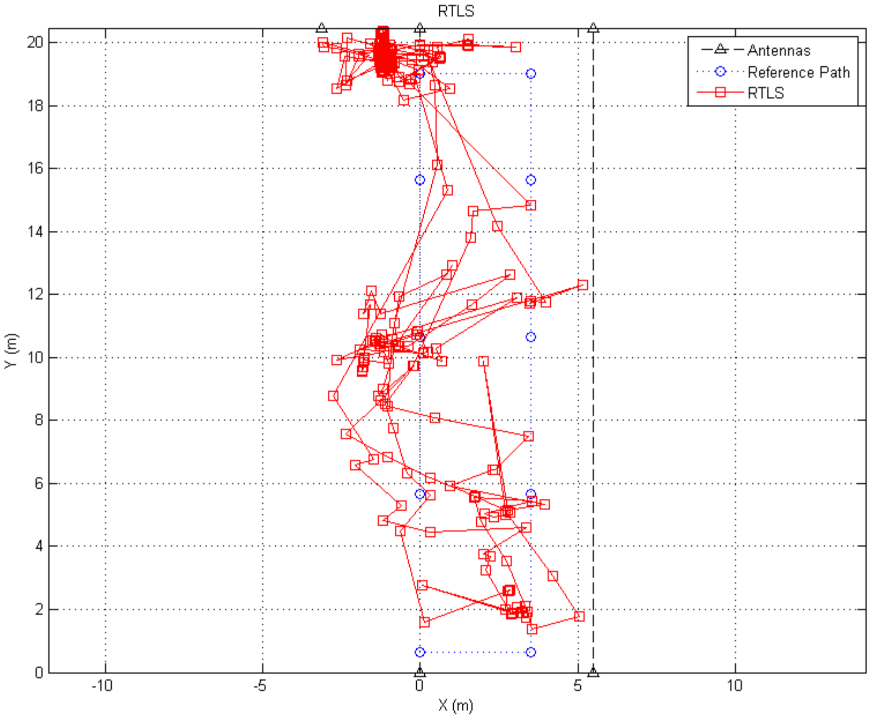


Figure B.11: RTLS Positions - 3rd experiment

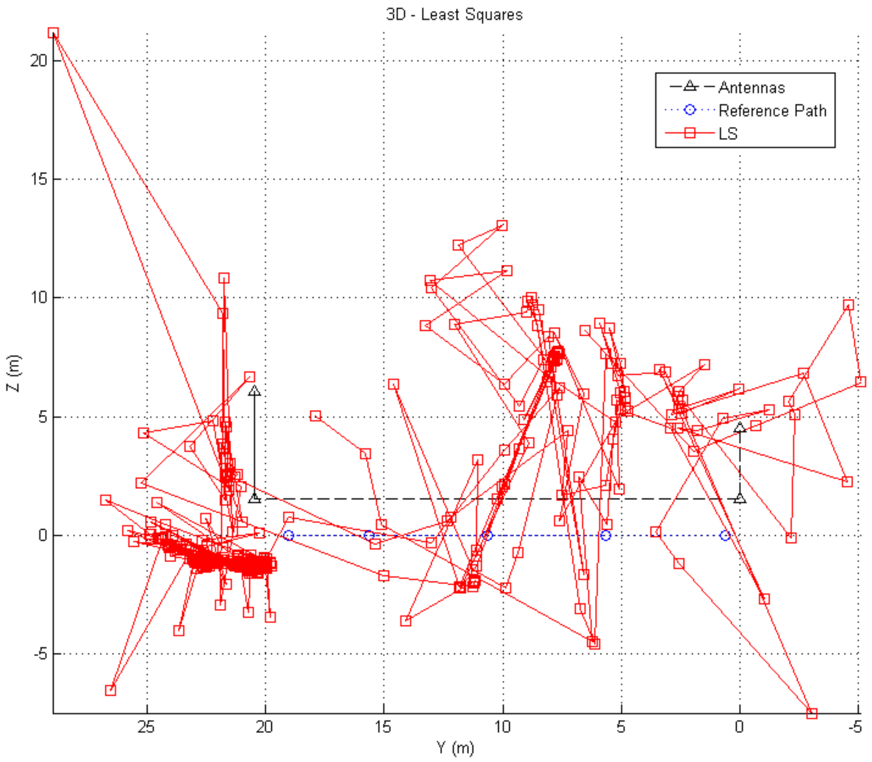


Figure B.12: LS Positions - 3rd experiment - Side View

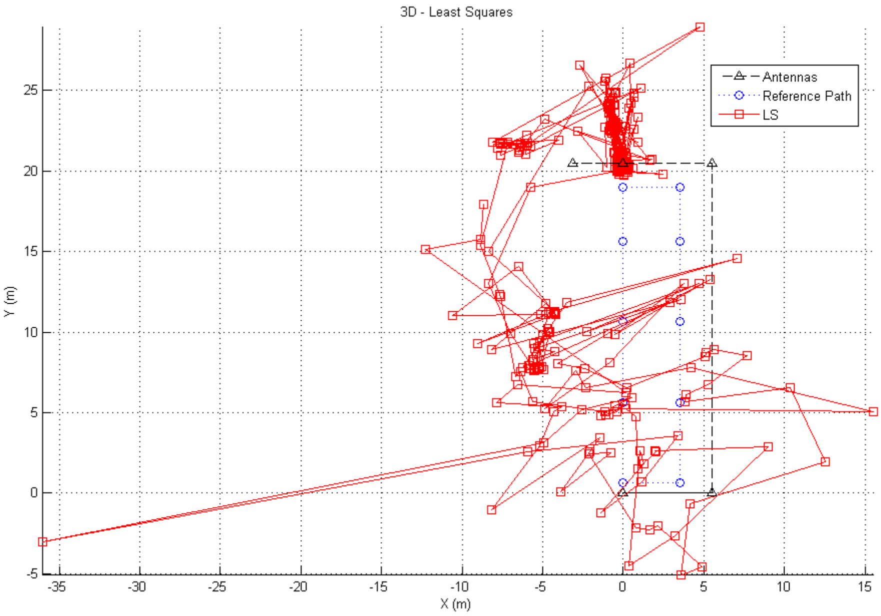


Figure B.13: LS Positions - 3rd experiment - Top View

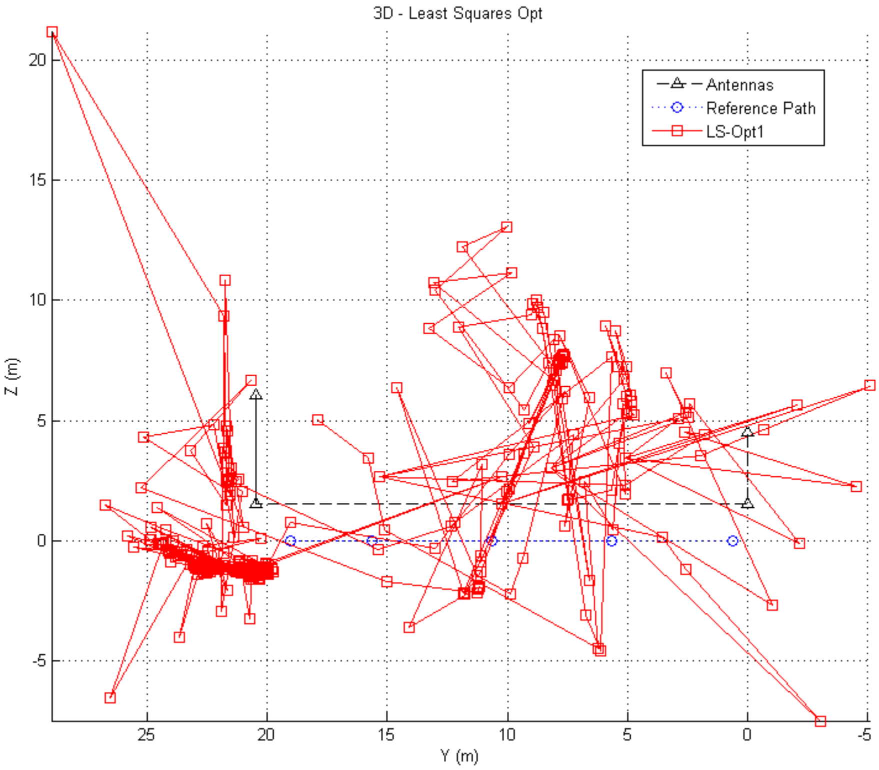


Figure B.14: LS Optimized Positions - 3rd experiment - Side View

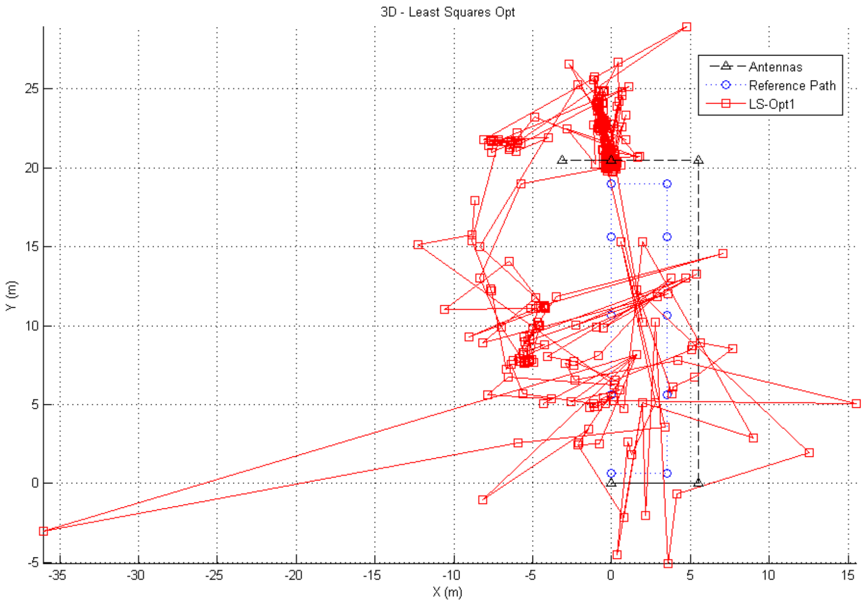


Figure B.15: LS Optimized Positions - 3rd experiment - Top View

Appendix C

Appendix - Outdoor Final Test

In this appendix remaining data will be presented, part of these in the chapter 5 in the section 5.4 of the *Outdoor Final Test*.

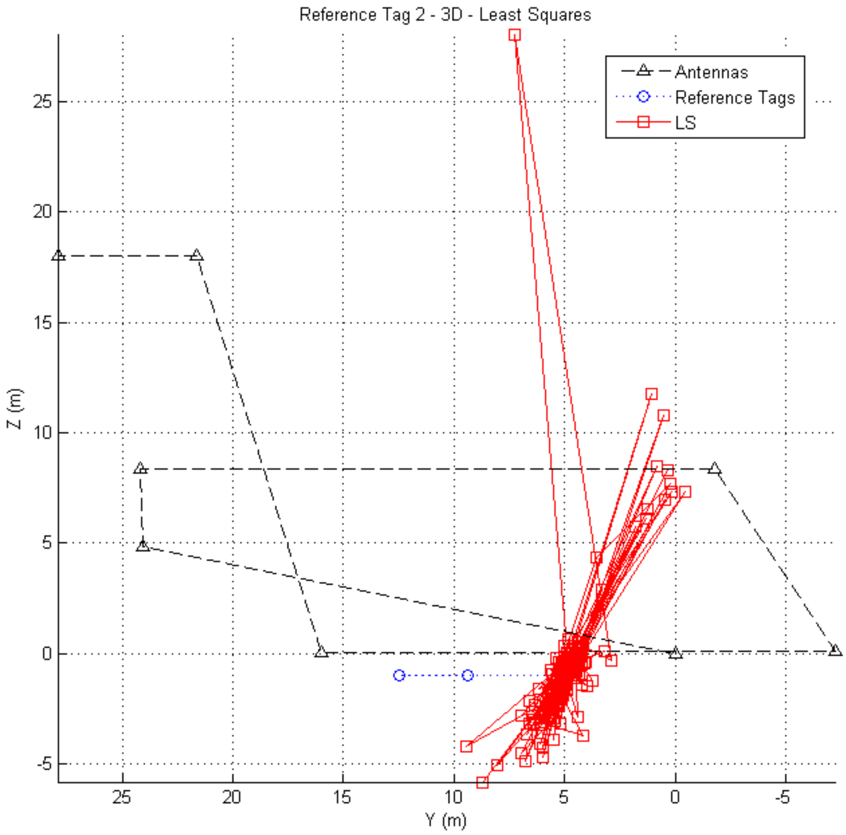


Figure C.1: Reference *tag2* - Side View

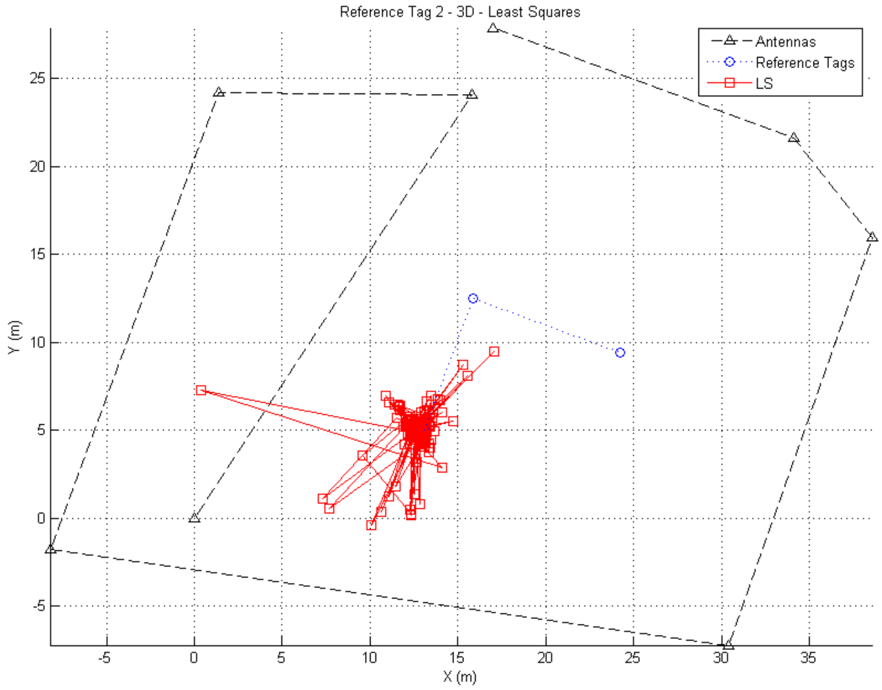


Figure C.2: Reference *tag2* - Top View

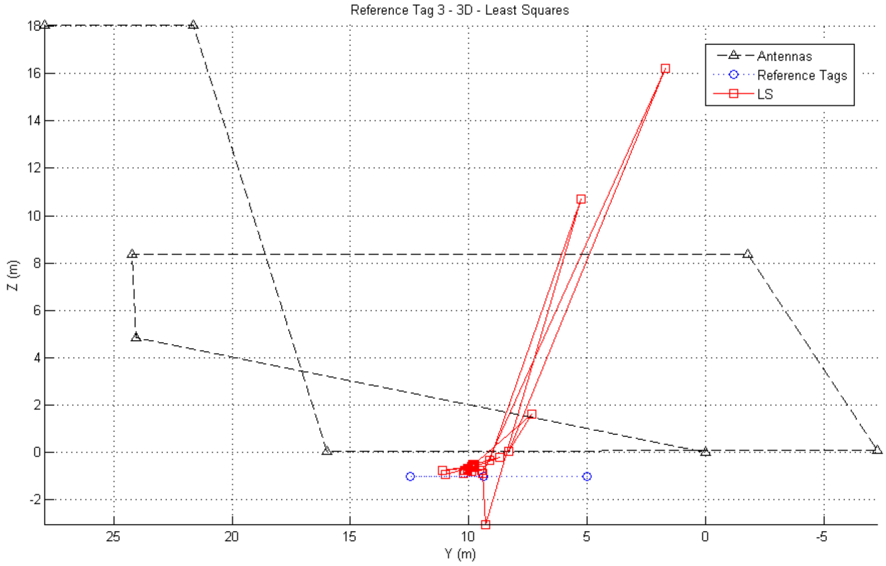


Figure C.3: Reference *tag3* - Side View

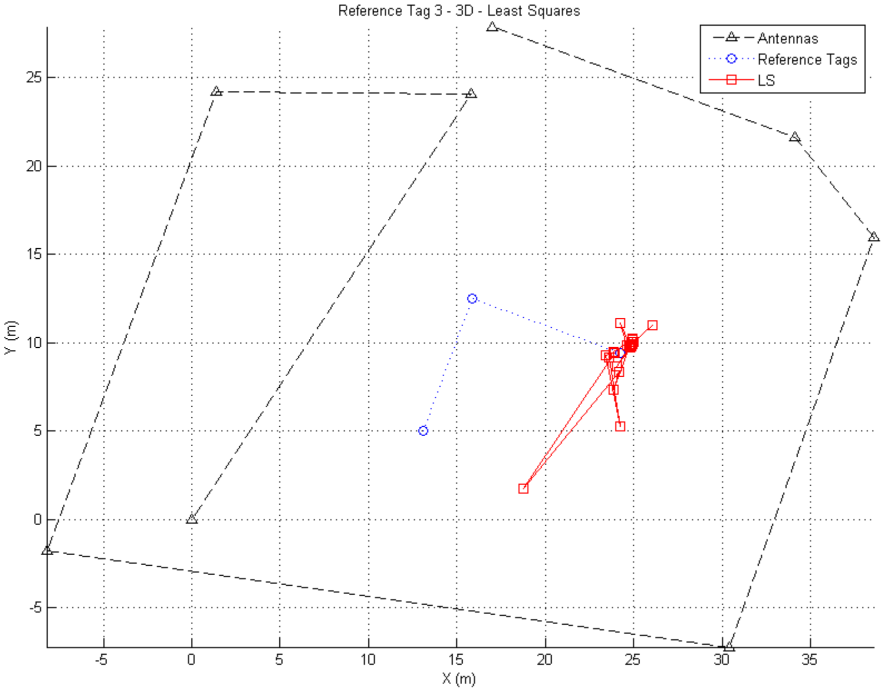


Figure C.4: Reference *tag3* - Top View

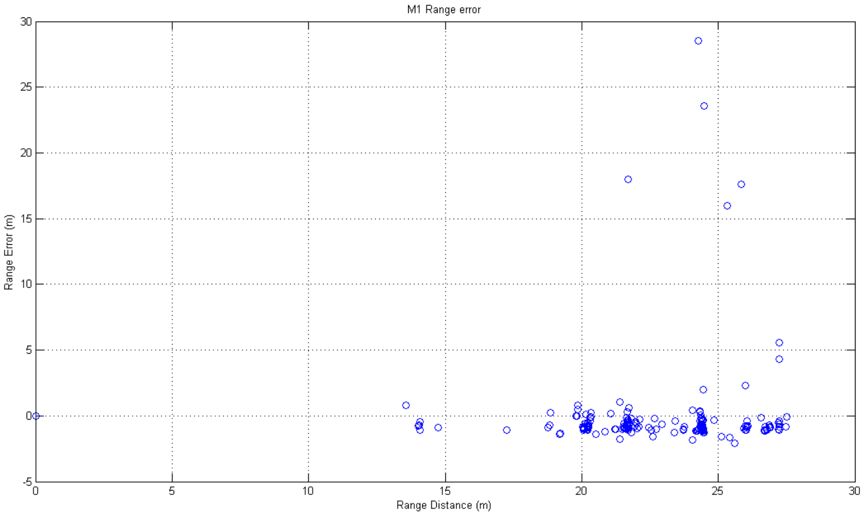


Figure C.5: M1 Range Error

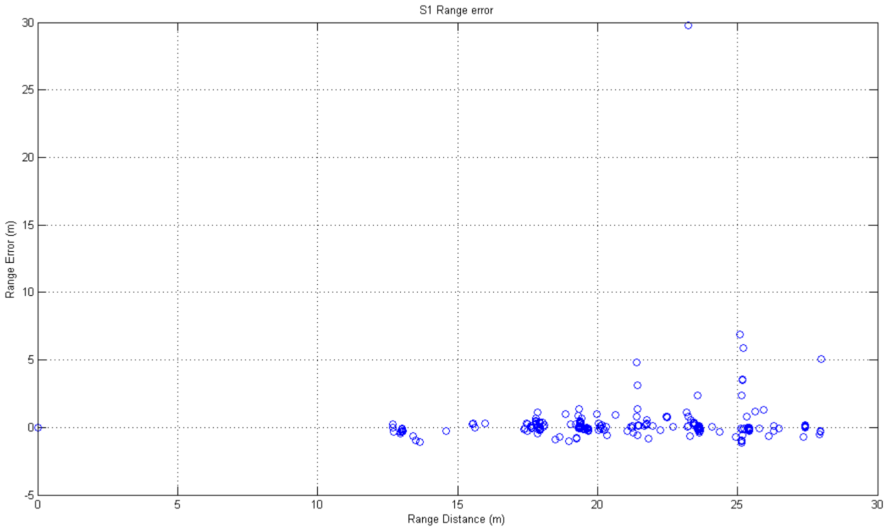


Figure C.6: S1 Range Error

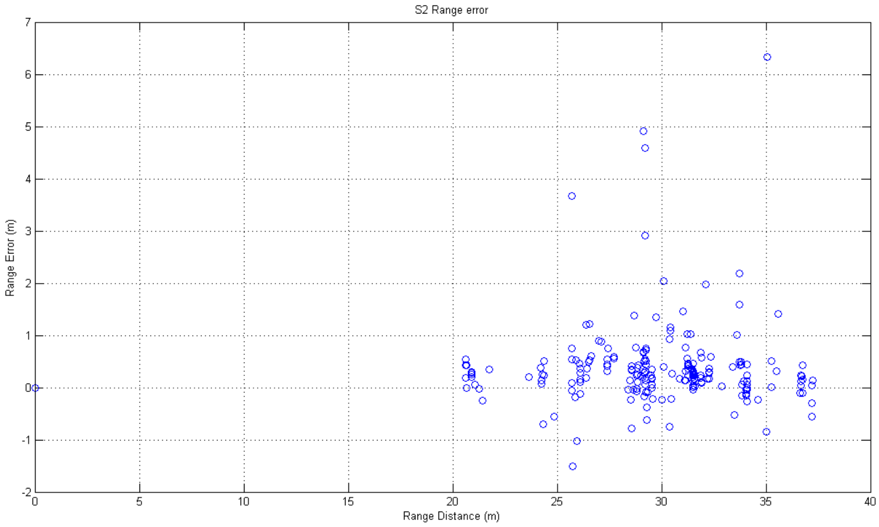


Figure C.7: S2 Range Error

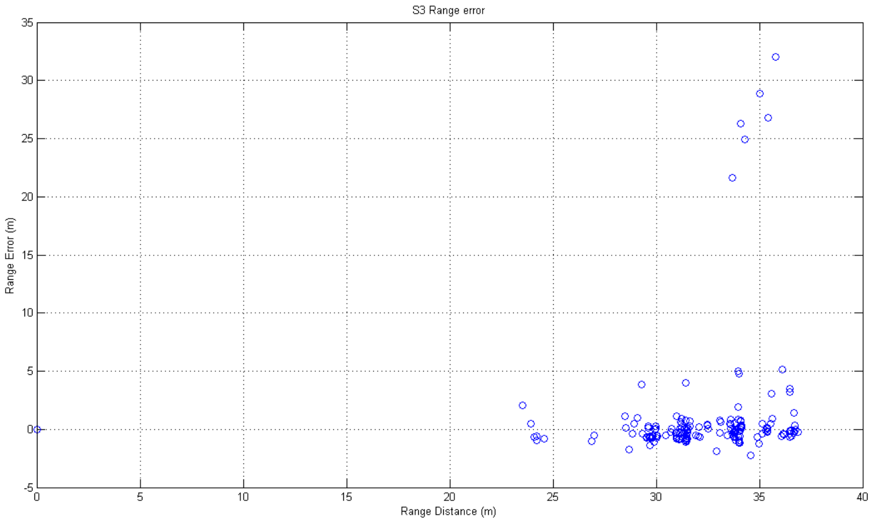


Figure C.8: S3 Range Error

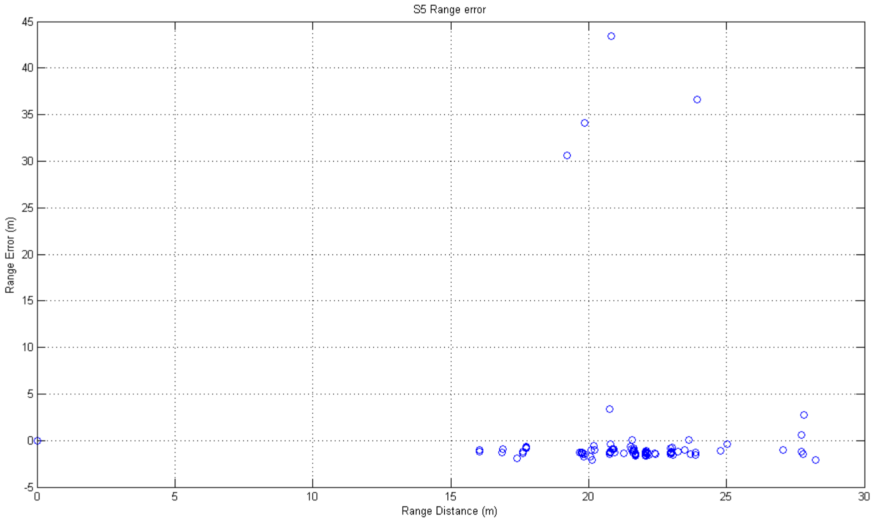


Figure C.9: S5 Range Error

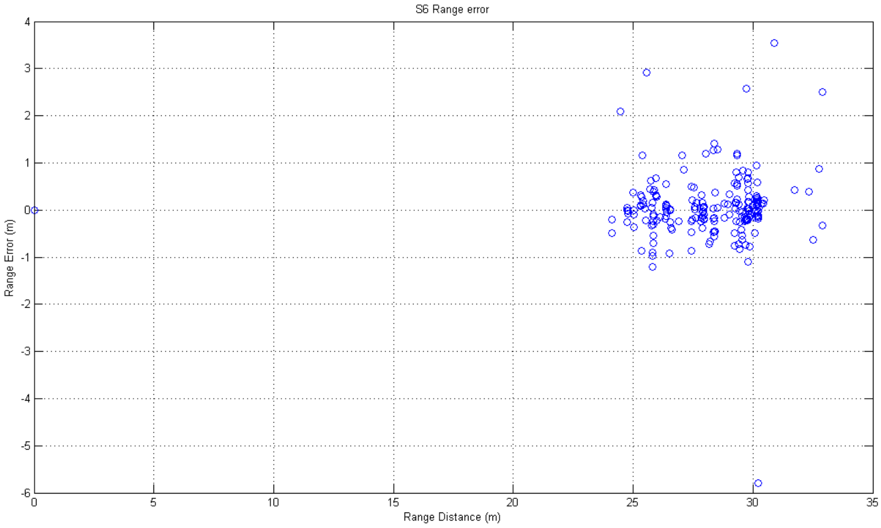


Figure C.10: S6 Range Error

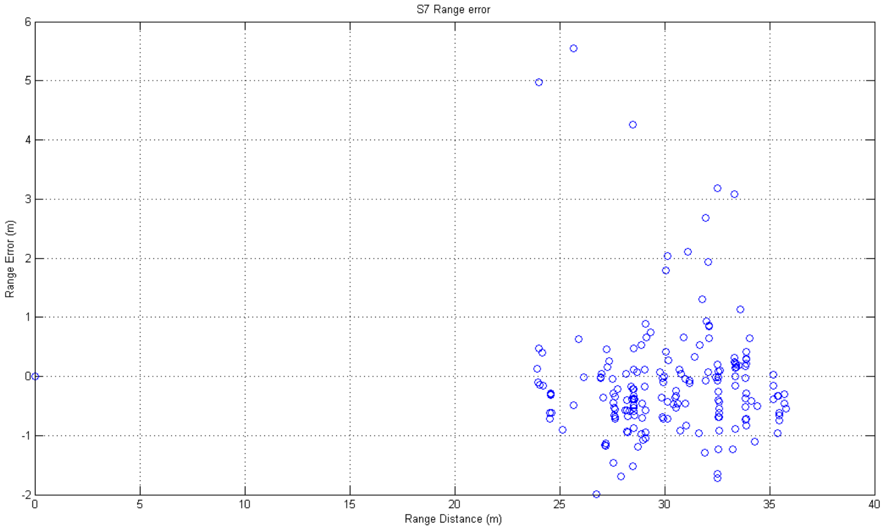


Figure C.11: S7 Range Error

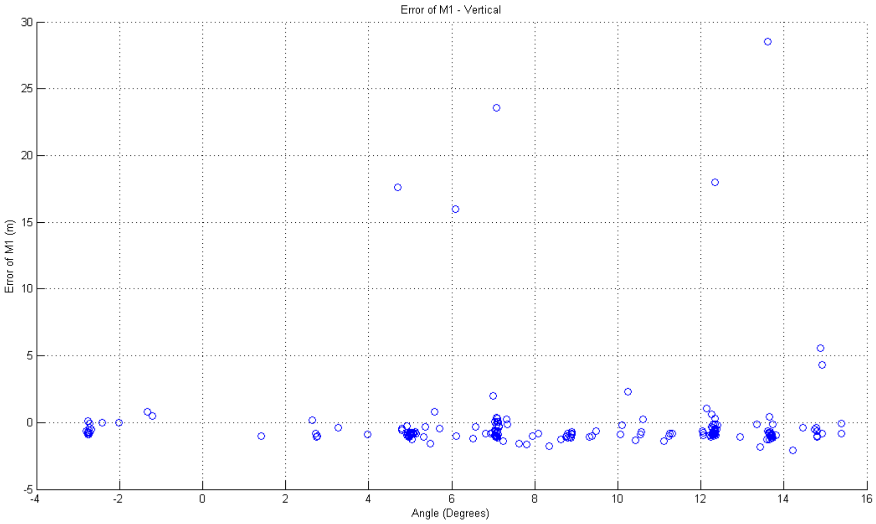


Figure C.12: M1 Error in perspective with its Vertical angles

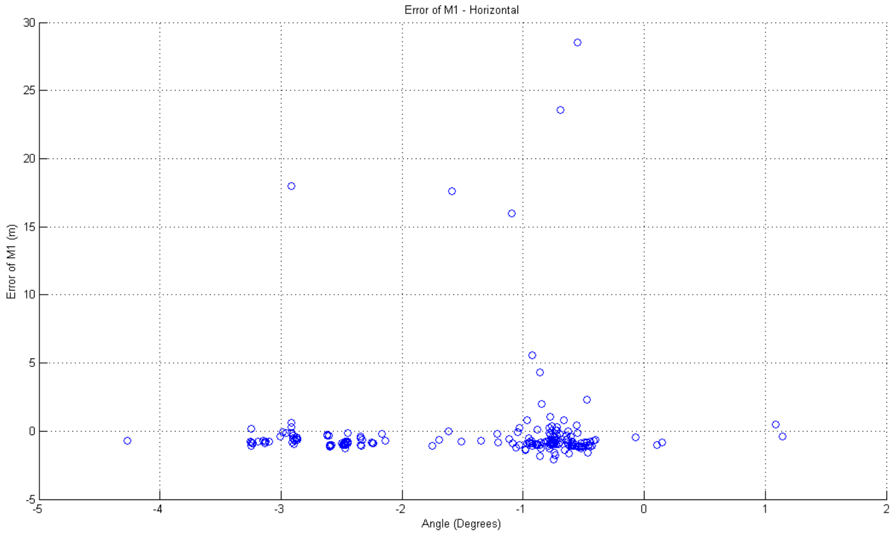


Figure C.13: M1 Error in perspective with its Horizontal angles

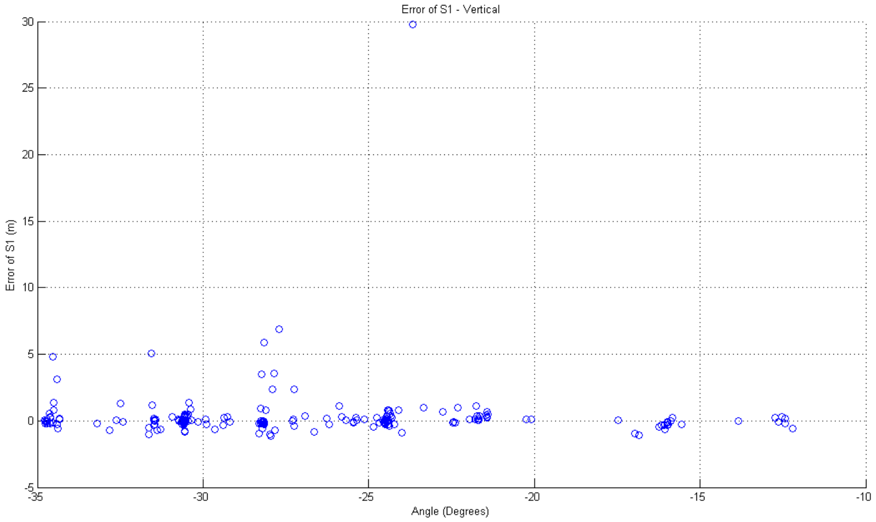


Figure C.14: S1 Error in perspective with its Vertical angles

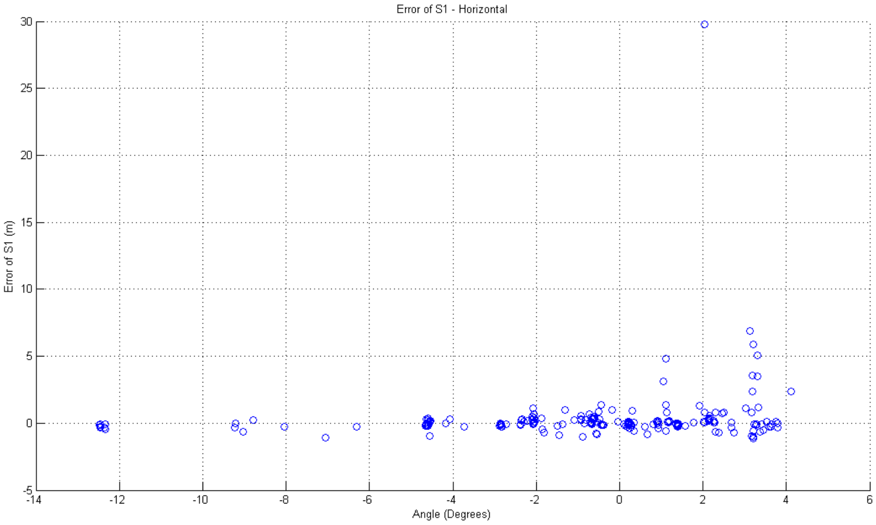


Figure C.15: S1 Error in perspective with its Horizontal angles

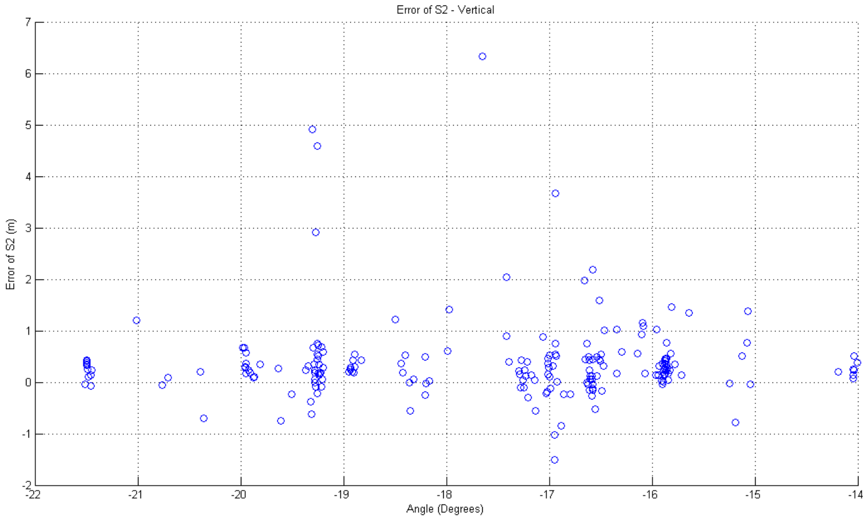


Figure C.16: S2 Error in perspective with its Vertical angles

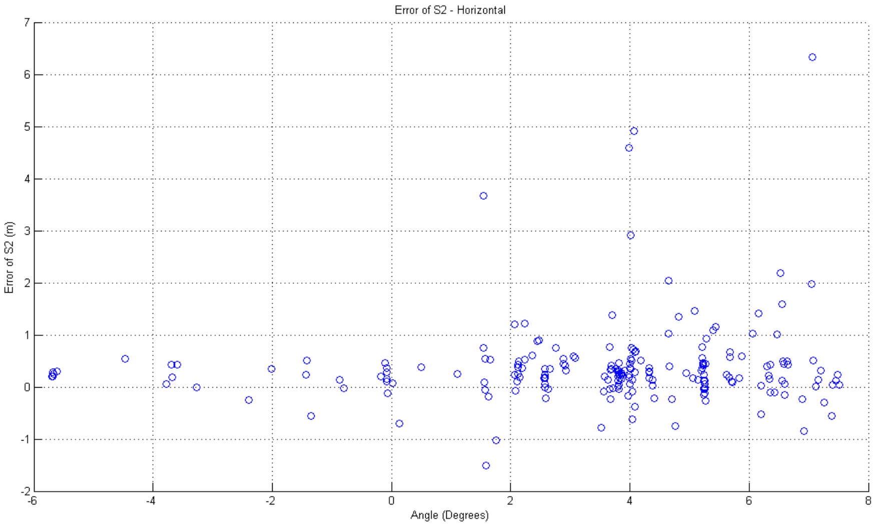


Figure C.17: S2 Error in perspective with its Horizontal angles

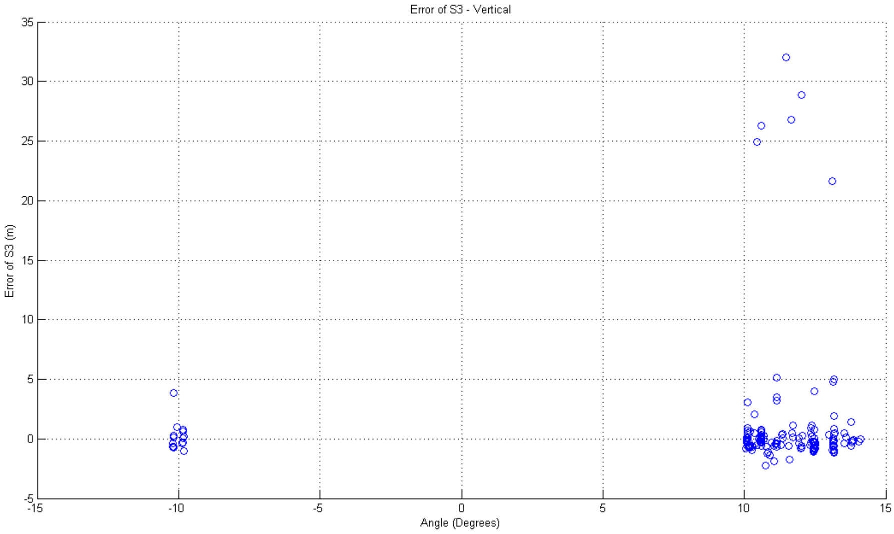


Figure C.18: S3 Error in perspective with its Vertical angles

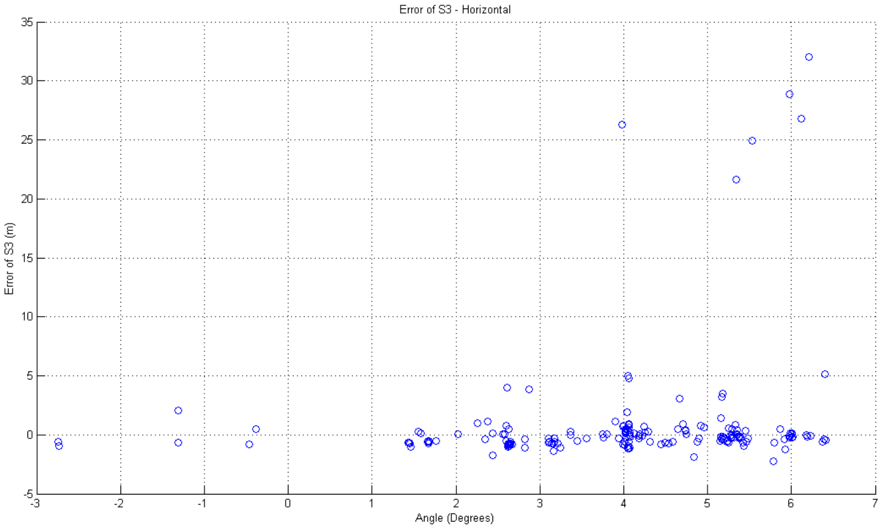


Figure C.19: S3 Error in perspective with horizontal angles

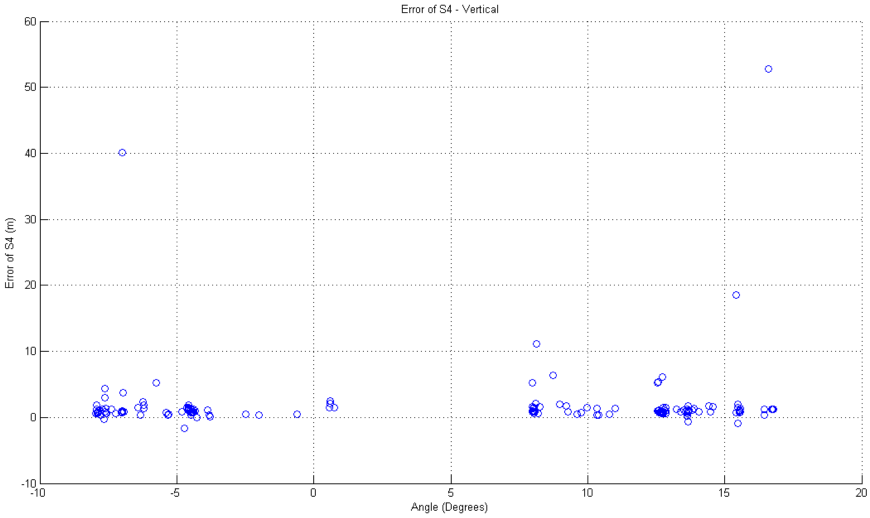


Figure C.20: S4 Error in perspective with vertical angles

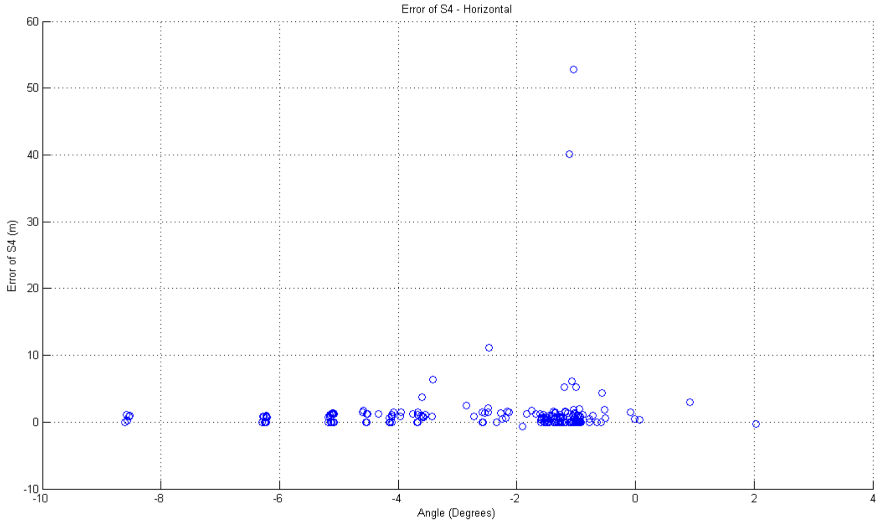


Figure C.21: S4 Error in perspective with horizontal angles

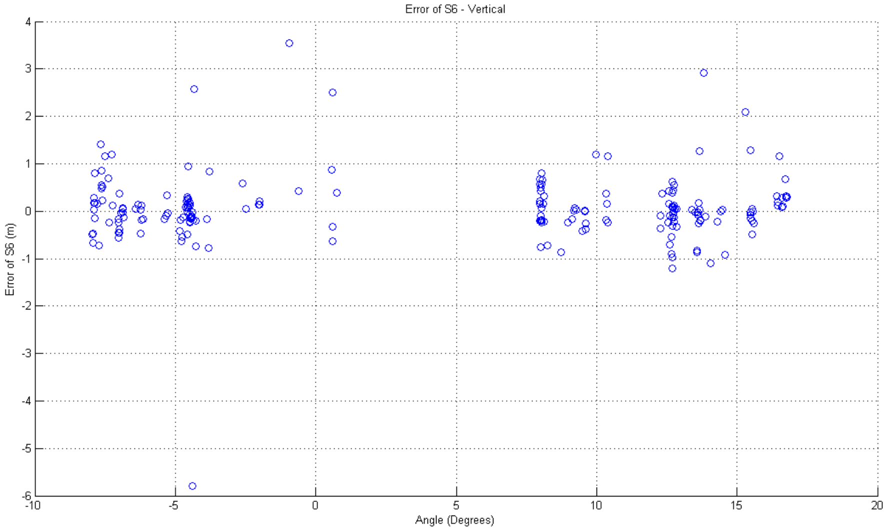


Figure C.22: S6 Error in perspective with vertical angles

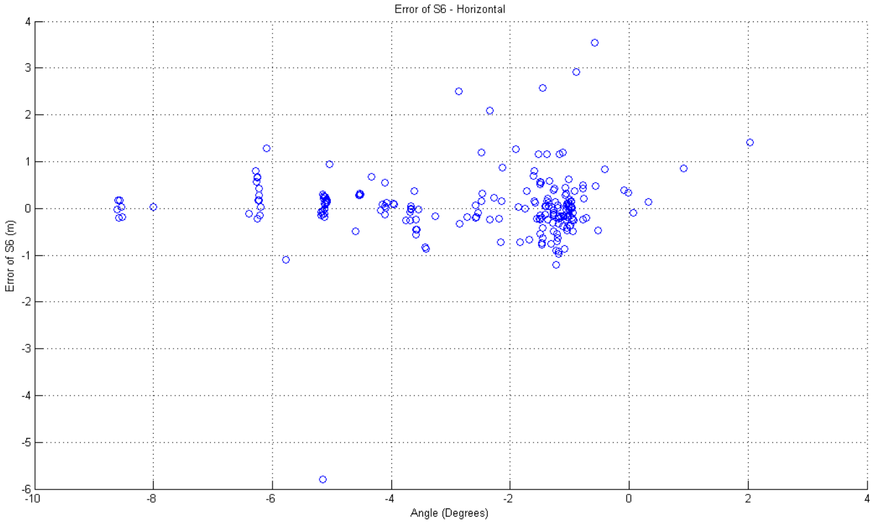


Figure C.23: S6 Error in perspective with horizontal angles

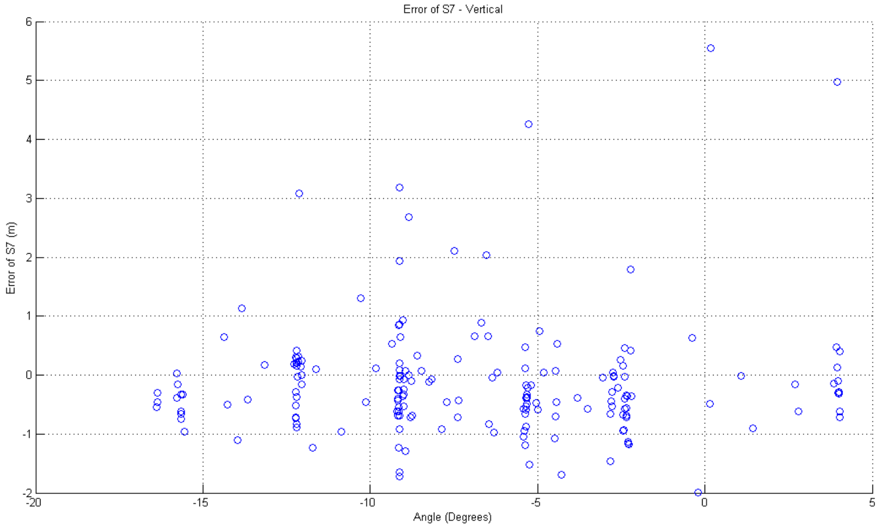


Figure C.24: S7 Error in perspective with vertical angles

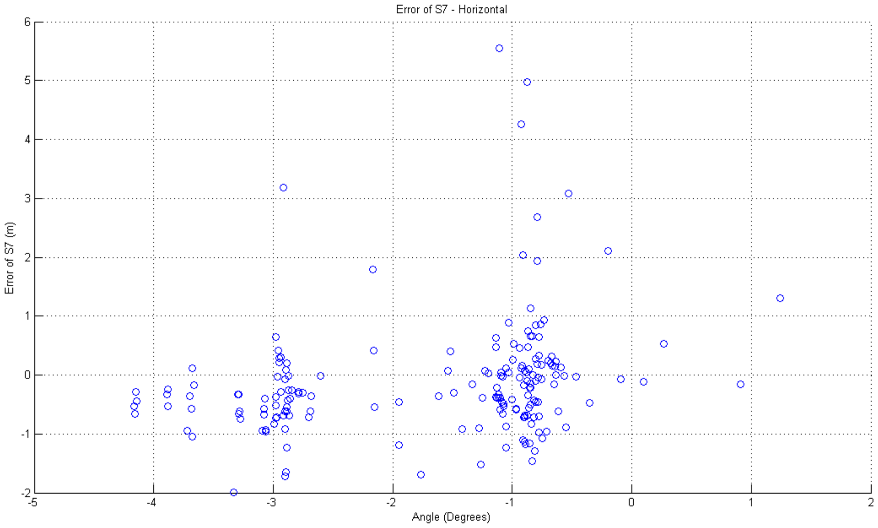


Figure C.25: S7 Error in perspective with horizontal angles

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