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Pozyx System Evaluation in Indoor Positioning

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Annotation

Graduation work is devoted to the Ultra-wideband technology deployment and testing its accuracy at Norwegian University of Science and Technology.

Work provides analysis of technologies based on Indoor Positioning Systems.

Evaluation of testing equipment was made in harsh environment, under line-of-sight, no-line-of-sight and combination of both by measuring coordinates and distances in an attempt to cover all possible situations.

Results obtained were post-processed to gain comparative data for analysis. Followed up by future recommendations.

Structure: introduction to indoor positioning systems and theoretical aspects, practical experiments of investigation and accuracy evaluation of Pozyx, conclusion and future work, references.

Thesis consist of: 60 p. text without appendixes, 23 figures, 11 tables, 45 reference entries. Appendixes included.

Keywords:

Ultra-wideband
Pozyx system evaluation
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Accuracy

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Abstract

The objective of the project is to compare the Pozyx Ultra-wideband (UWB) system in term of accuracy in harsh environment. The accuracy of three-dimensional (3D) coordinates and range is compared by the coordinates obtained with total station using traverse method and Pozyx UWB system.

In order to perform evaluation of Pozyx UWB system a reference network indoors is established to have 3D coordinates and distances to compare. Measurements with UWB-based Two Way Ranging (TWR) positioning system are done in line-of-sight (LOS), no-line-of-sight (NLOS) and combination of both. Indoor environment at Norwegian University of Science and Technology (NTNU) ground floor is suitable for mentioned situations. Measured coordinates and ranges are processed by taking an average value of certain time. The results are obtained from Pozyx IPS platform.

Finally, the results of the experiments in different situations are presented and concluded. UWB system shows that, whenever there is a LOS between anchors and tag the accuracy is 10 – 30 cm. However, NLOS has a great impact on the system's performance, which leads in degradation of accuracy in several meters.

Introduction

For as long as people can remember it has been important to know, where people are in the World. In the olden days, maps and compass were used to find the way around. Today, the Global Navigation Satellite System (GNSS) is used worldwide for outdoor environment. GNSS works well, where a clear view of the sky is available. However, in an indoor environment the signals are reflected by the materials between user and satellite, which makes it way harder to determine the position. That is why, there are new alternatives established to improve the accuracy indoors which GNSS cannot offer.

Indoor Positioning System (IPS) – is a new, emerging technology of measurements inside the buildings. IPS is mostly used to track, monitor and navigate. A good IPS can be defined by the accuracy when operating in harsh environment. Different technologies were studied and the most suitable IPS technique called UWB was chosen to evaluate at NTNU campus. UWB is showing the best performance compared to other IPS. This is because of its simplicity to penetrate obstacles in a centimetre accuracy.

This project aim is to investigate the precision of UWB technology comparing to total station measurements in harsh environment. In order to evaluate the accuracy of UWB system, 3 specific problem statements have been defined:

1. What accuracy of coordinates can be achieved in LOS and NLOS?
2. What accuracy of coordinates can be achieved in combination of both – LOS and NLOS?
3. What range accuracy can be achieved in LOS and NLOS?

Based on this project it will be clear, how viable is Pozyx UWB system positioning for use in NTNU Smaragd building ground floor.

Preface

First of all, we would like to give our sincere and most grateful thank to Norwegian University of Science and Technology. Nothing would happen if NTNU did not provide this opportunity and equipment for our bachelor degree. Big thanks to our supervisor, associate Professor Vilma Zubinaite for valuable guidance and positive attitude throughout the work on this thesis. We would also like to thank associate Professor Erling Onstein for suggesting a topic of bachelor thesis.

Secondly, a greatly thanks to engineer Morten Eggum and lecturer Andras Ladai who helped us to measure traverse with total station.

Last but not least, we would like to sincerely thank everyone we met this year in Erasmus studies. This experience was one of the best we have ever had. This made us grow as persons more.

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List of Abbreviations

IPS	*Indoor Positioning System*
GNSS	*Global Navigation Satellite System*
BS	*Base station*
RTLS	*Real Time Locating System*
RSS	*Received Signal Strength*
TOA	*Time of Arrival*
TDOA	*Time Difference of Arrival*
TWR	*Two Way Ranging*
AOA	*Angle of Arrival*
RTOF	*Roundtrip Time of Flight*
RF	*Radio frequency*
RFID	*Radio Frequency Identification*
UWB	*Ultra-Wideband*
RSSI	*Received Signal Strength Indicators*
AP	*Access Point*
WLAN	*Wireless Local Area Network*
WPAN	*Wireless Personal Area Network*
BLE	*Bluetooth Low Energy*
IR	*Infrared*
LOS	*Line-of-sight*
NLOS	*No-line-of-sight*
TOF	*Time of Flight*
MCU	*Micro Processor Unit*
LED	*Light-emitting Diode*
MQTT	*Message Queuing Telemetry Transport*
RTK	*Real Time Kinematic*
PRF	*Pulse Repetition Frequency*
API	*Application Programming Interface*

JSON	*JavaScript Object Notation*
IOT	*Internet of Things*
2D	*Two-dimensional*
3D	*Three-dimensional*
NTNU	*Norwegian University of Science and Technology*
WPAN	*Wireless Personal Area Networks*
CP	*Control Point*

1 Theory and Background

The purpose of this chapter is to explain the processes and technologies of Indoor Positioning and necessary information is given to understand parts of this project. Further, theory regarding to distance estimation, which is used to calculate the position of object, is presented. A deep review of theory regarding to Indoor Positioning techniques in this project is also given later in this part.

1.1 Indoors Positioning Systems

GNSS has difficulties indoors, because the signals are interrupted or reflected by the different obstacles like glass, concrete walls. For that reason technologies and systems like Ultra-Wideband, Ultrasound are developed each year to help to improve indoor positioning. IPS is a system to locate an object or to track a person inside the building. The system is based on different methods, technologies and information. Some of technologies are explained in the next section, since some IPS applications may require low-cost IPS, where others may require high accuracy IPS such as industrial environmental tracking. An IPS has these following performance metrics to determine its potential [11]:

1. **Accuracy** – depends on the technology used. Accuracy varies from 1 centimetres up to 10 meters;
2. **Availability** - the positioning service availability in terms of time percentage;
3. **Coverage Area** - the area covered by an IPS;
4. **Scalability** - the degree to which the system ensures the normal positioning function when it scales in one of these two dimensions: geography and number of users;
5. **Cost** - can be measured in different dimensions: money, time, space and energy;
6. **Privacy** - strong access control over how user’s personal information is collected and used.

Indoor positioning systems consist of two components:

1. Base station (BS) – store the known location information;
2. Device (user) – the node in a system, which needs to know the position indoors.

The number of components depends on the technology and algorithm are used. The most common algorithms reviewed in chapter *"Distance estimation"* [27].

In general, for IPS systems to locate indoors, there are two most prevalent tasks that has to be completed:

1. Estimate the distance between base station and user;
2. Trilateration, to find a user location in indoor environment.

These tasks are explained in *"Distance Estimation between base station and user"* and *"Trilateration"* chapters. Additionally, IPS often is related to Real Time Locating System (RTLS). RTLS are used to automatically track the location of people or objects in real time. It's basically connecting the IPS systems to the wireless network. Which makes it easier to present data to the user [28].

1.1.1 Indoor Positioning Applications

Most prevalent industries using indoor positioning:

1. Hospitals and health care:
   - Locating patients and visitors;
   - Locating medical equipment.
2. Sports and entertainment:
   - Improving player performance;
   - Enhanced analytics;
   - Guide people inside a shopping mall or airports;
   - Museum tours;
   - Location-based advertising and messaging.
3. Defence and military:
   - Locating people;
   - Robot navigation.
4. Logistic and warehousing:
   - Quality assurance;
   - Optimizing workflow;
   - Managing inventory;
   - Optimizing routes;

- Improved automation capabilities.

The indoor positioning market is currently in the state where the GNNS technology was at 15 years ago. The IPS technology market and human needs growing every year and more companies trying to integrate indoor positioning into their product and platforms or service offering. However, as with every new technology that comes up there is an issue with human privacy and personal space [31]. For example, *"when you know, where your customers are in your store, shopping mall or airport, you have the option of sending them location based offers directly to their smartphone based on their location."* [32]. This makes the market and advertising more aggressive in respect to customer. Despite these facts, the possibilities of indoor positioning systems will be endless in near future, especially with developing real time indoor navigation [32].

1.2 Distance Estimation

This section describes different types of distance measuring techniques (methods) for multiple systems. Distances that are given in these methods are used in trilateration between three or more reference points to be able to find the coordinates of tracking object related to the reference point's positions [15].

1.2.1 Distance Estimation Between Base Station and User

There are two most widely used distance measuring methods for multiple systems in Indoor Positioning:

- Multilateration – rely on measuring distances to compute the position. In order to get two – dimensional coordinates (X, Y), minimum three distances are needed, while, for three – dimensional coordinates (X, Y, Z), minimum four distances are needed [17];
- Multiangulation – computes the position by creating angles from receivers, which position is known [17].

Multilateration positioning can be divided in four categories such as:

- Received Signal Strength (RSS);
- Time of Arriva (TOA);

- Time Difference of Arrival (TDOA);
- Two Way Ranging (TWR).

Multiangulation can be used in combination with:

- Angle of Arrival (AOA) algorithms.

Furthermore, when the distances are known out of these methods, position of tracked system can be computed by trilateration [11].

1.2.1.1 Time of Arrival

Time of Arrival (TOA) is simply the method of finding the exact time that a signal was sent from the transmitter (BS) and the exact time the signal arrives at a receiver (user). Once this absolute time is known, the distance from the receiver can be calculated by multiplying the speed of light constant with a time difference [19]. The concept of TOA is shown in Figure 1.1.

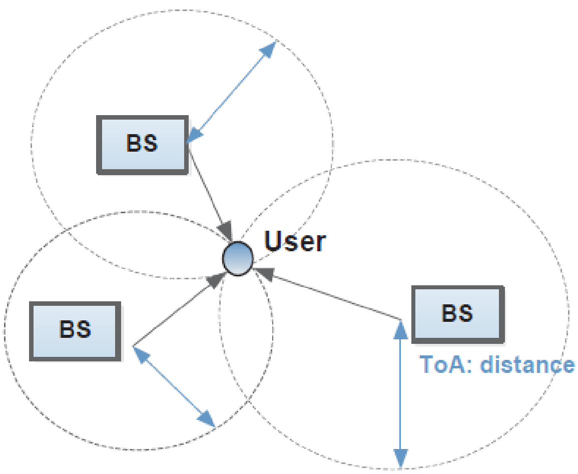


Figure 1. 1 Concept of Time of Arrival [27]

In general, the TOA algorithm generate a circle around the base station (BS) and maintain the BS as circle center, which position are known. Furthermore, circle radius equals to the distance to the user and three such circles can give one intersection point of possible user location [27]. Since, the TOA technique requires very precise knowledge of the transmission start time, there must be a very precise time synchronization of all stations to avoid time error and compensate clock drifts caused by temperature [19-22]. *"For example, a time measurement error as small as 100 nanoseconds can result in a localization error of 30 meters"* [21]. Which means, TOA based positioning method are challenged in environments where a lot of multipath, interference may exist. However, TOA based localization stands out from another methods that it gives location information for any range [22].

1.2.1.2 Time Difference of Arrival

Time Difference of Arrival (TDOA) is very similar to TOA. This distance measuring method uses difference in arrival time of TOA from several known points to calculate the relative distances to each. This is done, because there is a possibility, that low-cost receiver's clock bias (clock error) might be not relevant. TDOA requires a strict synchronization between reference points to make sure that the measuring signal is sent at the exact same time. Unlike TOA, where receiver does not need to share synchronization, since the relative difference in arrival time is measured instead of the absolute. Reference points are usually fixed and it is possible to connect them through a wire avoiding the need for more complex wireless clock synchronization algorithms [15, 16].

1.2.1.3 Roundtrip Time of Flight

Roundtrip Time of Flight (RTOF) is an algorithm that measures TOF of signal traveling from the transmitter to the receiver and back. In general, RTOF is moderate algorithm that replaces the time for both stations synchronization requirement in TDOA and distance estimation procedures splits in four stages [29, 30]:

1. Ranging and auxiliary information collection – performing distance measurements to at least for 3 anchors. Since range can be affected by multipath, most of the time range is measured couple times [30];
2. Pre-processing – removing errors, selection of right anchors for lateration if there is more than three;
3. Lateration algorithms – quadratic equations are solved for x and y getting the position of user location [30];
4. Post-processing – *"check if localization point belongs to the area of interest, and attract it if needed."* [30].

1.2.1.4 Received Signal Strength

Received Signal Strength (RSS) system uses reference points but unlike other systems it also uses already searched objects as transmitters and the other side as receivers. Algorithms, based on RSS measures the signal strength of the received signals to estimate the distance between transmitter and receiver. RSS system is quite sensitive for not line-of-sight environment. This leads to less accurate results and makes it less usable in indoor positioning [17]. RSS is usually used in low cost applications, where accuracy and results does not have much impact.

1.2.1.5 Two Way Ranging

Two Way Ranging (TWR) is the common protocol for positioning. It can be accomplished by using two transceivers. Transceiver is a device with a function to send and receive signals. In TWR, the distance from these two transceivers (tag and anchor) is determined by sending a packet back and forth, also by measuring time how long it took for the packet to return [23, 24]. The concept of two way ranging is shown in Figure 1.2.

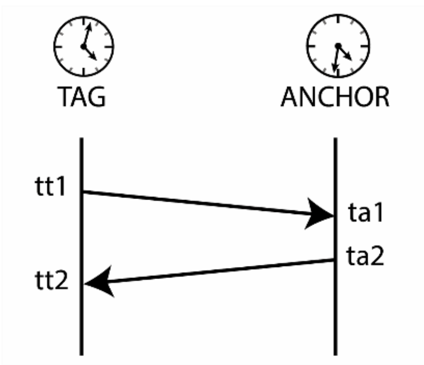


Figure 1. 2 Concept of Two way ranging [23]

In general, the tag begin the communication sending the first message at time tt1. The anchor, after certain amount of time, replies with a packet containing timestamps ta1 and ta2. It is the reception moments of the first packet and the reply to the tag. After this process tag can compute the TOF, in order to estimate the distance between tag and anchor. The main drawbacks of TWR is that more messages required for localization, which leads to higher energy consumption [26]. On the other hand, TWR does not need clock synchronization, *"since both the round-trip time(s) and the reply time(s) can be calculated separately using timestamps derived from one device"*, which increases the reliability of the system [24]. Second, most of the time based positioning techniques suffers from the temperature dependence of the speed of light. The TWR positioning protocol does not have this issue and it is more precise overall [25].

1.2.1.6 Angle of Arrival

Angle of Arrival (AOA) determines the position using the two incoming angles signals arriving from transmitter (BS) to receiving sensor (User) as shown in Figure 1.3.

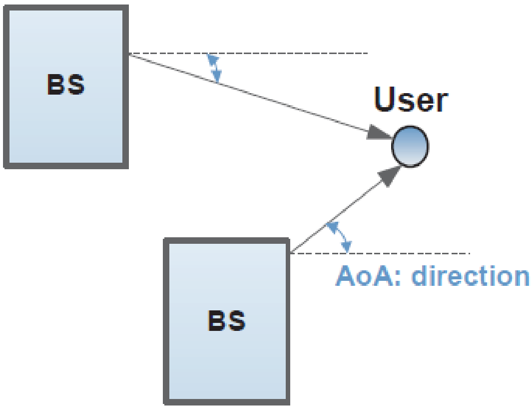


Figure 1. 3 Concept of Angle of Arrival [27].

AOA is defined by the direction of propagation from a transmitter on the antenna array. Geometric relationships can then be used to estimate location of the user from the intersection of more than two direction lines [27]. This technique has been used widely in cellular industry to provide location tracking services for mobile phone users because, it only needs two measuring units for two-dimensional (2D) positioning and three for 3D position. Also the main advantage against time based measuring techniques is that it does not need clock synchronization between transmitter and receiver. However, AOA is still not perfect method to determine the distances for localization in indoor positioning, cause despite the fact that it works well in situation with direct LOS, AOA technique suffers from decreased precision when there are signal reflections (multipath) from surrounding objects such as walls, floor ceiling, etc. For this reason, AOA only can be used for short range, which makes this technique less used than time based solutions [21, 22].

1.2.2 Trilateration

This method rely on measuring distances between receiver and transmitter, where three or more distances are needed to calculate position of the object [4]. The position is determined using

TAO to measure time taken by a signal to arrive at a receiver from a transmitter. TDOA, which is an improvement of TOA, is used in some instances. TDOA measures the difference in TOA at two different receivers and determines the relative position of the transmitter based on difference in the propagation time of signals [17]. For 2D environments, minimum three distances are needed, for three-dimensional (3D) environment, minimum four distances are needed to calculate position of an object [4]. The accuracy depends on the signal received and multipath) [17].

1.3 Techniques for Indoor Positioning

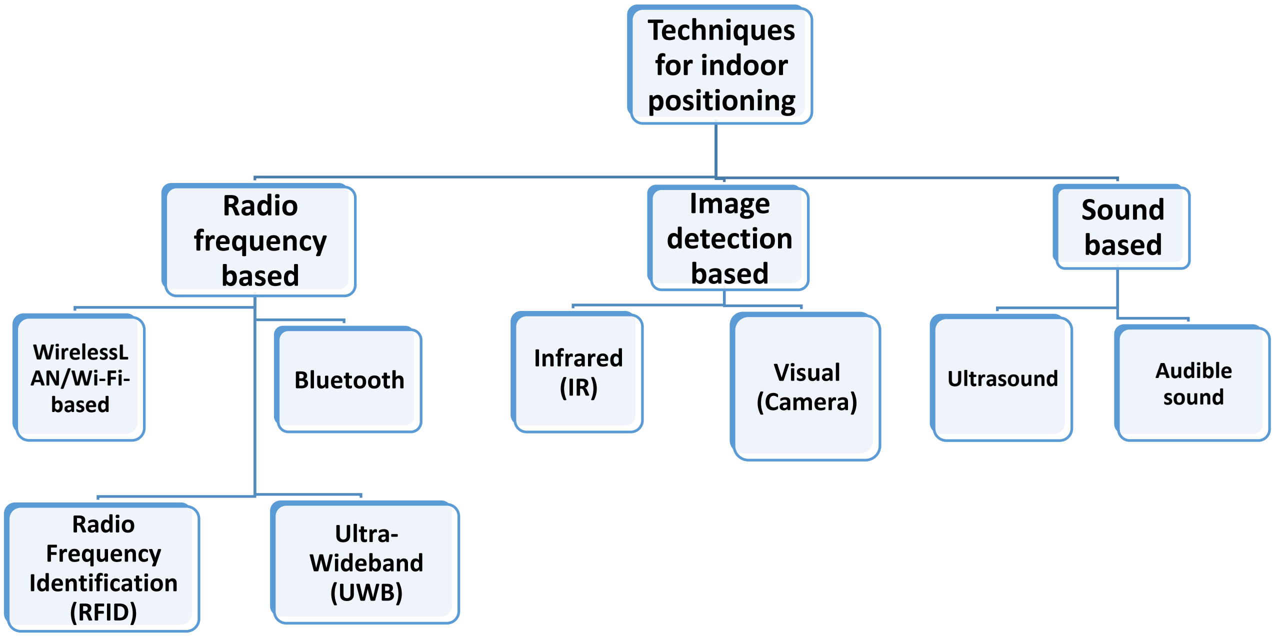


Figure 1. 4 Techniques for indoor positioning.

Indoor positioning is a field where many technologies and different approaches are released. These techniques can be divided into three main categories: Radio frequency, Image detection and sound based. Also, it can be subdivided into even smaller groups (see Figure 1.4). The most common ones for indoor environments are the focus of this chapter and a summary will be provided at the end to highlight their general characteristic.

1.3.1 Radio Frequency Based

Radio frequency (RF) based positioning system is a localization technology that uses RF signals and infrastructure to estimate the position of an object or a person for tracking and navigation purposes. The RF positioning systems are further categorized into WirelessLAN/Wi-Fi, Bluetooth, Radio Frequency Identification (RFID) and UWB. These positioning systems have unique advantages and limitations, and the succeeding sub-chapters highlight them [4].

1.3.2 WirelessLAN/Wi-Fi-Based Positioning System

WLAN (Wireless Local Area Networks, IEEE 802.11 standard; 'Wi-Fi' is utilized reciprocally or as a superset of IEEE 802.11 and indicates the enlisted trademark of the Wi-Fi Alliance) can be utilized to assess the location of a cell phone within this network [1]. Shortly, a WLAN is a wireless high-speed net chain that uses high frequency radio waves to interface and communicate between gadgets and devices, mostly inside the closed environments [4].

The most prevalent WLAN localization method is to make utilization of Received Signal Strength Indicators (RSSI). In standard, WLAN-based positioning systems can be subdivided into four techniques:

- Cell ID – Fundamental Wi-Fi positioning solution. It matches the target's position with its connection to an Access Point (AP) [7];
- Trilateration method – it’s a technique that computes an object position by intersecting three circles. Usually three Access Points transmits electromagnetic wave to the wire or antenna inside mobile phone or WLAN devices [5, 7];
- Fingerprinting – this method is progressively appropriate for indoor environments. It’s primarily based on the connection between a given location and its corresponding radio signature [5];
- Propagation modelling – is a scientific model used in visualizing radio map, converting RSSI values into geometrical parameters and scientific units such as distance or angles [4].

Since Wi-Fi AP are available in large scale in today's indoor environment, the Wi-Fi range can reach from 50 m to 100 m and despite the multipath error in harsh environments the accuracy is around from 1 to 5 meters [1, 6].

Comparing to the other indoor positioning methods, WLAN/Wi-Fi systems offers scalability in few ways: first, in today’s indoor environment, WLAN infrastructure is available everywhere. Second, advantage of using WLAN is that line of sight is not required [5, 6].

However, WLAN/Wi-Fi cannot be considered as direct solution for indoor positioning cause of its structure and purpose. This technology is more for data transmission and communication [8].

1.3.3 Bluetooth

Bluetooth is invented as a low-power technology for interconnectivity across Wireless Personal Area Networks (WPAN). It is an open wireless technology standard for connecting hand-held wireless devices and transmitting fixed data over short distances through established connection [1]. In indoor environments Bluetooth technology is commonly related to the use of beacons, which are small radio transmitters that send out radio signals in a radius of 10-30 meters [2]. Additionally, that sort of positioning system consists of combining the Bluetooth devices, Bluetooth beacons, tags, server and WLAN. The main task of server is to compute the position of the device, then send the information to the application and display data to the user. Furthermore, to improve user privacy the server stores only beacon position information and calculation of user position is then computed in user device [4].

On the one hand, beacons has a limited range, especially in a harsh environments, they can determine a position accurately up to 1-3 meters. Furthermore, Bluetooth devices has latency unsuitable for real-time positioning applications and mobility limitations what makes this system ineffective for precise geodetic measurements [1].

On the other hand, Bluetooth technology advantage for exchanging data between electronic devices is that the technology is very safe, inexpensive and small size. Moreover, the new Bluetooth Low Energy (BLE) is based on low power consumption. "*Beacons can be used for both client-based as well as server-based applications*", that allows for users get accurate position up to one meter by using the app – cross platform [2].

Bluetooth technology as indoor positioning systems is used in hospitals and health care institutions. Commonly for locating patients, visitors or medical equipment [3].

1.3.4 Radio Frequency Identification

Radio Frequency Identification (RFID) uses radio waves to transmit the identity of an object (or person) wirelessly. RFID technology is most commonly used to automatically identify objects in large systems. It is based on exchanging different frequencies of radio signals between two main components: readers and tags. Tags are attached to all the objects that need to be tracked. The tags consist of a microchip and a radio antenna. There are two types of tags: active and passive tags [11].

There are three main parts of passive tag system: RFID reader, RFID antenna and RFID tags. Passive tag is cheap and simple. This tag does not contain the battery. The power is supplied by the reader. When radio waves from the reader are encountered by a passive RFID tag, the coiled antenna within the tag forms a magnetic field. The tag draws power from it, energizing the circuits in the tag. The tag then sends the information encoded in the tag's memory. The major disadvantage is that the tag can only be read at very short distances, from 1 to 2 meters, but these passive tags does not need a battery so it can serve up to 20 years or more [12].

RFID active tag consist of the same three main parts as passive tag, but is way more expensive, equipped with a battery and a small antenna, what increases the range significantly, around to 30 meters. Battery makes it possible to send the specific signal information every few seconds to reader, so the tag will not need to wait to hear the reader’s signal [13, 14].

1.3.5 Ultra-Wideband

UWB is one of the most recent, accurate and promising technologies. UWB is a radio technology for short-range, high-bandwidth communication holding the properties of strong multipath resistance and to some extent penetrability for building material which can be favourable for indoor distance estimation, localization and tracking. A typical UWB setup features a stimulus radio wave generator (Anchors) and receivers (Tags) which capture the propagated and scattered waves [1].

There are four different positioning methods: TOA, TDOA, TWR and RSS. The first three methods are more reliable, because they measures time that signal travels instead of measuring signal strengths, that has difficulties in not line-of-sight environment [17].

UWB waves works on a large frequency bandwidth (>500 MHz) and operates in the wavelength of microwaves. Also, the high bandwidth and extremely short pulses waveforms help in reducing the effect of multipath interference and facilitate determination of TOA for burst transmission between the transmitter and corresponding receiver, which makes UWB a more desirable solution for indoor positioning than other technologies [11]. Unlike RFID systems, which operate on single bands radio spectrum, UWB transmits a signal over multiple bands of frequencies simultaneously, from 3,1 to 10,6 GHz. Short duration pulses allows to determine which signals are correct and which are generated from multipath [15].

UWB location exploits the characteristics of time synchronization of UWB communication to achieve very high indoor location accuracy (5-30 centimetres) [15]. Low frequency components in the UWB signal spectrum has the ability to penetrate building materials like concrete, glass or wood walls. This means, unlike other technologies such as infrared and ultrasound sensor, this technique does not require a line-of-sight and is not affected by the existence of other communication devices. However, metallic and liquid materials cause UWB signal interference but this can be avoided by using more readers and strategic placement of UWB equipment [15]. Operating range cannot exceed 100 meters, because the low power spectral density prevents harmfulness to the human body and bounds the interference of UWB signals with other narrowband receivers [1].

1.4 Image Detection Based

In this section, the image detection based indoor positioning are described. Cameras are becoming a dominating technique for positioning which covers a wide field of applications at all levels of accuracy [1]. Taking into account, the fact that image detection can offer very detailed data about the tracking area, there is a serious threat to privacy. Additionally, the image processing requires huge resources that would lead to a large cost [17].

1.4.1 Infrared

Infrared-based (IR) indoor localization systems use infrared light pulses to locate signals in a closed environments. IR is used in WPAN since it is a short-range narrow-transmission-angle beam suit-able for aiming and selective reception of signals [15]. Infrared systems are based on LOS mode which is a big disadvantage, because it suffers from no-detection areas that are occluded from the transmitter or sensor [16].

There are two types of measuring principles: thermal imaging and active beacons. Thermal imaging is using infrared light (or heat) invisible to the human eye, which can obtain a completely passive image of the surrounding world from natural thermal emission. While active beacon is a fixed infrared receiver placed at known locations throughout an indoor space and mobile beacons whose positions are unknown [1].

Commonly, infrared has been used in an open-space warehouse for detection or tracking of objects or people. Systems based on high resolution infrared cameras are able to detect artificial IR light sources at sub-millimetre accuracy, because image contains larger number of pixels per unit of area. Although, systems based on active beacons or those using natural radiation are mainly used for rough positional estimation or detecting the presence of a person in a room [1].

1.4.2 Visual (Camera) System

This technique standout from others by the fact that camera is the only main sensor and does not require target to carry any kind of device. The position of an object or a person is determined by identifying and matching the image patterns that is within view with a mobile sensor or camera in a mobile device [1]. Technique is very easy to set up and could use existing cameras in the area. The main disadvantage of the system is that it needs clear LOS to the tracking object. System suffers from a low accuracy, interference from multiple effects such as a bright light and motion blur, and significant accumulative errors which could lead to poor performance. This loss can be solved by increasing pixel density for an accurate detection of target but that can rapidly increase the price of equipment and complexity of system compared to other systems [33].

1.5 Sound Based Indoor Positioning

In this section, two main sound based indoor positioning systems are described. These systems mostly are used for multiple tracking applications at centimetre level precision. *"Sound is a mechanical wave that is an oscillation of pressure transmitted through a medium. Positioning systems use the air and building material as propagation media."* [1]. System determines user location using sound waves via multilateration based on distance measurement to static nodes mounted at the ceiling or walls [1].

1.5.1 Ultrasound

Ultrasound is defined as "*a mechanical wave that is an oscillation of pressure transmitted through a medium*" [2]. Ultrasound technique does not require line-of-sight unlike techniques based on radio frequency. Also, Ultrasound does not interfere with electromagnetic waves. In indoor positioning these waves benefit from leverage building material and the air as a propagation medium [1]. Distances are then measured using TOA measurements of ultrasound pulses travelling from emitters to the receivers, but the waves have quite short range, maximum is about 10 meters. The position is estimated by multilateration from three or more receivers at fixed and known coordinates of their location [1].

1.5.2 Audible Sound

In general, audible sound positioning system make use of sound waves in the near audible spectrum of 17 kHz to 22 kHz. The main principal is to make the system easily expandable by using already existing sound cards of standard devices [1]. Audible sound system usually consists of three parts:

1. Mobile devices – act as a transmitter that sends sound to the receiver;

2. Acoustic receivers – main task to estimate the TOF/TOA of the acoustic signal and send it to the server;

3. Wireless network and central station – processes the received information and computes the position of transmitter and sends the position data to mobile device.

Additionally, in the different system approach, the mobile devices also could act like a receiver through the device microphone. Such a system would consist of signal generator (speaker), signal detector (microphone) and wireless network. However, the principle of operation remains the same as in a first setup [4].

In general, accuracy of audible system is quite impressive. At a 3D positioning, accuracy of 1 cm to 2 cm can be achieved indoors within a maximum range of 10 m, but to maintain such a high quality of precision in a harsh environments is complicated and expensive. It is needed to take into account that most of equipment have low penetration power through obstacles, low update rate, limited bandwidth, which affects audible sound signals and makes it a challenge to use this technology widely in indoor positioning [1, 4].

1.6 Overview of Indoor Positioning Techniques.

Utility of the indoor positioning technologies are disclaimed by summarizing advantages and disadvantages in table 1.1 below.

Table 1. 1 *Comparison of main indoor positioning techniques.*

Category	Technology	Algorithm	Accuracy	Coverage	Privacy/ Security	Application	Advantages	Disadvantages	Reference
Radio frequency based	Wi-Fi	RSSI, TDOA	2-10 m	20-50 m	Low	pedestrian navigation	Use existing communication networks that may cover more than one building; the majority of devices available nowadays are equipped with WLAN connectivity; LOS is not required [34].	The recalculation of the predefined signal strength map in case of changes in the environment (e.g., open/closed doors and the moving of furniture in offices). [34].	[16,1,4]
	Bluetooth	RSSI, TDOA	1-3 m	1-30 m	Medium	Person tracking	Does not require LOS between communicating devices; it is also built into most smartphones, personal digital assistants, etc. [34].	Radio interference is more likely to occur [34].	[17,1,4]
	RFID	RSSI	1-5 m	1-10 m	Low	pedestrian navigation	Penetrate solid, non-metal objects; do not need Line of Sigh between transmitters and receivers [34].	Cannot be integrated easily with other systems, RF communication is not inherently secure and consumes more power than IR devices [34].	[16,1,4]
	UWB	TWR, TOA, TDOA	10 – 30 cm	1 - 50 m	Low	robotics, automation	High accuracy positioning, effectively passes through walls, equipment, and any other obstacles [34].	High cost of UWB equipment; although UWB is less susceptible to interference relative to other technologies, it is still subject to interference caused by metallic materials [34].	[1,4]
Image detection based	Infrared (IR)	TOA, TDOA	57 cm - 3m	1-5 m	Low	people detection, tracking	It is suitable for sensitive communication because it will not be accessible outside a room or a building [34].	Does not penetrate walls, therefore it is typically used in small spaces such as one room; requires LOS between sender and receiver when using direct IR; [34].	[16,1,4]
	Visual (Camera)	AOA	10 cm	1-10 m	Low	metrology, robot navigation	They are relatively cheap compared with other technologies such as ultrasound and ultra wideband technologies [34].	Requires LOS, coverage is limited [34].	[1,4]
Sound based	Ultrasound	AOA, TOA, TDOA	1 cm – 2 m	2-10 m	Low-Medium	hospitals, tracking	Does not require LOS; do not interfere with electromagnetic waves [34]	Does not penetrate solid walls; there may be LOSs of signal because of obstruction; false signals because of reflections; and interference caused by high frequency sounds [34].	[1,4]
	Audible sound	TOA	Meters	1-20 m	Low				[1,4]

In table 1.1 the most common indoor positioning technologies are described. These technologies are summarized according to what algorithm they use to estimate the distance, how accurate they are, how well they cover the area in indoor environment and where they are most commonly used.

1.7 Traverse

Traverse is a method in the field of surveying to establish control networks. Traverse networks involve placing survey stations along a line or path of travel, and then using the previously surveyed points as a base for observing the next point. Traverse networks have many advantages, including:

- Less reconnaissance and organization needed;
- While in other systems, which may require the survey to be performed along a rigid polygon shape, the traverse can change to any shape and thus can accommodate a great deal of different terrains;
- Only a few observations need to be taken at each station, whereas in other survey networks a great deal of angular and linear observations need to be made and considered;
- Traverse networks are free of the strength of figure considerations that happen in triangular systems;
- Scale error does not add up as the traverse is performed. Azimuth swing errors can also be reduced by increasing the distance between stations.

The traverse is more accurate than triangulaterąation (a combined function of the triangulation and trilateration practice) [43].

1.7.1 Types of Traverse

Frequently in surveying engineering and geodetic science, control points (CP) are setting/observing distance and direction (bearings, angles, azimuths, and elevation). The CP throughout the control network may consist of monuments, benchmarks, vertical control, etc.

There are mainly two types of traverse. Traverse may be either a closed traverse or an open traverse:

1. Closed traverse: the traverse which either originates from a station and returns to the same station completing a circuit or runs between two known stations are called a closed traverse;

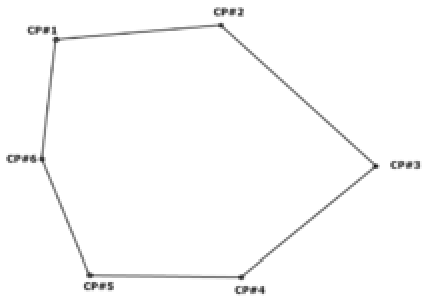


Figure 1. 5 Diagram of a closed traverse [43].

2. Open traverse: the traverse which neither returns to its starting station nor closes on any other known station is called open traverse.

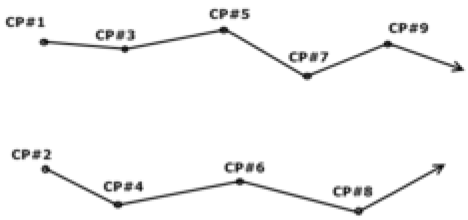


Figure 1. 6 Diagram of an open traverse [43].

2 Methods

This section presents in detail the hardware, software and methods used for location estimation in this thesis. The hardware equipment is provided by Pozyx, Powel AS and Leica companies. Meanwhile, Gemini Oppmåling, Pozyx Companion and Anaconda software were used for processing the data.

2.1 Equipment

2.1.1 Pozyx System Description

Pozyx NV is a Belgian company specialized in indoor positioning using UWB radio frequencies. The company was found in 2015 in Ghent, Belgium. Pozyx has a hardware (shield) which provides information of the tag position and its motion. It is compatible with Arduino board and using header pin to connect together. This shield includes UWB that can be applied for indoor positioning. The device also contains other sensors like: pressure sensor, gyroscope, accelerometer and altimeter [35].

In this project, the test equipment is a Developer's kit provided by Pozyx which includes tag, anchor and other necessary cables to provide power supply. This kit uses the wireless TWR UWB protocol.

2.1.1.1 Tag

Tag is a device where all calculations are made. One of these tags serves as the master tag which can be connected to a computer. The master tag knows the positions of all remote tags and makes them available through the software or libraries [36]. It needs to be carried by the target in order to determine its location and the power source must be portable too. Inside the tag there is a UWB chip, Decawave DW1000 transreceiver which is used to determine position. Every Pozyx device, tag and anchor contains "the center of the shield" – a Micro Processor Unit (MCU) STM32F4 that provides all functionalities. MCU communicates with all the sensors and performs all calculations in real time. The centroid of the board is UWB antenna which is used as a local reference point to device's local coordinate-system, which must be considered when several devices are used for trilateration purposes. Pozyx tag uses two-way ranging as default distance calculation algorithm, which is a variant of TOA. The tag sends out messages to the anchors, measures the distances to anchors and returns information to the tag. Pozyx system also supports TDOA. The tag is sending out one-way message to an anchors, whereas anchors (anchors time must be synchronized) measures the time differences of received signals. There is also a micro USB to connect the tag to computer and update the shield. The wire debug is used to reprogram the tag completely and allow users to access every sensor directly. There are several Light-emitting Diodes (LED) to know the current activity of a tag. Pozyx tag can interact with external devices, such as an Arduino board, which allows the user to adapt device to own needs, tracking and 3D positioning. Also, the tag includes sensors like: gyroscope, magnetometer, accelerometer and altimeter [35].

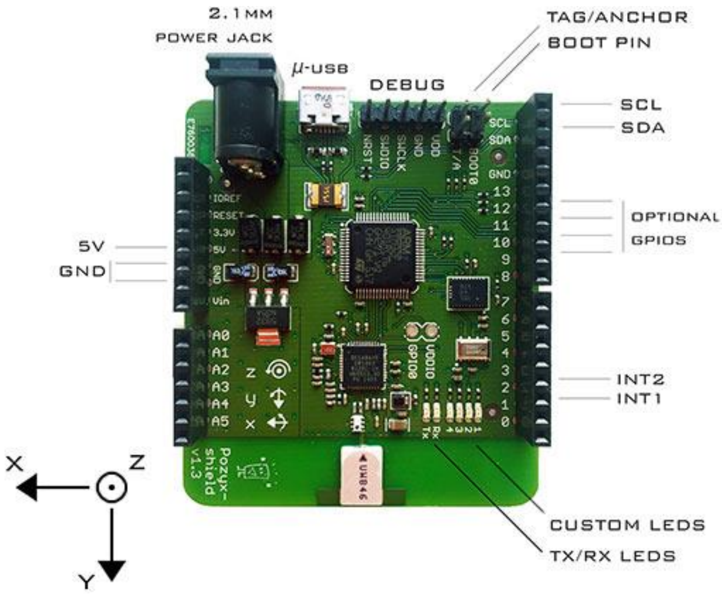


Figure 2. 1 Pozyx developer's tag [36].

2.1.1.2 Anchor

The Pozyx anchor is the same device as tag. The difference is that, it is a base station which receives and sends back all the necessary information to the Pozyx tag to position the target. It has fixed and known position. Anchors has the same role as satellites in GNSS positioning. The device has a black cover with it that allows to mount the device on the wall [35].

Figure 2. 2 Pozyx developer's anchor [36].

2.1.1.3 Leica Viva TS16

The world's first self-learning total station. Automatically and continuously adapts for best measurement performance to site conditions, such as rain, fog, dust, sun, heat shimmer and reflections. Identifies and ignores irrelevant targets and reflections. The Leica Viva TS16 learns the environment, delivers accurate positions even in difficult dynamic applications, and offers the fastest re-lock in case of interrupted line of sight [18].

- Automated target aiming range up to 1500m;
- Automated target locking range up to 1000m;
- Accelerated target search with PowerSearch;
- Robust and highly-accurate position delivery in high dynamic applications.

The Leica Viva TS16 total station comes with the revolutionary Captivate software, turning complex data into the most realistic and workable 3D models. With easy-to-use apps and familiar touch technology, all forms of measured and design data can be viewed in all dimensions. Leica Captivate spans industries and applications with little more than a simple swipe, regardless of whether you work with GNSS, total stations or both [18]. Leica Viva TS16 for this thesis is provided by NTNU.

Image assisted surveying:

- 5 megapixel wide angle overview camera;
- Video frame rate of up to 20 Hz onboard and remote;

- Automatic panoramic image capture;
- Tap and turn for aiming.

Pinpoint R1000 distance measurement:

- Single EDM for high accuracy and wide range at the same time;
- Visible measurement beam of small spot size;
- Measurement range on any surface up to 1000 m.

Powered by Leica Captivate:

- Engaging software with immersive experience;
- Full 5" WVGA display;
- Familiar apps at the simplicity of touch [18].

2.2 Software

2.2.1 Pozyx Companion Software

Pozyx work together with companion software (cloud). This software contains basic features client share regardless of use-case or application. When connected to the cloud it is easy to perform software updates or do remote monitoring. This software was used to communicate, calibrate, set-up positioning settings, UWB settings for anchors and tags. Also, was used to change data update rate [37].

2.2.2 Arduino Software (IDE)

The Arduino development environment contains a text editor for writing code, a message area, a text console, a toolbar with buttons for common functions, and a series of menus. It connects to the Arduino hardware to upload programs and communicate with them [38]. This software was used, because Pozyx provides a C++ code that allows easily measure the distances between tag and anchor. Code can be found in APPENDIX 4.

2.2.3 Gemini Oppmåling

Gemini Oppmåling is a program designed to handle all types of surveying, read data on several different formats. System solves the daily tasks that contractors, municipalities and other consultants face when it comes to land-measured data [39]. This Norwegian software was used to post-process data measured by Traverse method with total station.

2.2.4 Message Queuing Telemetry Transport Protocol

Message Queuing Telemetry Transport (MQTT) is an “Internet of Things” (IOT) protocol that allows to capture sensor data in a publish/subscribe method. By default, only positions are embedded with MQTT packet [40]. To connect to MQTT stream, scientific python development environment called Spyder (Anaconda distribution) was used. This allowed to obtain and store tag coordinates in real time. Pozyx Companion also shows coordinates in real time but it is impossible to export as data.

2.3 Testing Environment

The testing area is part of the Smaragd building ground floor, NTNU. There are six areas for experiment: two 3D-print laboratories, garage, geolab, geomatics equipment room and corridor.

Figure 2. 3 Ground floor plan with six test environments. Garage (room: 01 013) in red, 3D-print laboratories (rooms: 01 011, 01 012) in green, corridor (room: 01 010) in brown, geolab (room: 01 009) in yellow and geomatics equipment (room: 01 008) in blue.

Fig. 2.3 Shows highlighted in red area of a garage (room: 01 013) size of 489,413 m^2, 3D-print laboratory (room: 01011) size of 85,961 m^2 and 3D-print laboratory (room: 01 011) size of 77,777 m^2. Highlighted in yellow area of a geolab (room: 01 009) size of 58,270 m^2. As blue, area of geomatics equipment room (room: 01 008) size of 38,769 m^2. As brown, area of corridor size of 26,479 m^2. Whole testing environment contains different size rooms which are suitable for various experiments.

In testing area, there are several error that can occur during the project:

- Radio transparency, when signals partially bounce off of obstacles causing reflections. There are two types of materials that reflect and observes signal the most. Metals – they are the most common conductors. Conductors reflect most of the radio waves [41]. Insulators – materials like wood, plastic, glass and etc. all are great insulators and are very transparent to radio waves, but the impact will generally be negligible. Concrete walls with plumbing, wiring and metal support structures also will be the problem, because the wall thickness is 20 cm;

- Direct path delay – delay comes from time which is needed for signal to pass through different type of material. Impact for results will be bigger if the signal will be absorbed.

2.4 Closed Traverse Network

For this project closed traverse was chosen as a method to establish control network inside Smaragd ground floor. Decision to use closed traverse is because result of traverse is a vector model of polygon, with angles and lengths as well as real-world coordinates of the vertices of the polygon, and knowledge about the error of measurement [5].

Three points were measured as known reference points to start closed traverse. Points were measured by Real Time Kinematic (RTK) method using Leica GS16 GNSS smart antenna. Measurements were done in EUREF89 UTM zone 32 coordinate system. Each point was measured 3 times for 10 seconds with at least 15 minutes interval. Average of 3 measurements was set as true and known coordinate.

Table 2. 1 Points measured by RTK method.

Point ID	Interval	N-coord. m	E-coord., m	Height, m
P0	1	6740521.946	591471.193	183.180
P0	2	6740521.943	591471.192	183.168
P0	3	6740521.931	591471.194	183.177
C1	1	6740572.765	591529.486	187.142
C1	2	6740572.738	591529.471	187.095
C1	3	6740572.776	591529.472	187.057
P13	1	67405474.355	591355.819	179.648
P13	2	67405474.364	591355.827	179.654

Table 2. 1 Points measured by RTK method table, continued.

Point ID	Interval	N-coord. m	E-coord., m	Height, m
P13	3	67405474.375	591355.816	179.643

Table 2. 2 Average of measured points by RTK method.

Point ID	N-coord., m	E-coord., m	Height, m
P0	6740521.940	591471.193	183.175
C1	6740572.765	591529.477	185.075
P13	6740474.365	591355.821	179.648

Before the measurements started, calibration of total station was made. This has to be done to be sure that measurements will be with high precision and reliability. Without calibration even the most careful and precise assembly process will result in small deviations which can lead to so called instrument errors like horizontal collimation error, tilting axis error or vertical index error. However, since calibration file was impossible to take out, there was a photos taken and table of results was made.

Table 2. 3 Total station calibration results.

l Component quality (1σ)	0.0003 g
t Component quality (1 σ)	0.0001 g
I V-index quality (1σ)	0.0003 g
Hz-col quality (1σ)	0.0004 g
ATR Hz quality (1σ)	0.0000 g
Atr V quality (1σ)	0.0001 g

Closed traverse measurements has started from P0 point, because it was the closest point to the Smaragd building. All the angles of closed traverse was measured clockwise from the backward direction to the forward direction in two total station phases (sets of measurements). For example, if total station is at P1 point, P0 set to be as a known backsight and P2 point is being established. After establishing a new point, sets of measurements are done in two phases. Sets of measurements are done *A-B-B-A* measurement method. In this case P0-P2-P2-P0 and this is done 3 times. Same principal is done for whole network. After sets of measurements are done at points P2, P3, P4, P5, P6, P7 and P8, detailed points on the walls are established. Wall points are going to be used as points for anchors.

Using closed traverse method solid points were established in rooms: 01 008, 01 009, 01 011, 01 012 and 01 013. In the same rooms detailed points were measured, where anchors will be placed. Detailed points are measured in different heights to help to improve results of Pozyx system in 3D.

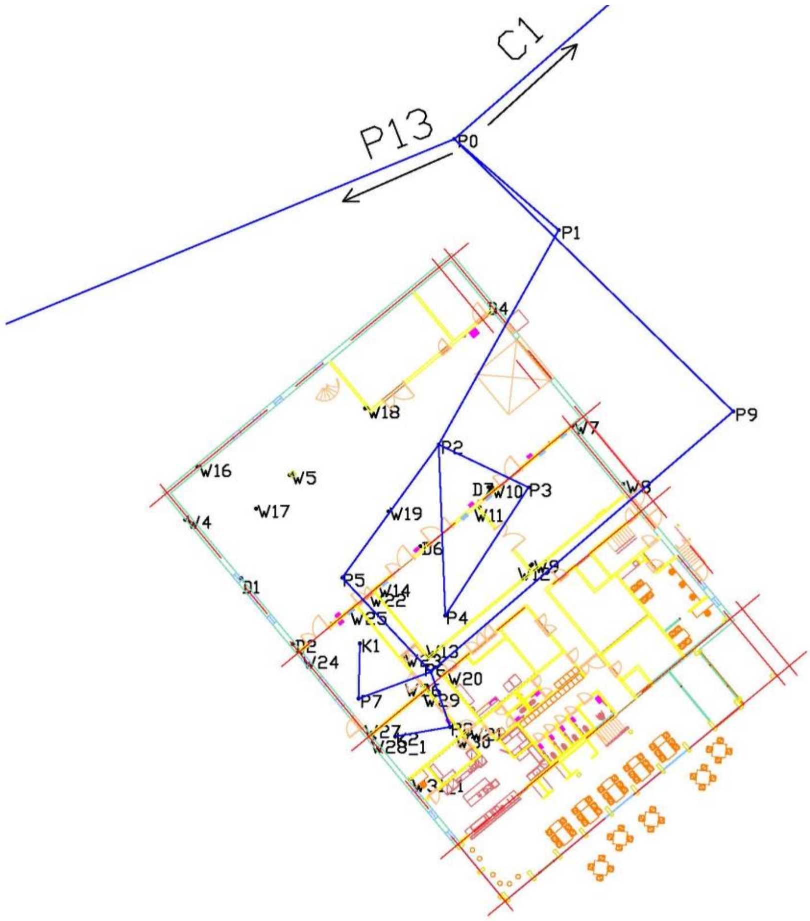


Figure 2. 4 Established traverse network.

Blue colour marks traverse network. In total 9 solid points (marked P***X***) and 38 detailed points (marked W***X*** and D***X***) were made. All the true coordinates with errors of measurements can be found in APPENDIX 1.

2.5 Pozyx System Coordinates Evaluation Methods

Coordinates are measured for 70 seconds at each point and average of data is set as a coordinates to compare with true coordinates obtained with total station.

2.5.1 Method 1. 4 anchors in each room

First method to test out the Pozyx system is to put 4 anchors in each room with LOS. Measure the coordinates to see the differences with true coordinates.

Figure 2. 5 Method 1 testing area.

Fig. 2.5 shows where the anchors are placed in each room. Since 4 anchors can cover 400-800 m^2, 4 anchors in each room is more than enough. 3D-print laboratory (room: 01 012) and geomatics equipment room (room: 01 008) has inside a lot of metal constructions which should have the impact for final results of observation. Coordinates are observed at P2, P3, P4, P5, P7, K1, K2 and P8 points.

2.5.2 Method 2. Difference between 4 and 6 anchors

Second method is to test garage (room: 01 013) with LOS and see if the accuracy of system is increasing with more anchors added.

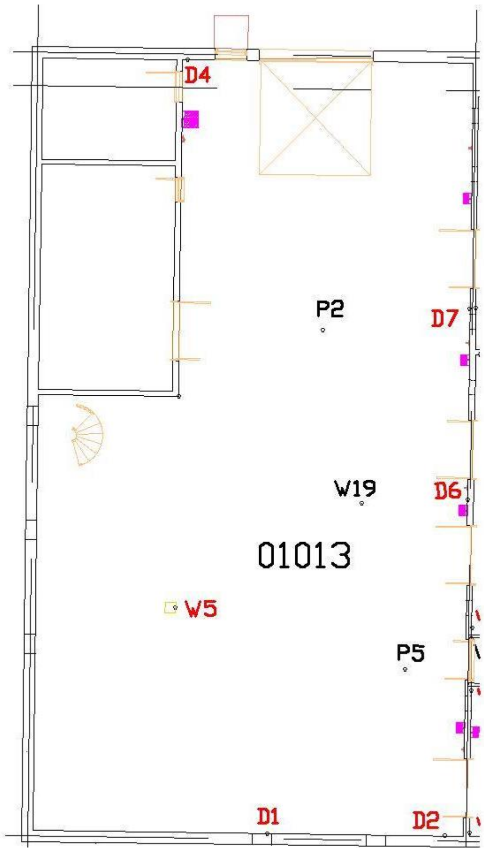


Figure 2. 6 Method 2 testing area.

Fig. 2.6 shows where the anchors are placed for testing method 2. Two more anchors were placed together with 4 anchors from method 1, 6 in total. Coordinates are observed at W19, P2 and P5 points.

2.5.3 Method 3. Expanding area and number of anchors

Third method is to connect 3D-print laboratory (room: 01 012) with garage (room: 01 013) in LOS.

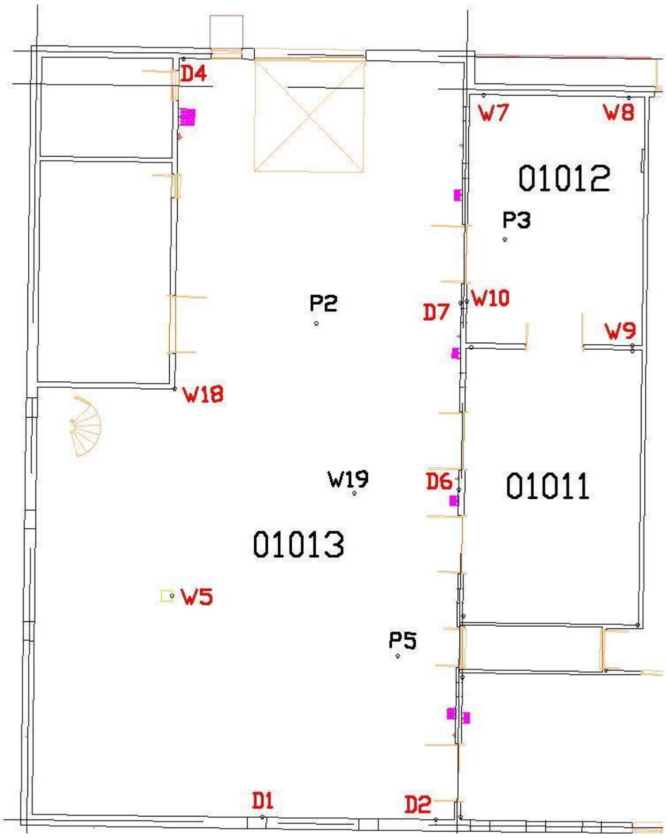


Figure 2. 7 Method 3 testing area.

Fig. 2.7 shows anchors positions for method 3. 7 anchors in garage and 4 anchors in 3D-print laboratory. 11 anchors in total were placed. Coordinates are observed at P2, P3, P5 and W19 points.

2.5.4 Method 4. Expanding area and usage of all 14 anchors

Fourth method is to add another 3D-print laboratory (room: 01 011) room along with those mentioned in third method and place all 14 anchors.

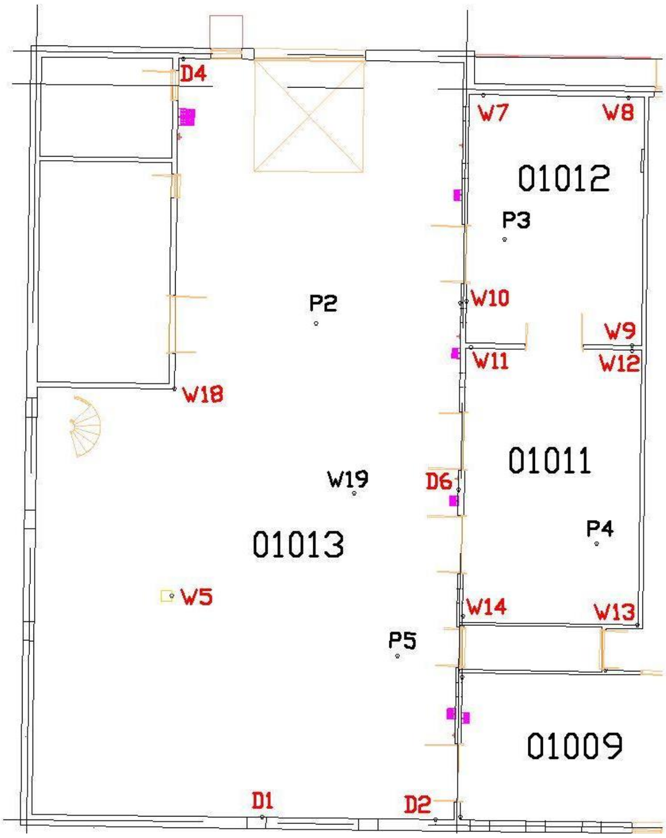


Figure 2. 8 Method 4 testing area.

Points are in LOS. 6 anchors in garage (room: 01 013), 4 anchors in 3D-print laboratory (room: 01 012) and last 4 anchors in another 3D-print laboratory (room: 01 011). Coordinates observed at P2, P3, P4, P5 and W19 points.

2.5.5 Method 5. Tag and anchors in NLOS

The last method is to measure points in corridor where all points will be in NLOS. No anchors are placed in corridor. Pozyx system has to penetrate the concrete walls.

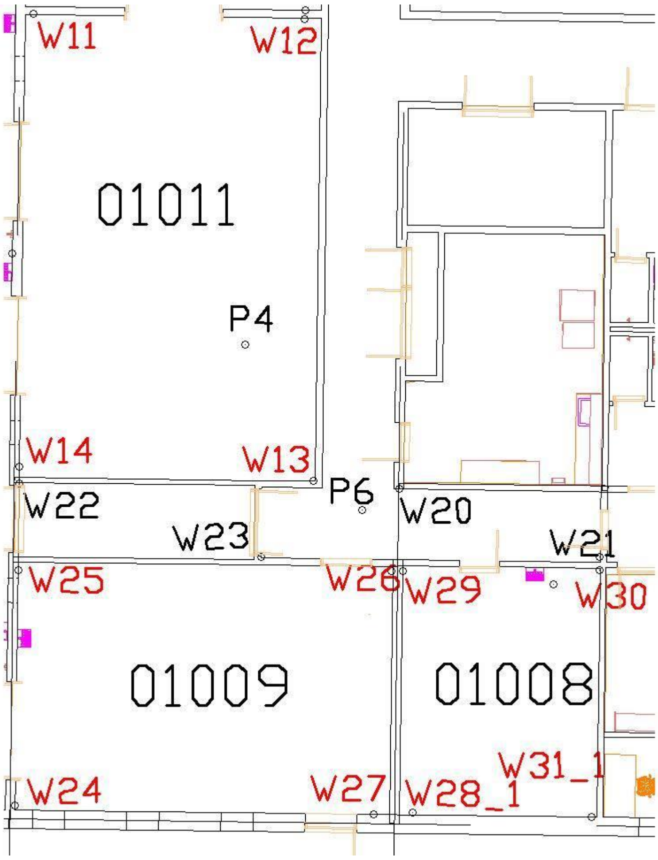


Figure 2. 9 Method 5 testing area.

4 anchors placed in 3D-print laboratory (room: 01 011), 4 anchors in geolab (room: 01 009) and 4 anchors in geomatics equipment (room: 01 008). 12 anchors were placed in total. Coordinates are observed at P6, W20, W21, W22 and W23 points.

2.6 Pozyx system range measurements

Distances between tag and anchor were measured when the highest amount of anchors in room were placed around the known point. Distances are measured for 10 seconds and average of measurements is set to compare with true distance.

2.6.1 Method 1. LOS situation

First method. LOS is between the tag and all the anchors that are placed. 4 distances are measured in: 3D-print laboratory (room: 01 012), 3D-print laboratory (room: 01 011), geolab (room: 01 009), geomatics equipment room (room: 01 008) for points P3, P4, P7, P8, K1, K2. 7 distances in garage (room: 01 013) for each of points P2, P5, W19.

2.6.2 Method 2. NLOS situation

Second method. NLOS for tag and all the anchors. 12 anchors in total. 4 anchors in: 3D-print laboratory (room: 01 011), geolab (room: 01 009), geomatics equipment room (room: 01 008). 12 distances for each of W20, W21, W22, and W23 points which are in corridor.

2.7 Pozyx Settings

All the anchors and tags were set to the same settings while measuring. There are four types of settings that can be modified by the user: Position settings, UWB settings, Push to cloud and connectivity settings.

2.7.1 Position setting

1. Algorithm – the positioning algorithm. For Developer’s kit *UWB only* (no post processing data) algorithm;
2. Dimension – dimension of positioning. 3 options available: 2D, 2.5D and 3D. While measuring it was set to *3D* because X, Y and Z coordinates are needed;
3. Height – the height of the tag in mm when using 2.5D positioning. Was set to 0, because all the measurements were made in *3D*;
4. Ranging protocol – protocol that will be used for making UWB range measurements. Two options available: Precise and Fast. During the measurements was set to *precise*. Precision is slower than fast, but it is more precise and can be used for longer ranges;
5. Filter type – type of filter to use to smoothen the position estimates. During the measurements was set to *Moving median* to avoid positioning jittery;

6. Filter strength – A higher filter strength will make the position estimates less jittery but will introduce more delay. During the measurements was to maximum (15);
7. Sensor data – selecting what data should be collected from the tag. More data can reduce the update rate. During the measurements was set only to *coordinates*.

2.7.2 UWB settings

Settings allow to change the wireless behaviour of the Pozyx system:

1. Channel – independent UWB channel. During the measurements was set to *Channel 2*. Center frequency 3993.6 MHz, 499 MHz bandwidth. Purely from physics the lower the channel frequency the better the range. Also, Pozyx recommends to use this channel;
2. Data bitrate – describes how long it will take to determine ranging and positioning process. During the measurements data bitrate was set to *850 kbps* because with higher data bitrate (6.81 Mbps) calibrations of anchors and tag were not successful;
3. Pulse Repetition Frequency (PRF) – is the number of pulses of a repeating signal in a specific time unit. Higher frequency means shorter wavelengths which helps to reduce interference. During the measurements PRF was set to *64 MHz* rate;
4. Preamble length – required to receive and decode the UWB packets. A longer preamble length gives better reception (better range) at the expense of longer packets. Shorter preamble lengths may slightly reduce the accuracy. To avoid reducing the accuracy during the measurements preamble length was set to maximum *2048 symbols*;
5. Tx gain – transmit antenna gain in dB (decibel). In other words describes how well the antenna converts input power into radio waves headed in a specified direction. This value depends on the channel set. Since the channel was set to *channel 2*, dB rate during the measurements was set to *15.5 dB.*

2.7.3 Push to cloud

1. Data rate – all tag data is pushed to the Pozyx cloud for visualization. Data update rate during the measurements was set to *5 Hz*. This means that the data will be uploaded 5 times per 1 second.

2.7.4 Connectivity

To use Pozyx data in project there was an Application Programming Interface (API) *Key* generated which is used to securely connect to the MQTT broker to receive position data. All the MQTT client settings to connect and receive data were provided by Pozyx in python code. All the MQTT data was sent as a JavaScript Object Notation (JSON) array. Python code can be found in APPENDIX 2.

3 Results

This chapter presents results from the gathered and processed data. All the data is used as raw data from Pozyx equipment then compared with results obtained with total station. Results are divided into two parts:

1. Differences of coordinates (N-coord. E-coord., Height) between Pozyx equipment and Leica Viva TS16 total station;
2. Differences of distances between Pozyx equipment ant Leica Viva TS16 total station.

In first case, raw data from Pozyx equipment was obtained in JSON file format using MQTT protocol. To be able to represent data obtained, JSON to CSV online converter was used.


```
[{"version": "1","tagId": "26437","timestamp": "1557656115","success": "TRUE","data":
{"coordinates": {"x": "6740476569","y": "591466633","z": "184430"},
"metrics": {"latency": "137","rates": {"success": "7.059999943","update": "7.059999943"}}}}
```


Figure 3. 1 Raw data *in JSON format.*

version	tagId	timestamp	success	data__coordinates__x	data__coordinates__y	data__coordinates__z	data__metrics__latency	data__metrics__rates__success	data__metrics__rates__update
1	26437	1557656115	TRUE	6740476569	591466633	184430	137	7.059999943	7.059999943

Figure 3. 2 Converted JSON data to XLSX.

Fig. 3.1 shows raw data in JSON file format and fig. 3.2 shows corrected data in table:

1. *tagId* is an identification number of tag;
2. *Timestamp* needs to be formatted and means the time data was obtained in second accuracy;
3. *Success TRUE* means positioning algorithm was successful and coordinates were obtained. If Pozyx operation was misbehaved due to various reasons *Error 0x05* will appear;
4. *Data_coordinates_x*, *data_coordinates_y* and *data_coordinates_z* means coordinates in X, Y and Z in millimetre accuracy;
5. *Latency* shows time spent of package for signal to travel from tag to anchor and back;
6. *Data_metrics_rates_success*;
7. *Data_metrics_rates_update*.

3.1 Differences of coordinates between Pozyx system and Leica Viva TS16 total station

3.1.1 Method 1 results

The test objective is to show the accuracy of system with 4 anchors in each room. 4 same anchors are moved from room to room.

Table 3. 1 Comparison between coordinates with 4 anchors.

Point ID	Method	N-coord., (mm)	E-coord., mm	Height, mm	Convex area (m^2)
LOS					
P2	Traverse	6740495113	591469836	183268	223.061
	UWB	6740495171	591469716	182838	
	Difference in mm	-58	120	430	
P3	Traverse	6740491359	591477712	183264	70.322
	UWB	6740491260	591477752	183216	
	Difference in mm	99	-40	48	
P4	Traverse	6740480093	591470411	183266	83.280
	UWB	6740480126	591470460	183007	
	Difference in mm	-33	49	259	
P5	Traverse	6740483428	591461356	183268	223.061
	UWB	6740483659	591461371	183176	
	Difference in mm	-231	-15	92	
P7	Traverse	6740472806	591462783	183257	57.014
	UWB	6740472871	591462725	183518	
	Difference in ,,	-65	58	-261	
w19	Traverse	6740489255	591465423	183276	223.061
	UWB	6740489532	591465438	182491	
	Difference in mm	277	-15	785	
K1	Traverse	6740477647	591462909	183259	57.014
	UWB	6740477487	591462882	183341	
	Difference in mm	160	27	-82	
K2	Traverse	6740469484	591466007	183269	32.587
	UWB	6740469577	591465789	183175	
	Difference in mm	-93	218	94	
P8	Traverse	6740470324	591470831	183257	32.587
	UWB	6740470216	591471028	183312	
	Difference in mm	108	197	55	

Table 3.1 shows the differences in LOS of N-coord., E-coord. and height measured with Leica Viva TS16 total station with traverse method and Pozyx UWB system with 4 anchors mounted on the walls.

3.1.2 Method 2 results

The test objective is to show if the accuracy is getting closer to true coordinate by increasing the amount of anchors from 4 to 6 in garage (room: 01 013).

Table 3. 2 Comparison between coordinates with 6 anchors.

Point ID	Method	N-coord.	E-coord.	Height	Convex area (m^2)
LOS					
P2	Traverse	6740495113	591469836	183268	
	UWB	6740495110	591469755	183501	
	Difference in mm with 6 anchors	3	81	-233	
	Difference in mm with 4 anchors	-58	120	430	
P5	Traverse	6740483428	591461356	183268	
	UWB	6740483450	591461512	183370	303.774
	Difference in mm with 6 anchors	-22	-156	102	
	Difference in mm with 4 anchors	-231	-15	92	
W19	Traverse	6740489255	591465423	183276	
	UWB	6740489379	591465387	183535	
	Difference in mm with 6 anchors	-124	36	259	
	Difference in mm with 4 anchors	277	-15	785	

Table 3.2 shows the differences of true coordinates (N-coord., E-coord. and height) measured with Leica Viva TS16 total station and the coordinates measured with Pozyx UWB system in LOS with 6 anchors and 4 anchors from method 1.

3.1.3 Method 3 results

The test objective is to measure known points and see if anchors from other room helps to improve the accuracy of system even if anchors are in NLOS. 7 anchors are mounted in garage (room: 01 013) and 4 anchors in 3D-print laboratory (room: 01 012). 11 anchors in total.

Table 3. 3 Comparison between coordinates in 2 rooms. Combination of LOS and NLOS.

Point ID	Method	N-coord.	E-coord.	Height	Convex area (m^2)
LOS of 4 anchors in 01 012 room. NLOS of 7 anchors in 01 013 room					514.027
P3	Traverse	6740491359	591477712	183264	
	UWB	6740491335	591477631	183455	
	Difference in mm	24	81	-191	
LOS of 7 anchors in 01 013 room. NLOS of 4 anchors in 01 012 room					
P2	Traverse	6740495113	591469836	183268	
	UWB	6740495075	591470033.4	183435	
	Difference in mm	38	-197	167	
P5	Traverse	6740483428	591461356	183268	
	UWB	6740483391	591461409	183510	
	Difference in mm	37	-53	-242	
w19	Traverse	6740489255	591465423	183276	
	UWB	6740489473	591465332	183438	
	Difference in mm	-218	91	-162	

Table 3.3 shows the differences of true coordinates (N-coord., E-coord. and height) measured with Leica Viva TS16 total station and the coordinates measured with Pozyx UWB system in combination of LOS and NLOS.

3.1.4 Method 4 results

The test objective is to measure known points and see if 3 more anchors helps to improve the accuracy of system even if anchors are in NLOS. 6 anchors are mounted in garage (room: 01 013), 4 anchors in 3D-print laboratory (room: 01 012) and 4 anchors in 3D-print laboratory (room: 01 011). 14 anchors in total.

Table 3. 4 Comparison between coordinates in 3 rooms. Combination of LOS and NLOS.

Point ID	Method	N-coord.	E-coord.	Height	Convex area (m²)
LOS of 4 anchors in 01 011 room. NLOS of 6 anchors in 01 013 room and 4 anchors in 01 012 room.					532.987
P4	Traverse	6740480093	591470411	183266	
	UWB	6740475259	591465151	181968	
	Difference in mm	4834	5260	1298	
LOS of 4 anchors in 01 012 room. NLOS of 6 anchors in 01 013 room and 4 anchors in 01 011 room.					
P3	Traverse	6740491359	591477712	183264	
	UWB	6740491342	591477692	183485	
	Difference in mm	17	20	-221	
LOS of 6 anchors in 01 013 room. NLOS of 4 anchors in 01 012 room and 4 anchors in 01 011 room.					
P2	Traverse	6740495113	591469836	183268	
	UWB	6740495182	591469803	183509	
	Difference in mm	69	-33	241	
P5	Traverse	6740483428	591461356	183268	
	UWB	6740483539	591461336	18559	
	Difference in mm	-111	20	291	
W19	Traverse	6740489255	591465423	183276	
	UWB	6740489270	591465580	183452	
	Difference in mm	-15	-157	176	

Table 3.4 shows the differences of true coordinates (N-coord., E-coord. and height) measured with Leica Viva TS16 total station and the coordinates measured with Pozyx UWB system in combination of LOS and NLOS.

3.1.5 Method 5 results

The test objective is to test Pozyx system accuracy when anchor and tag does not have LOS. 4 anchors are mounted in 3D-print laboratory (room: 01 012), 4 anchors in geolab (room: 01 009) and 4 anchors in geomatics equipment (room: 01 008).

Table 3. 5 Comparison between coordinates in NLOS.

Point ID	Method	N-coord.	E-coord.	Height	Convex area (m^2)
NLOS of 12 anchors					195.440
W20	Traverse	6740476306	591469339	185411	
	UWB	6740475008	591470307	185380	
	Difference in mm	1298	-968	31	
W22	Traverse	6740482214	591464018	185384	
	UWB	6740482282	591463987	185835	
	Difference in mm	-68	31	-451	
W23	Traverse	6740476385	591466704	183482	
	UWB	6740476543	591466691	184398	
	Difference in mm	-158	13	-916	
W21	Traverse	6740469895	591472374	183471	
	UWB	6740469692	591473445	184767	
	Difference in mm	203	-1071	-1296	
P6	Traverse	6740475163	591469145	183275	
	UWB	6740475591	591469300	182987	
	Difference in mm	-428	-155	288	

Table 3.5 shows the differences of true coordinates (N-coord., E-coord. and height) measured with Leica Viva TS16 total station and the coordinates measured with Pozyx UWB system in NLOS.

3.2 Differences of distances between Pozyx system and Leica Viva TS16 total station

3.2.1 Results of distances in LOS situation

The test objective is to test the accuracy of Pozyx UWB system distance estimation comparing to Leica Viva TS16 total station. 4 anchors in 3D-print laboratory (room: 01 012), 3D-print laboratory (room: 01 011), 4 anchors in geolab (room: 01 009) and 4 anchors in geomatics equipment (room: 01 008). 7 anchors in garage (room: 01 013).

Table 3. 6 Distances accuracy comparison in LOS.

Distance ID	Measured distance (mm)	True range (mm)	Difference (mm)
LOS			
K1-W24	5527	5238	289
K1-W25	3630	3782	-152
K1-W26	7187	6979	208
K1-W27	8189	8380	-191
K2-W28.1	2875	2765	110
K2-W29	5091	5083	7
K2-W30	6654	6207	447
K2-W31.1	4568	4479	90
P2-D1	21719	21066	652
P2-D2	21925	21875	50
P2-D4	12802	12982	-180
P2-D6	9380	9289	91
P2-D7	5861	5753	108
P2-W5	13466	13544	-79
P2-W18	7259	7282	-23
P3-W10	3689	3736	-47
P3-W7	7332	7071	261
P3-W8	8434	8364	70
P3-W9	7267	7121	146
P4-W11	10231	10056	175
P4-W12	8849	8930	-80
P4-W13	4141	3810	330
P4-W14	6941	6917	24
P5-D1	9558	9131	427

Table 3.6 Distance accuracy comparison in LOS table, continued.

Distance ID	Measured distance (mm)	True range (mm)	Difference (mm)
LOS			
P5-D2	7991	7746	245
P5-D4	26917	27082	-165
P5-D6	7533	7686	-154
P5-D6	7523	7686	-163
P5-W18	15403	15028	375
P5-W5	10454	10352	102
P7-W24	6568	6453	115
P7-W25	8641	8196	445
P7-W26	6229	6006	223
P7-W27	3575	4040	-465
P8-W28.1	7013	7034	-21
P8-W29	3660	3890	-231
P8-W30	1358	1518	-160
P8-W31.1	6249	6162	87
W19-D1	14602	14378	224
W19-D2	14742	14622	120
W19-D4	20224	20065	159
W19-D6	4641	4624	17
W19-D7	9141	9033	109
W19-W18	9357	9319	39
W19-W5	9485	9499	-13

Table 3.6 shows the differences of true distances and the distances that were measured with Pozyx UWB system in LOS. True distances are measured with Leica Viva TS16 total station.

3.2.2 Results of distances in NLOS situation

The test objective is to test how obstacles affects Pozyx system accuracy when anchor and tag does not have LOS. 4 anchors in 3D-print laboratory (room: 01 011), 4 anchors in geolab (room: 01 009) and 4 anchors in geomatics equipment (room: 01 008).

Table 3. 7 Distance accuracy comparison in NLOS.

Distance ID	Measured distance (mm)	True range (mm)	Difference (mm)
NLOS			
W21-W11	18628	19739	-1111
W21-W12	14383	15568	-1185
W21-W14	15177	14946	230
W21-W13	7811	7540	270
W21-W31.1	7579	6560	1019
W21-W29	4589	4992	-402
W21-W28.1	8458	8202	256
W21-W25	15809	14789	1020
W21-W24	17991	16140	1850
W21-W27	9173	8459	713
W21-W26	6209	5331	878
W23-W11	15873	14834	1039
W23-W12	15199	13789	1410
W23-W14	7311	6559	751
W23-W13	2660	2356	304
W23-W31.1	12809	10656	2153
W23-W30	9638	8646	992
W23-W29	3637	3640	-2
W23-W28.1	8252	7507	744
W23-W25	6754	6183	571
W23-W24	9173	8918	255
W23-W27	7572	7313	258
W23-W26	4190	3297	893
W20-W11	14968	14973	-5
W20-W12	12324	12154	170
W20-W14	9751	9597	153
W20-W13	2563	2104	458
W20-W31.1	9657	9696	-38
W20-W30	6003	5588	415
W20-W29.1	2694	2025	669
W20-W28.1	8357	8317	39
W20-W25	9771	9855	-83
W20-W24	12591	12631	-40
W20-W27	8131	8316	-184
W20-W26	2710	1985	724
W22-W11	12184	11968	216
W22-W12	14005	14046	-40
W22-W14	655	454	201
W22-W13	7581	7489	91
W22-W31.1	18813	16791	2022

Table 3.7 Distance accuracy comparison in NLOS table, continued.

Distance ID	Measured distance (mm)	True range (mm)	Difference (mm)
LOS			
W22-W30	15062	14941	120
W22-W29	11406	10002	1404
W22-W28.1	9460	12905	-3445
W22-W25	3033	2305	727
W22-W24	8418	8230	187
W22-W27	12445	12592	-146
W22-W26	10078	9661	417

Table 3.7 shows the differences of true distances and the distances that were measured with Pozyx UWB system in NLOS. In order to estimate the distance, UWB signal had to penetrate the concrete walls together with reinforcement inside the wall.

3.3 Summary

From the results obtained in the tests, it can be said that Pozyx system accuracy meet the factory accuracy standard, which is 10 – 30 cm in 3D positioning. Method 2 greatly shows the difference in 3D when measuring with 4 and 6 anchors, especially in height. While measuring with other methods coordinates were constant and most of them did not exceed 30 cm. Distance estimation clearly showed the impact of measuring in NLOS.

4 Discussion

This chapter discusses the results and the retrieved information from different researches. Two different methods were used in this project: differences of coordinates and differences of distances between Pozyx UWB system and Leica Viva TS16 total station.

4.1 Differences between coordinates

4.1.1 Method 1

The first method and its goal was to see if 4 anchors does not exceed factory standard accuracy in N-coord., E-coord. and height. Table 3.1 shows that N-coord. and E-coord. differences in LOS are quite similar. N-coord. difference varies between -93 mm to 277 mm., E-coord. varies from -40 mm to 218 mm. and height from -261 mm to 785 mm. 4 out of 9 N-coord. and 3 out of 9 E-coord. differences does not exceed the accuracy that is provided by Pozyx Company, which is 10 cm for 2D (ideal conditions, when there are no obstacles) and 10 – 30 cm for 3D with 4 anchors in LOS. 2 out of 9 points got the difference more than 30 cm in height. Important to mention, that P3, P8 and K2 points were measured in the rooms, where a lot of metal holders for the equipment is standing. Metal is the most common conductor which absorb most of the radio waves. However, Pozyx system did well in this kind of environment. The most common problem is that with 4 anchors to reach 10 cm accuracy in height is hard. To measure accurate (10 cm) in height, 6 anchors in area must be placed in order to make multilateration process successful.

This test showed that 4 anchors are only enough for accurate (10 cm) 2D positioning, even though, in 5 out of 9 points system did well in 3D with 4 anchors and did not exceed 10 - 30 cm.

4.1.2 Method 2

The second method and its goal was to see if 6 anchors improve results compared to 4 anchors in LOS. According to Pozyx, 6 anchors should improve 3D positioning, especially in height.

Table 3.2 shows that the accuracy got improved in 3D positioning except in P5 point, where E-coord. raised up by 14 cm comparing to 4 anchors measurements. Still, it does not go further factory standard accuracy (10 – 30 cm in 3D). Worth mentioning, that height got increased, because more anchors increased the range and robustness of the system in case of obstruction.

4.1.3 Method 3 and 4

The third, fourth methods and their goal was to increase convex area and check the efficiency of LOS and NLOS combination. Results in Table 3.3 and Table 3.4 shows that increasing the anchors number and having more than 6 anchors does not impact the results. Results were between 10 -30 cm in accuracy. The only problem during the measurements was at P4 point. Fig. 4.1 shows, when 14 anchors were mounted on the walls, Pozyx master tag could not find 2 anchors (marked in green). In other words, Pozyx master tag could not range with two anchors mounted in 3D-print laboratory (room: 01 011). This approach, with a single master tag, does not scale well to large areas, as all other tags and anchors must be within radio range of the master tag, in order to achieve scalable TWR [23]. Instantly, 2 anchors missing has led big differences of coordinates in meters, since the P4 point was out of convex area.

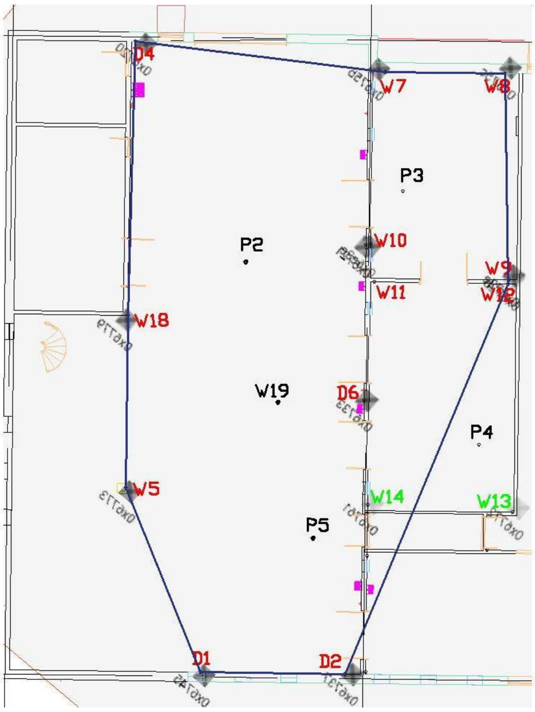


Figure 4. 1 Convex area during the measurements.

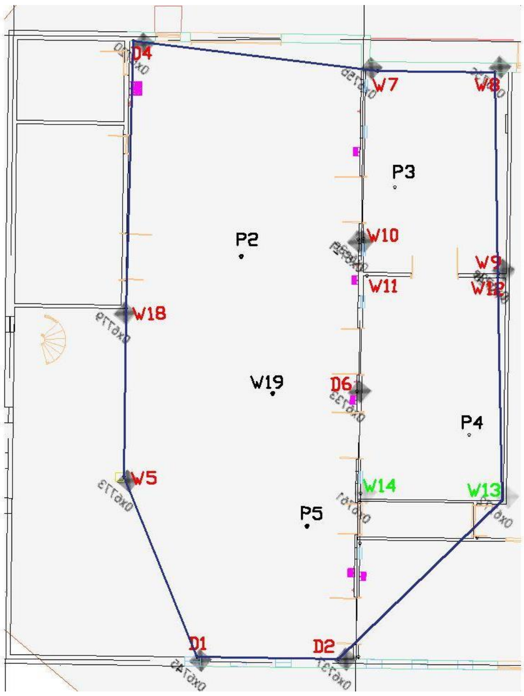


Figure 4. 2 How convex area should be covered.

Fig. 4.1 shows convex area when the measurements were ongoing. P4 point is out of convex area, what makes coordinates incredibly different. The difference between coordinates is 1 m and above. Fig. 4.2 shows how convex area should look with all 14 anchors.

4.1.4 Method 5

The last method of measuring coordinates goal was to see the Pozyx performance in NLOS situation and ability to penetrate concrete walls, which thickness is 20 cm. In table 3.5 you can see that the test results as expected are the worst. Every point has at least one coordinate out of three which exceeds the factory standard accuracy over 70 cm. Overall, accuracy drifts from a few cm to 1.3 m. These drifts of coordinates was expected before the measurements, because walls width is 20 cm and consist of different materials. Walls include other things that are hidden inside it like reinforcement and electricity cables. All these drifts of coordinates can be explained in one sentence - radio wave signal has to spend extra time trying to get through the materials and this result in inaccurate TOF measurement. Also, to estimate location Pozyx system uses the data only from LOS signal. Since, in this test there is no LOS signal, all the data received is a reflection.

4.2 Distance accuracy evaluation

The main goal of method 1 was to compare distances measured in LOS, while method 2 relies on comparing distances in NLOS. Table 3.6 shows that in LOS results varies from 7 to 652 mm. Table 3.7 shows that almost all of the results in NLOS are not accurate at all, compared to the ones obtained with total station and exceeds true distance from -3445 to 2153 mm. As the results show, the accuracy does not depend how far anchor is away from a tag. The range of the system depends on LOS, NLOS conditions and RSS availability on the channel. By default in the channel, RSS values can vary between -79 and -103 dBm.

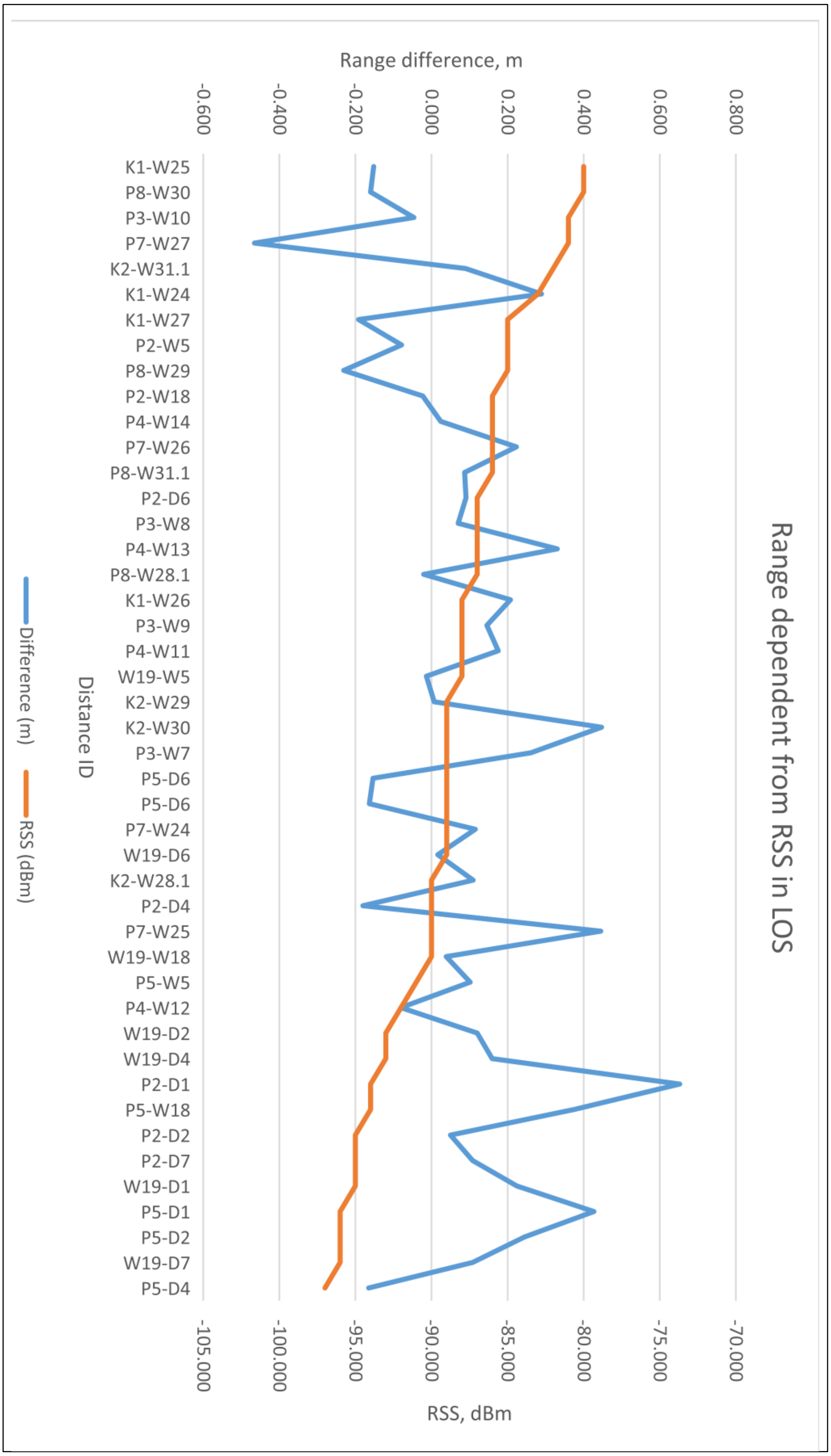


Figure 4. 3 Diagram of range dependent from RSS in LOS.

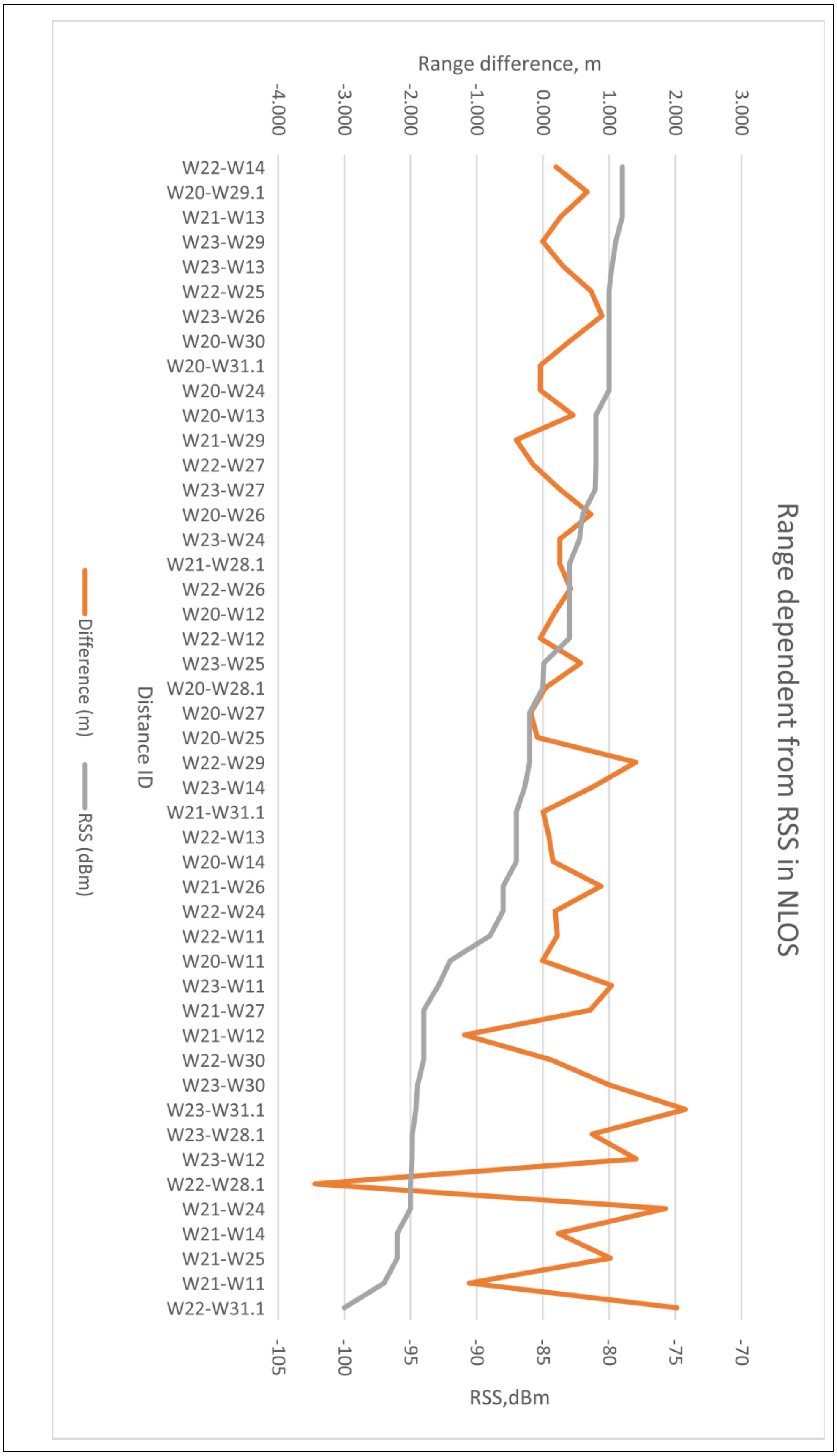


Figure 4. 4 Diagram of range dependent from RSS in NLOS.

The range dependent from RSS in LOS (Fig. 4.3) shows that in LOS situation the range accuracy does not depend from RSS. The distances calculation in LOS relies on sending radio waves from one module to another and measuring TOF. Then dividing TOF by speed of light.

NLOS situation is a bit different. It has a direct relationship with the strength of the signal. Fig 4.4 shows that, whenever RSS is weaker and is below -90 dBm differences of distances are getting higher comparing to true distance.

What is more, distances drift a lot while measuring. Drift in LOS is shown in Fig. 4.5 and drift in NLOS is shown in Fig. 4.6.

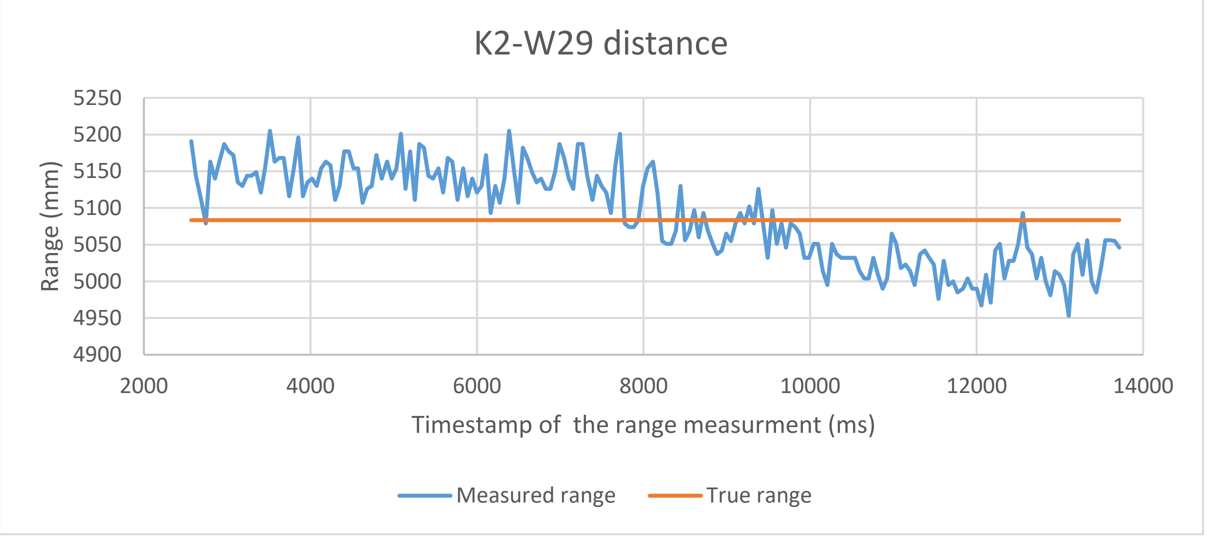


Figure 4 5 Diagram of K2-W29 distance showing range drift during time in LOS.

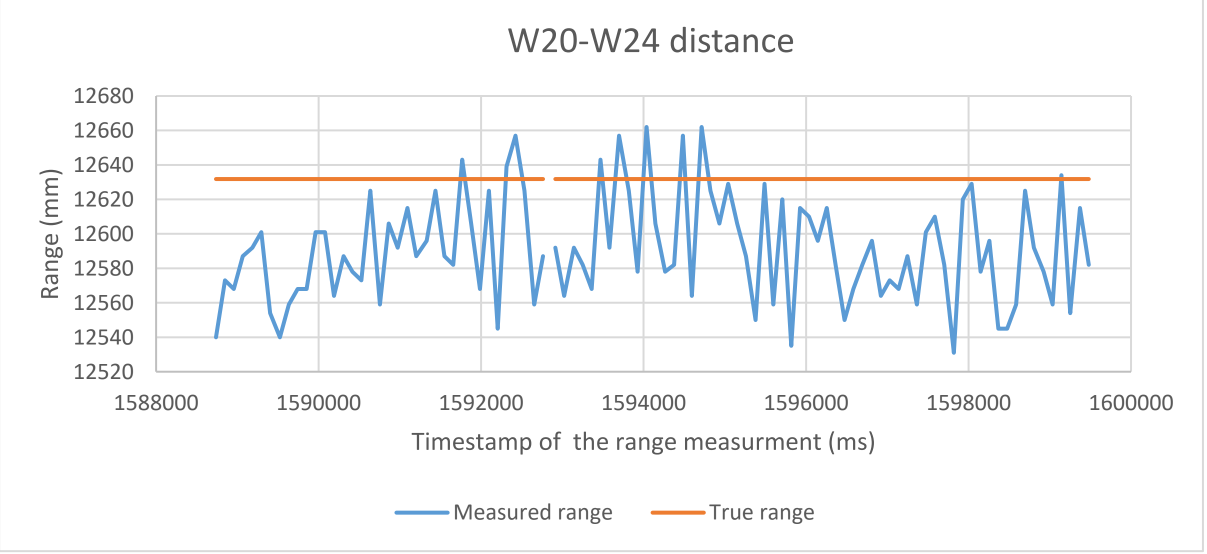


Figure 4 6 Diagram of W20-W24 distance showing range drift during time in NLOS.

These drifts appears because for positioning with Pozyx system throughout the project only one algorithm was used - *UWB only*. *UWB only* treats radio waves and TOF data as new without taking into account previous data. Since, distance is shifting all the time, there might be an impact to the result, because average of distances was taken. All distances drifts can be found in APPENDIX 3.

5 Conclusions and Recommendations

In this final chapter we will discuss how this thesis managed to answer the problem stated. Also, we will summarize the measurements, discuss limitations of the system and future work.

The thesis analyses and compares coordinates obtained using indoor positioning system – Pozyx, which is based on TWR measurements. The equipment used in this project is provided by Pozyx and Leica. The investigation focuses on comparing coordinates and range measured between Leica Viva TS16 total station and Pozyx UWB system. The testing environment provide situations with LOS, NLOS and combination of both. Experiments start with measuring coordinates and distances with 4 anchors in LOS, followed by increasing the number of anchors and expansion of area. The experiment ended up by measuring coordinates and distances in NLOS. The results are used to analyse, compare and evaluate the Pozyx UWB system.

5.1 Conclusion

The problem of this thesis is to evaluate precision of Ultra-wideband technology comparing to total station measurements in harsh environment. 10 cm accuracy is considered by Pozyx as best accuracy for 2D positioning. 10 – 30 cm is considered by Pozyx as best accuracy for 3D positioning. To investigate the accuracy and evaluate it 7 experimental measurements were made:

Pozyx system accuracy in general:

Pozyx UWB system accuracy in LOS at the most of the points is in accuracy of 1 – 30 cm. However, impact for accuracy is huge and reaches the accuracy of 1 m or more at all of the points, when anchors and tag has NLOS.

1. **Measurements with 4 anchors with LOS in each room reaches the following accuracy:**
    - N-coord. varies between 3,3 cm and 27,7 cm. 5 points out of 9 coordinates are in accuracy of 10 cm. 4 out of 9 coordinates are in accuracy of 10 – 30 cm;

- E-coord. varies between 1,5 cm and 21,8 cm. 6 points out of 9 coordinates are in accuracy of 10 cm. 3 out of 9 coordinates are in accuracy of 10 – 30 cm;
- Height varies between 4,8 cm and 78,5 cm. 5 points out of 9 heights are in accuracy of 10 cm. 2 out of 9 heights are in accuracy of 10 – 30 cm. 2 out of 9 heights are higher than 30 cm.

Concluding experiment 1, 7 point out of 9 coordinates are in accuracy of 10 – 30 cm.

2. **6 anchors improvement in height comparing to 4 anchors in LOS:**
    - N-coord varies between 0,3 cm and 12,4 cm. 2 points out of 3 coordinates are in accuracy of 10 cm. 1 out of 3 coordinate is in accuracy of 10 -30 cm;
    - E-coord. varies between 3,6 cm to 15,6 cm. 2 points out of 3 coordinates are in accuracy of 10 cm. 1 out of 3 coordinate is in accuracy of 10 – 30 cm;
    - Height varies between 10,2 cm to 25,9 cm. 3 points out of 3 coordinates are in accuracy of 10 – 30 cm.

Height, comparing to 4 anchors got improved by:

- At point P2 height got improved from 43,0 cm to 23,3 cm;
- At point P5 height remained almost the same. With 4 anchors 9,2 cm and with 6 anchors 10,2 cm;
- At point W19 height got improved from 78,5 cm to 25,9 cm.

Pozyx statement that 4 anchors is for 2D positioning and 6 anchors is for 3D positioning is reasonable and approved. In measurements with 4 anchors, 2 points out of 3 coordinates were not in accuracy of 10 – 30 cm. 3 points out of 3 coordinates are in accuracy of 10 – 30 cm after experiment 2.

3. **Coordinates accuracy in LOS and NLOS combination:**
    - N- coord. varies between 2,4 cm and 21,8 cm. 3 points out of 4 coordinates are in accuracy of 10 cm. 1 point out of 4 coordinate is in accuracy of 10 – 30 cm;
    - E-coord. varies between from 5,3 cm to 19,7 cm. 3 out of 4 coordinates are in accuracy of 10 cm. 1 point out of 4 coordinate is in accuracy of 10 – 30 cm;
    - Height varies between from 16,2 cm to 24,2 cm. 4 points out of 4 coordinates are in accuracy of 10 -30 cm.

Accuracy neither got improved, neither reduced. 4 out of 4 coordinates are in accuracy of 10 - 30 cm.

4. **Coordinates accuracy in LOS and NLOS combination with increased convex area:**
    - N-coord. varies between 1,5 cm to 11,1 cm. 3 points out of 4 coordinates are in accuracy of 10 cm. 1 out of 4 coordinate is in accuracy of 10 – 30 cm;
    - E-coord. varies between 2,0 cm to 15,7 cm. 3 points out of 4 coordinates are in accuracy of 10 cm. 1 out of 4 coordinate is in accuracy of 10 – 30;
    - Height varies between 17,6 cm to 29,1 cm. 4 points out of 4 coordinates are in accuracy of 10 – 30 cm.

P4 point coordinates are not acceptable. Difference in coordinates are: N-coord. 483,4 cm, E-coord. 526,0 cm and height 129,8 cm. This difference can be expected whenever the point is out of convex area.

5. **Coordinates accuracy in NLOS situation:**
    - N-coord. varies between 6,8 cm to 129,8 cm. 1 point out of 5 coordinates is in accuracy of 10 cm. 2 out of 5 coordinates are in accuracy of 10 – 30 cm. 2 out of 5 coordinates are over 30 cm in accuracy;
    - E-coord. varies between 1,3 cm to 107,1 cm. 2 points out of 5 coordinates are in accuracy of 10 cm. 1 out of 5 coordinates is in accuracy of 10 – 30 cm. 2 out of 5 points are in accuracy over 30 cm.
    - Height varies between 3,1 cm to 129,6 cm. 1 point out of 5 coordinates is in accuracy of 10 cm. 1 out of 5 coordinates is in accuracy of 10 – 30 cm. 3 out of 5 coordinates are in accuracy over 30 cm.

These results show, that obstacles with conductors have a huge impact in coordinates.

6. **Distance accuracy in LOS and NLOS situation:**

Distances measured varies between 0,7 cm to 65,2 cm in LOS and from 0,3 cm to 344,5 cm in NLOS. The experiments show that LOS and NLOS produce completely different results. Test have shown that RSS which comes from an anchor does not affect the accuracy of distance estimation in LOS. However, situation in NLOS is different. In the experiment it has been seen, how conductors (metals, concrete walls) seriously affect distances obtained, both in the RSS and in the accuracy when measuring distance between anchor and tag.

Overall, Pozyx system TWR protocol estimates 3D positioning in most of experiments in 10 – 30 cm accuracy and meet factory standards. Since, Pozyx system accuracy is mostly affected by the environment it is necessary to be LOS between anchors and tag. This will reduce the errors gained from radio transparency and direct path resulting the equipment showing more accurate result.

5.2 Future work

This thesis only focuses on evaluating 3D positioning accuracy of Pozyx UWB system in harsh environment. However, Pozyx system has a wide variety of sensors and functions available, which can be subjects for further studies. For example:

- Test out different positioning algorithms using Arduino or Raspberry Pi shield. There are two more algorithms without UWB only: Least squares and maximum likelihood estimation;
- To improve accuracy combine Pozyx UWB technology with other indoor positioning techniques;
- Test Pozyx system auto calibration, when system itself creates local coordinate system and evaluate accuracy;
- Use tag together with Arduino or Raspberry Pi shield and make an autonomous robot which can bring stuff from point A to point B;
- Test other Pozyx sensors (orientation, acceleration, angular velocity, magnetic field, quaternion, linear acceleration, gravity, pressure, max linear acceleration) data and evaluate it.
- Track people to evaluate traffic;
- UWB localization in a multi-robot system;
- Create a mobile app to connect mobile phone embedded with Pozyx tag to allow user to find a certain object or a thing inside the building.

Reference

[1] Mautz, R. (2012). "Indoor Positioning Technologies" PhD thesis, ETH Zurich, Department of Civil, Environmental and Geomatic Engineering, Institute of Geodesy and Photogrammetry.

[2] "Indoor Positioning, Tracking and Indoor Navigation with Beacons". Available at: https://www.infsoft.com/technology/sensors/bluetooth-low-energy-beacons. Accessed: 2019-02-13.

[3] "How to Choose the Right Indoor Positioning System". Available at: https://www.eliko.ee/choose-right-indoor-positioning-system/. Accessed: 2019-02-13.

[4] Wilson S., Michael A.O., Nhlanhla B.W. M., (2017). "A state-of-the-art survey of indoor positioning and navigation systems and technologies"

[5] Suyash G. (2018). " Wi-Fi- based Indoor Positioning System Using Smartphones". Available at: https://www.talentica.com/assets/white-papers/wifi-indoor-positioning-using-smartphones.pdf. Accessed: 2019-02-13.

[6] Farid Z., Nordin R., and Ismail M., (2013). "Review Article Recent Advances in Wireless Indoor Localization Techniques and System".

[7] Shah D., Shah K. (2012). "Wi-Fi Based Positioning System".

[8] Kula G., Ozyerb T., Tavlib B. (2014). "9th International Conference on Future Networks and Communications (FNC-2014) IEEE 802.11 WLAN Based Real Time Indoor Positioning: Literature Survey and Experimental Investigations".

[9] Ray B. (2018). "How An Indoor Positioning System Works?". Available at: https://www.airfinder.com/blog/indoor-positioning-system. Accessed: 2019-02-13.

[10] Svalastog, M. S. (2007). "Indoor positioning - technologies, services and architectures". Master's thesis, University of Oslo.

[11] Alarifi, A., Al-Salman, A., Alsaleh, M., Alnafessah, A., Al-Hadhrami, S., Al-Ammar, M. A., Al-Khalifa, H. S. (2016). "Ultra wideband indoor positioning technologies: Analysis and recent advances".

[12] "Passive RFID Tag (or Passive Tag)". Available at: http://www.technovelgy.com/ct/technology-article.asp?artnum=47. Accessed: 2019-02-11.

[13] "Active Tag (Active RFID Tag)". Available at: http://www.technovelgy.com/ct/Technology-Article.asp?ArtNum=21. Accessed: 2019-02-11.

[14] Smiley S. (2016). "Active RFID vs. Passive RFID: What's the Difference?". Available at: https://blog.atlasrfidstore.com/active-rfid-vs-passive-rfid. Accessed: 2019-02-12.

[15] Liu H., Darabi H., Banerjee P., Liu J. (2007). „Survey of wireless indoor positioning techniques and systems".

[16] Ramon F., García-Vázquez B. J. P., Galván-Tejada C. E., Muñoz-Rodriguez D., Vargas-Rosales C., Fangmeyer Jr. J. "Review Article Evolution of Indoor Positioning Technologies: A Survey". Available at: https://doi.org/10.1155/2017/2630413. Accessed: 2019-02-12.

[17] Van Loy N., Verbeeck G., Knapen E. (2018). "High accuracy indoor positioning system to monitor spatial use in dwellings".

[18] "Leica Viva TS16 Total Station". Available at: https://surveyequipment.com/leica-viva-ts16-total-station/. Accessed: 2019-03-05.

[19] O'Keefe B. (2017). "Finding Location with Time of Arrival and Time Difference of Arrival Techniques".

[20] Djaja-Josko V., Kolakowski J. (2016). "A new method for wireless synchronization and TDOA error reduction in UWB positioning system". Institute of Radioelectronics and Multimedia Technology Warsaw University of Technology Warsaw, Poland.

[21] "Location Tracking Approaches". Available at: https://www.cisco.com/c/en/us/td/docs/solutions/Enterprise/Mobility/WiFiLBS-DG/wifich2.pdf. Accessed: 2019-02-24

[22] Chauhan D. R., Shaikhji Z. M. (2015). "TIME SYNCHRONIZATION FOR TIME OF ARRIVAL BASED LOCALIZATION".

[23] "Positioning protocols explained". Available at: https://www.pozyx.io/pozyx-academy/positioning-protocols-explained. Accessed: 2019-02-24.

[24] Utter M. (2015). "Indoor Positioning using Ultra-wideband Technology".

[25] Lachmann J. (2018). “UWB: Two Localization Techniques in Comparison”. Available at: https://www.infsoft.com/blog-en/articleid/305/uwb-two-localization-techniques-in-comparison. Accessed: 2019-02-22.

[26] Ridolfi M., Van de Velde S., Steendam H., De Poorter E. (2018). “Analysis of the Scalability of UWB Indoor Localization Solutions for High User Densities”.

[27] Kim S., Ha S., SAAD A., Kim J. (2015). “Indoor Positioning System Techniques and Security”.

[28] Streich K. (2017). “Technologies for Server-Based Indoor Positioning Compared: Wi-Fi vs. BLE vs. UWB vs. RFID”. Available at: https://www.infsoft.com/blog-en/articleid/188/technologies-for-server-based-indoor-positioning-compared. Accessed: 2019-02-21.

[29] ”Liu H., Darabi H., Banerjee P., Liu J. (2007). “Survey of Wireless Indoor Positioning Techniques and Systems”.

[30] Nikodem M., Jankowski T. (2015). “Evaluation of ToF-based Indoor Localization for Inaccurate Distance Measurements”.

[31] Parv L. (2018). “Infographic: Indoor Positioning Market and Applications”. Available at: https://www.eliko.ee/infographic-indoor-positioning-applications/. Accessed: 2019-02-22.

[32] Nedergaard M. (2017). “Indoor Positioning Systems - Complete guide”. Available at: https://blog.mapspeople.com/mapsindoors/indoor-positioning-101. Accessed: 2019-02-24.

[33] Gaspar T., Oliveira P. (2011) “Single pan and tilt camera indoor positioning and tracking system”.

[34] Alarifi A., Al-Salman A., Alsaleh M., Alnafessah A., Al-Hadhrami S., Al-Ammar M. A., Al-Khalifa H. S. (2016). “Review Ultra Wideband Indoor Positioning Technologies: Analysis and Recent Advances”.

[35] Pozyx Accurate positioning. (2019) Available at: https://www.pozyx.io/ Accessed: 2019-03-01.

[36] Developer’s kit. (2019). Available at: https://www.pozyx.io/shop/product/developer-s-kit-65 . Accessed: 2019-05-07.

[37] Pozyx Companion software (2019). Available at: https://www.pozyx.io/product-info/companion-software . Accessed: 2019-05-07.

[38] Arduino Development Environment (2019). Available at: https://www.arduino.cc/en/Guide/Environment0018?fbclid=IwAR1JVfOpWbOpiFdcojEE0suBAuiu6u8ePwm-cgNtkaCFpAIARXzm6XsSHsM . Accessed: 2019-05-07.

[39] Gemini Oppmåling (2019). Available at: https://www.powel.com/globalassets/product-information/contracting/wp_gemini-oppmaling_2016.pdf . Accessed: 2019-05-07.

[40] Connect with MQTT (2019). Available at: https://www.pozyx.io/documentation/creator/connect-with-mqtt . Accessed: 2019-05-07.

[41] Ultra-Wideband and obstacles (2019). Available at: https://www.pozyx.io/pozyx-academy/uwb-and-obstacles . Accessed: 2019-05-07.

[42] Survey procedures for closed traverse (2009). Available at: http://courses.washington.edu/esrm468/esrm304/Survey%20procdures%20for%20a%20closed%20traverse.htm?fbclid=IwAR1FA0eYxYxexRZJnqZGstwnNbBTc2b1jrSJe02SO5jcbENSq7eLMh0iHU4 . Accessed: 2019-05-07.

[43] Traverse (surveying) (2019). Available at: https://www.revolvy.com/page/Traverse-%28surveying%29 . Accessed: 2019-05-07.

APPENDIX 1

All points measured with traverse method.

Gemini | Oppmåling — Punktliste

Prosjekt: C:\ProgramData\Gemini\survey\Work\GERASBEWPATAISYTASS.gmi
Koordinatsystem: EUREF89 - SONE 32 / NN 2000 høyder — 03.05.2019

PunktID	Tema	N-koord.	Ø-koord.	Høyde	Geoide H	Status
C1	-----	6 740 572,765	591 529,477	185,075	38,630	K
P13	-----	6 740 474,365	591 355,821	179,648	38,643	K
P0	-----	6 740 521,940	591 471,193	183,175	38,635	K
P1	-----	6 740 513,943	591 480,368	183,024	38,635	K
P2	-----	6 740 495,113	591 469,836	183,268	38,636	K
P3	-----	6 740 491,359	591 477,712	183,264	38,635	K
W1	-----	6 740 507,266	591 473,843	185,538	38,635	D
W2	-----	6 740 494,058	591 477,298	183,926	38,635	D
W3	-----	6 740 476,998	591 457,539	185,521	38,637	D
W4	-----	6 740 488,513	591 447,551	184,552	38,637	D
W5	-----	6 740 492,438	591 456,734	185,422	38,636	D
W6	-----	6 740 486,201	591 468,216	184,296	38,636	D
P4	-----	6 740 480,093	591 470,411	183,266	38,636	K
W7	-----	6 740 496,794	591 481,598	185,578	38,635	D
W8	-----	6 740 491,662	591 486,048	183,871	38,635	D
W9	-----	6 740 484,594	591 478,035	185,464	38,635	D
W10	-----	6 740 491,194	591 474,383	184,953	38,635	D
W11	-----	6 740 489,607	591 473,430	184,490	38,635	D
W12	-----	6 740 484,456	591 477,885	185,467	38,635	D
W13	-----	6 740 476,661	591 469,044	184,199	38,636	D
W14	-----	6 740 482,513	591 464,361	185,589	38,636	D
P5	-----	6 740 483,428	591 461,356	183,268	38,636	K
P6	-----	6 740 475,163	591 469,145	183,275	38,636	K
W15	-----	6 740 482,834	591 452,472	185,378	38,637	D
W16	-----	6 740 493,170	591 448,610	185,540	38,637	D
W17	-----	6 740 489,492	591 453,781	183,285	38,637	D
W18	-----	6 740 498,286	591 463,362	184,292	38,636	D
W19	-----	6 740 489,255	591 465,423	183,276	38,636	D
P7	-----	6 740 472,806	591 462,783	183,257	38,636	K
W20	-----	6 740 476,306	591 469,339	185,411	38,636	D
W21	-----	6 740 469,895	591 472,374	183,471	38,636	D
W22	-----	6 740 482,214	591 464,018	185,384	38,636	D
W23	-----	6 740 476,385	591 466,704	183,482	38,636	D
K1	-----	6 740 477,647	591 462,909	183,259	38,636	D
W24	-----	6 740 476,826	591 457,797	184,049	38,637	D
W25	-----	6 740 480,702	591 462,277	185,396	38,636	D
W26	-----	6 740 473,767	591 468,708	183,427	38,636	D
W27	-----	6 740 469,622	591 463,919	185,470	38,636	D
P8	-----	6 740 470,324	591 470,831	183,257	38,636	K
K2	-----	6 740 469,484	591 466,007	183,269	38,636	D
W28_1	-----	6 740 469,310	591 464,192	185,348	38,636	D
W29	-----	6 740 473,487	591 468,907	184,453	38,636	D
W30	-----	6 740 469,716	591 472,207	183,458	38,636	D
W31_1	-----	6 740 465,745	591 467,293	185,374	38,636	D
P9	-----	6 740 498,026	591 495,698	183,076	38,634	K

powel — Side 1

Known points. Heights with errors in measurements.

Gemini | Oppmåling Utjevning

Prosjekt: C:\ProgramData\Gemini\survey\Work\GERASBEWPATAISYTASS.gmi
Koordinatsystem: EUREF89 - SONE 32 / NN 2000 høyder 03.05.2019

Kjente punkt

PunktID	Tema	N-koord.	Ø-koord.	Høyde	GeoideH	Status	Delt status
P0	-----	6 740 521,940	591 471,193	183,175	38,635	K	XYZ

Beregnede punkt

PunktID	Tema	N-koord. Std. N	Ø-koord. Std. Ø	Høyde Std. H	Status a	fi b
P1	-----	6 740 513,943	591 480,368	183,024 0.000	U	
P2	-----	6 740 495,113	591 469,836	183,268 0.001	U	
P3	-----	6 740 491,359	591 477,712	183,264 0.001	U	
P4	-----	6 740 480,093	591 470,411	183,266 0.001	U	
P5	-----	6 740 483,428	591 461,356	183,268 0.001	U	
P6	-----	6 740 475,163	591 469,145	183,275 0.001	U	
P7	-----	6 740 472,806	591 462,783	183,257 0.001	U	
P8	-----	6 740 470,324	591 470,831	183,257 0.001	U	
P9	-----	6 740 498,026	591 495,698	183,076 0.000	U	

powel Side 1

Known points. N-coord. and E-coord. with errors in measurements

Gemini | Oppmåling — Utjevning

Prosjekt: C:\ProgramData\Gemini\survey\Work\GERASBEWPATAISYTASS.gmi
Koordinatsystem: EUREF89 - SONE 32 / NN 2000 høyder 03.05.2019

Kjente punkt

PunktID	Tema	N-koord.	Ø-koord.	Høyde	GeoideH	Status	Delt status
C1	-----	6 740 572,765	591 529,477	185,075	38,630	K	XYZ
P13	-----	6 740 474,365	591 355,821	179,648	38,643	K	XYZ
P0	-----	6 740 521,940	591 471,193	183,175	38,635	K	XYZ

Beregnede punkt

PunktID	Tema	N-koord. / Std. N	Ø-koord. / Std. Ø	Høyde / Std. H	Status / a	fi / b
P1	-----	6 740 513,943	591 480,368	183,025	U	155,0
		0.004	0.004		0.004	0.004
P2	-----	6 740 495,113	591 469,836	183,269	U	114,8
		0.005	0.008		0.009	0.005
P3	-----	6 740 491,359	591 477,712	183,263	U	106,0
		0.006	0.009		0.009	0.006
P4	-----	6 740 480,093	591 470,411	183,263	U	109,7
		0.006	0.011		0.011	0.006
P5	-----	6 740 483,428	591 461,356	183,269	U	138,8
		0.007	0.008		0.009	0.006
P6	-----	6 740 475,163	591 469,145	183,277	U	120,3
		0.005	0.008		0.009	0.005
P7	-----	6 740 472,806	591 462,783	183,260	U	133,4
		0.008	0.010		0.011	0.006
P8	-----	6 740 470,324	591 470,831	183,260	U	114,0
		0.006	0.010		0.010	0.006
P9	-----	6 740 498,026	591 495,698	183,080	U	39,0
		0.004	0.004		0.005	0.004

Additionally measured points after establishing traverse network

Point ID	N-coord. (m)	E-coord. (m)	Height (m)
D1	6740483.373	591452.001	183.373
D2	6740477.598	591457.003	185.926
D3	6740492.388	591456.675	183.667
D4	6740506.750	591474.818	186.150
D5	6740491.377	591474.210	183.338
D6	6740486.199	591468.224	185.325
D7	6740491.371	591474.203	183.406

APPENDIX 2

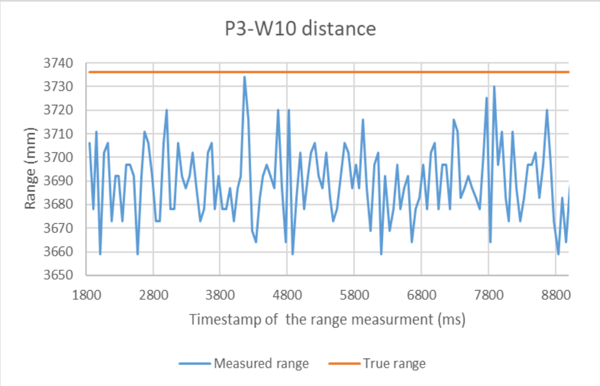
Python code to take out data from MQTT

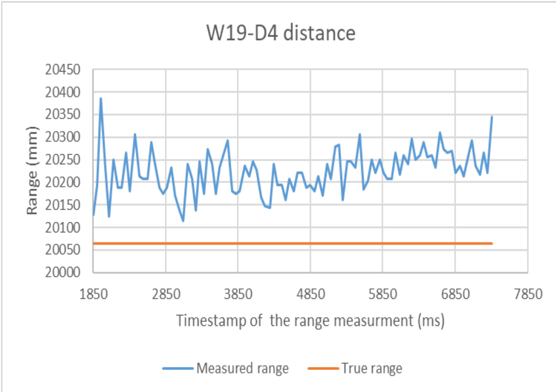
```
import paho.mqtt.client as
mqtt import ssl

host =
"mqtt.cloud.pozyxlabs.com"
port = 443
topic = "5cc81dbad708036c1c92806d"  # your mqtt topic
username = "5cc81dbad708036c1c92806d"  # your mqtt username
password = "3a338d92-4dc5-4d1f-858a-0928e83dcf65"  # your generated api key

def on_connect(client, userdata, flags, rc):
    print(mqtt.connack_string(rc))

# Callback triggered by a new Pozyx data packet
def on_message(client,
    userdata, msg): print("",
    msg.payload.decode())

def on_subscribe(client, userdata, mid,
    granted_qos): print("Subscribed to
    topic!")

client =
mqtt.Client(transport="websockets")
client.username_pw_set(username,
password=password)

# sets the secure context, enabling the WSS protocol
client.tls_set_context(context=ssl.create_default_context())

# set callbacks
client.on_connect =
on_connect
client.on_message =
on_message
client.on_subscribe =
on_subscribe
client.connect(host,
port=port)
client.subscribe(topic)

# works blocking, other, non-blocking, clients are available too.
client.loop_forever()
# -*- coding: utf-8 -*-
"""
```

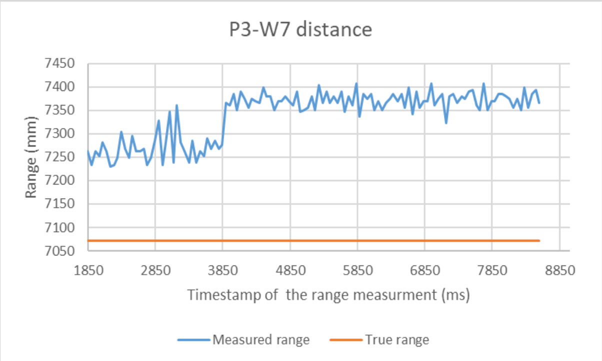
APPENDIX 3

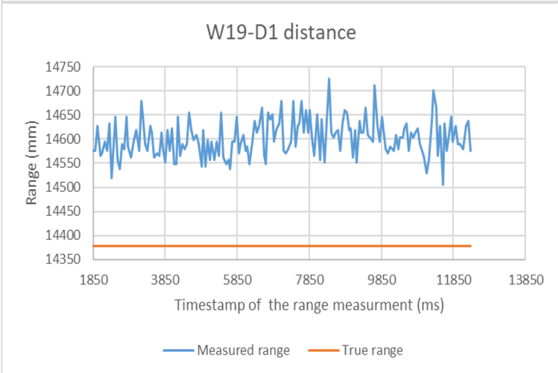
Distances drift in LOS between anchor and tag

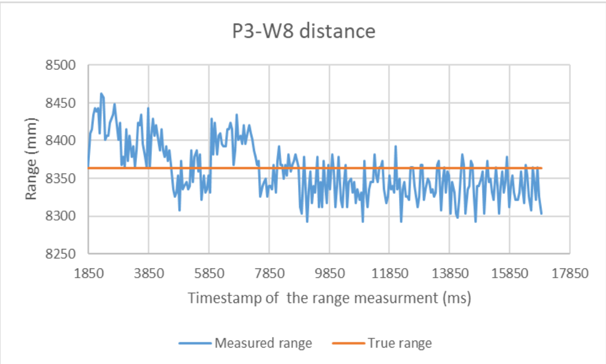
Space in the chart means that there was an error in during the measurement.

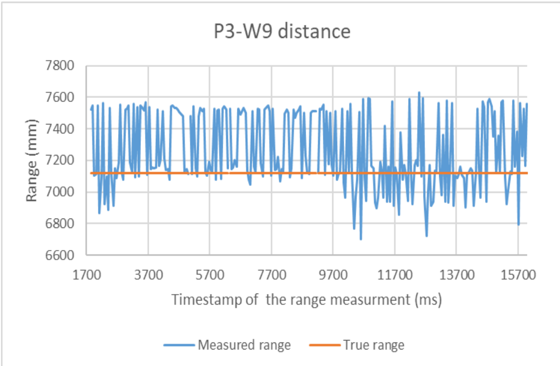


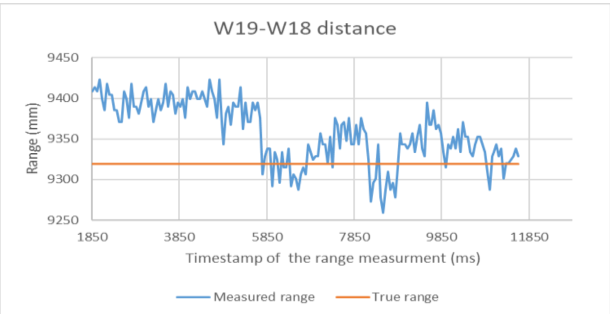


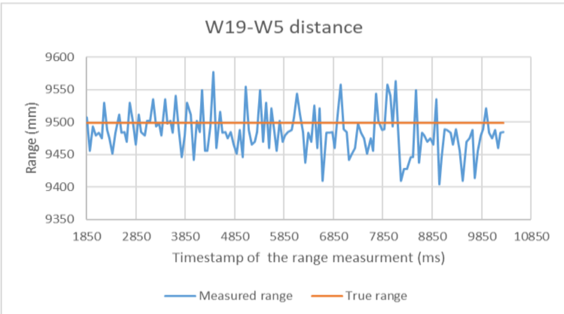


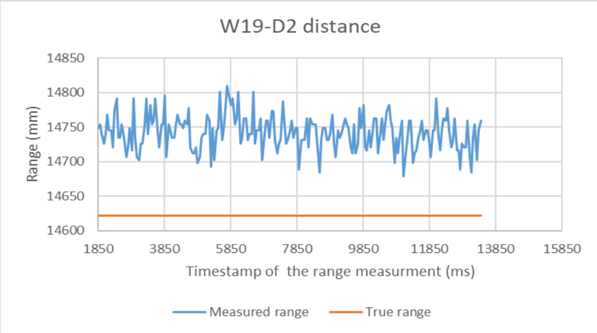


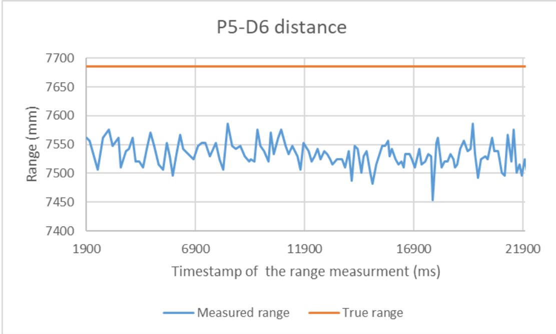


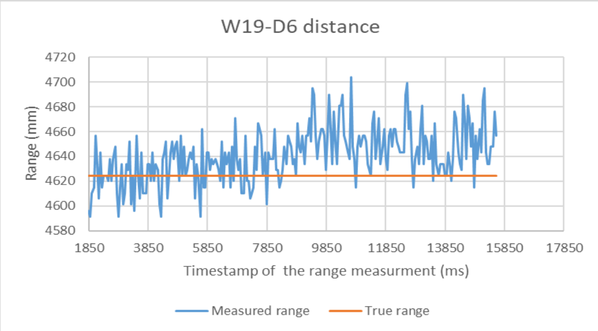


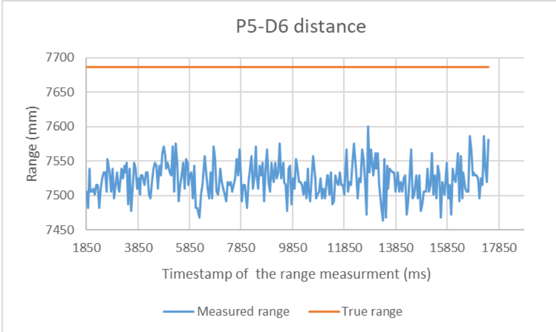


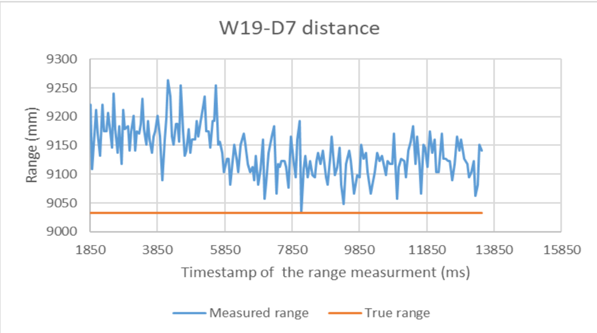


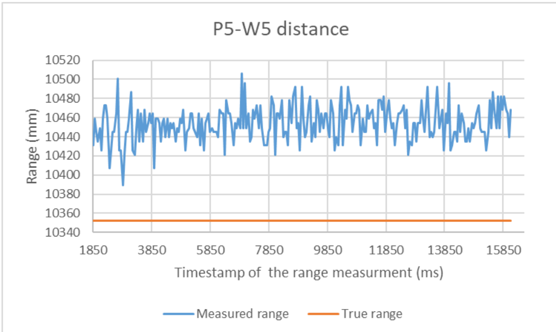

W19-D2 distance
Range (mm)
14850
14800
14750
14700
14650
14600
1850 3850 5850 7850 9850 11850 13850 15850
Timestamp of the range measurment (ms)
Measured range
True range

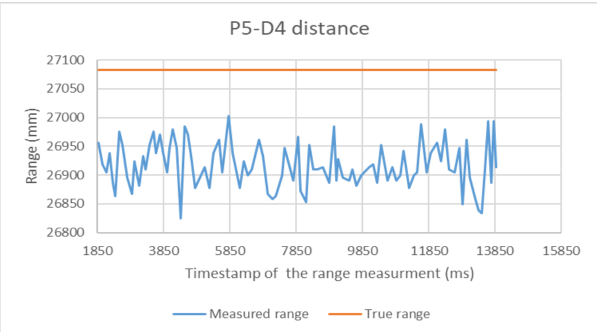

P5-D6 distance
Range (mm)
7700
7650
7600
7550
7500
7450
7400
1900 6900 11900 16900 21900
Timestamp of the range measurment (ms)
Measured range
True range

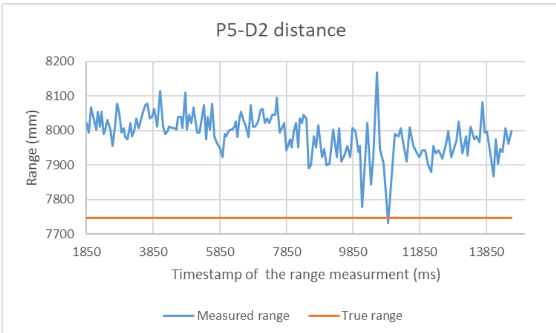

W19-D6 distance
Range (mm)
4720
4700
4680
4660
4640
4620
4600
4580
1850 3850 5850 7850 9850 11850 13850 15850 17850
Timestamp of the range measurment (ms)
Measured range
True range

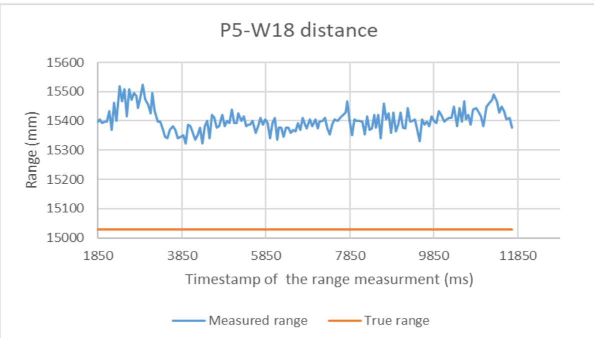

P5-D6 distance
Range (mm)
7700
7650
7600
7550
7500
7450
1850 3850 5850 7850 9850 11850 13850 15850 17850
Timestamp of the range measurment (ms)
Measured range
True range

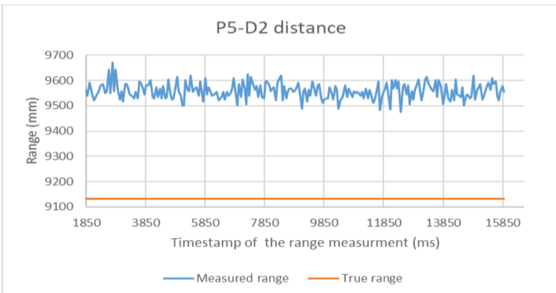

W19-D7 distance
Range (mm)
9300
9250
9200
9150
9100
9050
9000
1850 3850 5850 7850 9850 11850 13850 15850
Timestamp of the range measurment (ms)
Measured range
True range

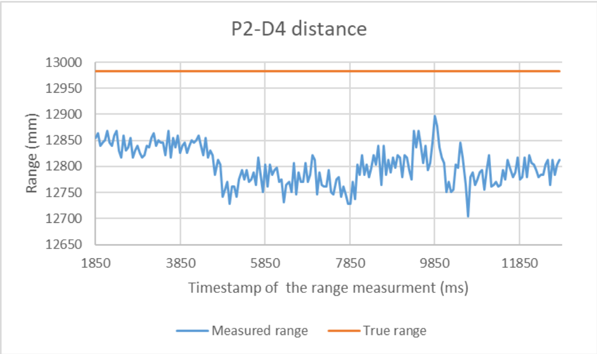

P5-W5 distance
Range (mm)
10520
10500
10480
10460
10440
10420
10400
10380
10360
10340
1850 3850 5850 7850 9850 11850 13850 15850
Timestamp of the range measurment (ms)
Measured range
True range

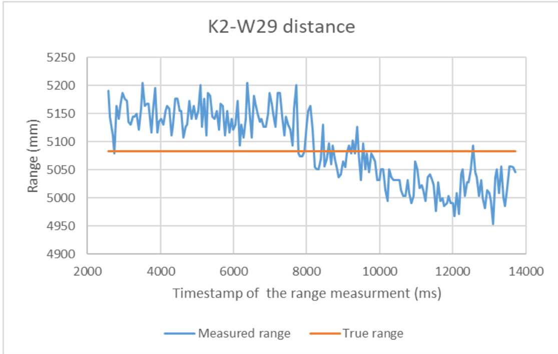

P5-D4 distance
Range (mm)
27100
27050
27000
26950
26900
26850
26800
1850 3850 5850 7850 9850 11850 13850 15850
Timestamp of the range measurment (ms)
Measured range
True range

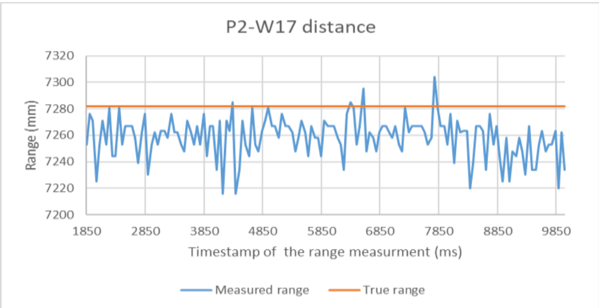

P5-D2 distance
Range (mm)
8200
8100
8000
7900
7800
7700
1850 3850 5850 7850 9850 11850 13850
Timestamp of the range measurment (ms)
Measured range
True range

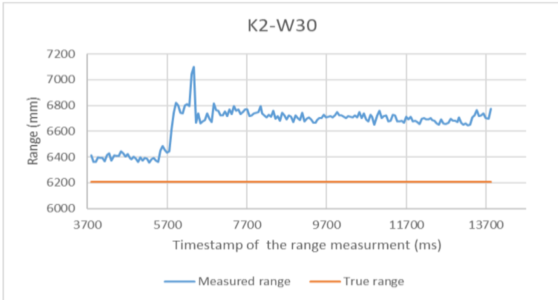

P5-W18 distance
Range (mm)
15600
15500
15400
15300
15200
15100
15000
1850 3850 5850 7850 9850 11850
Timestamp of the range measurment (ms)
Measured range
True range

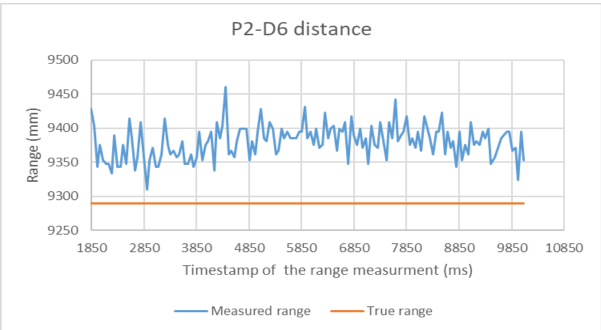

P5-D2 distance
Range (mm)
9700
9600
9500
9400
9300
9200
9100
1850 3850 5850 7850 9850 11850 13850 15850
Timestamp of the range measurment (ms)
Measured range
True range

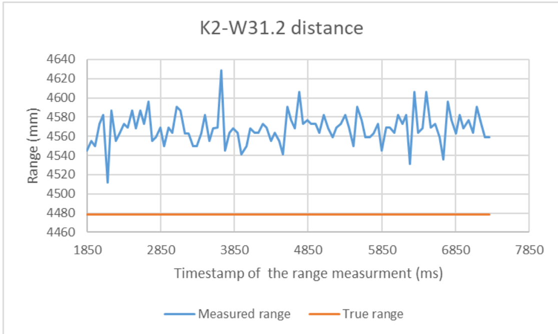

P2-D4 distance
13000
12950
12900
12850
12800
12750
12700
12650
Range (mm)
1850
3850
5850
7850
9850
11850
Timestamp of the range measurment (ms)
Measured range
True range

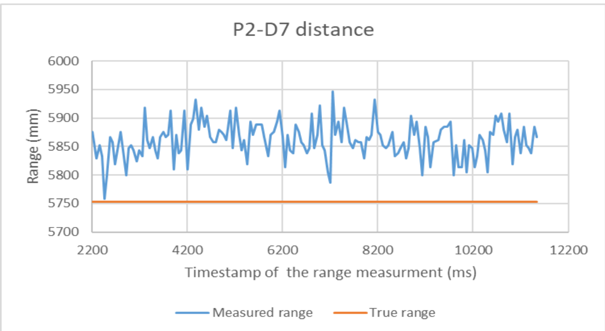

K2-W29 distance
5250
5200
5150
5100
5050
5000
4950
4900
Range (mm)
2000
4000
6000
8000
10000
12000
14000
Timestamp of the range measurment (ms)
Measured range
True range

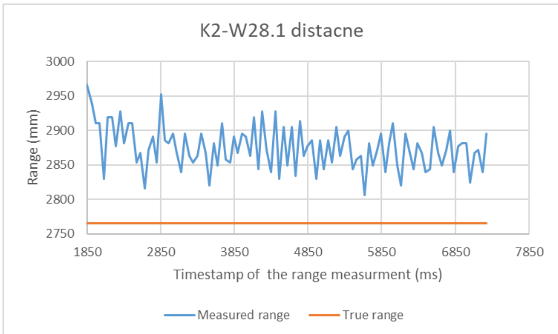

P2-W17 distance
7320
7300
7280
7260
7240
7220
7200
Range (mm)
1850
2850
3850
4850
5850
6850
7850
8850
9850
Timestamp of the range measurment (ms)
Measured range
True range

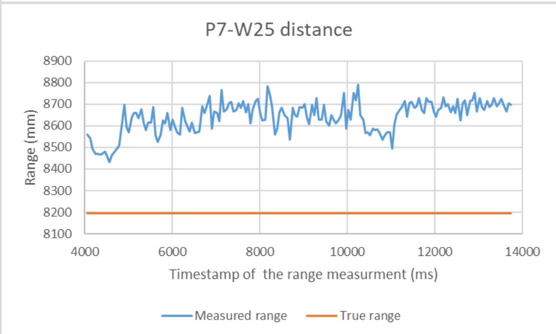

K2-W30
7200
7000
6800
6600
6400
6200
6000
Range (mm)
3700
5700
7700
9700
11700
13700
Timestamp of the range measurment (ms)
Measured range
True range

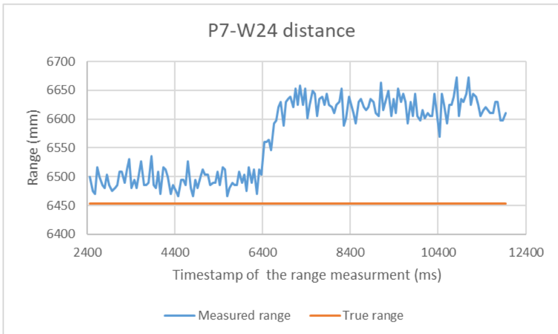

P2-D6 distance
9500
9450
9400
9350
9300
9250
Range (mm)
1850
2850
3850
4850
5850
6850
7850
8850
9850
10850
Timestamp of the range measurment (ms)
Measured range
True range

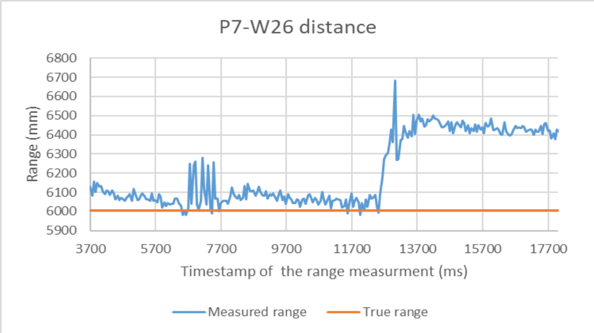

K2-W31.2 distance
4640
4620
4600
4580
4560
4540
4520
4500
4480
4460
Range (mm)
1850
2850
3850
4850
5850
6850
7850
Timestamp of the range measurment (ms)
Measured range
True range

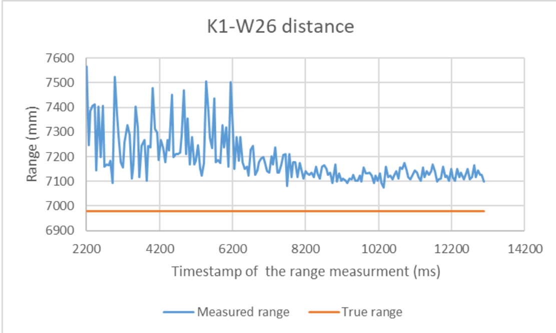

P2-D7 distance
6000
5950
5900
5850
5800
5750
5700
Range (mm)
2200
4200
6200
8200
10200
12200
Timestamp of the range measurment (ms)
Measured range
True range

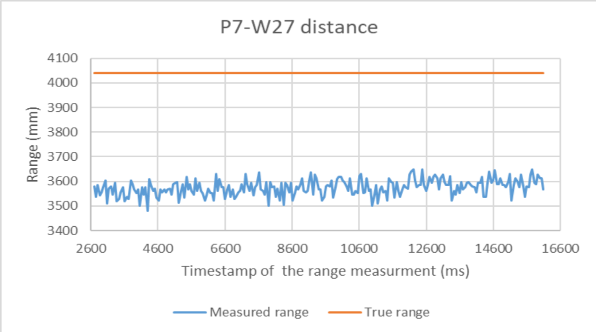

K2-W28.1 distacne
3000
2950
2900
2850
2800
2750
Range (mm)
1850
2850
3850
4850
5850
6850
7850
Timestamp of the range measurment (ms)
Measured range
True range

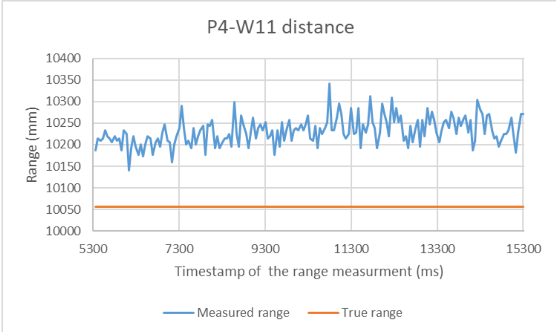

P7-W25 distance
8900
8800
8700
8600
8500
8400
8300
8200
8100
Range (mm)
4000
6000
8000
10000
12000
14000
Timestamp of the range measurment (ms)
Measured range
True range

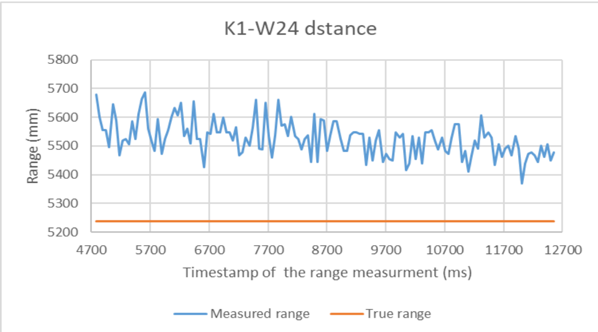

P7-W24 distance
6700
6650
6600
6550
6500
6450
6400
Range (mm)
2400
4400
6400
8400
10400
12400
Timestamp of the range measurment (ms)
Measured range
True range

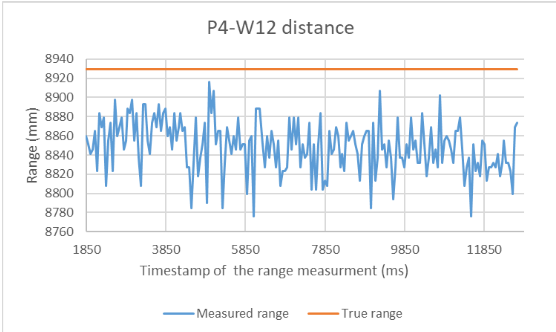

P7-W26 distance
Range (mm)
6800
6700
6600
6500
6400
6300
6200
6100
6000
5900
3700 5700 7700 9700 11700 13700 15700 17700
Timestamp of the range measurment (ms)
Measured range
True range


K1-W26 distance
Range (mm)
7600
7500
7400
7300
7200
7100
7000
6900
2200 4200 6200 8200 10200 12200 14200
Timestamp of the range measurment (ms)
Measured range
True range

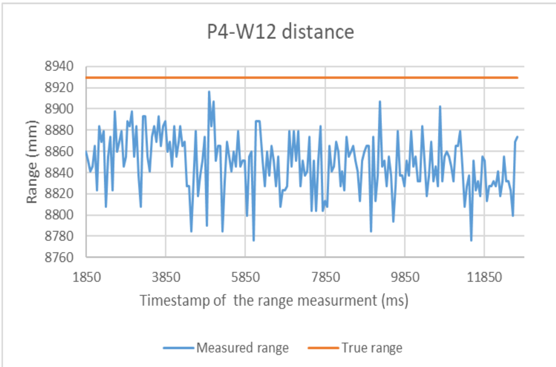

P7-W27 distance
Range (mm)
4100
4000
3900
3800
3700
3600
3500
3400
2600 4600 6600 8600 10600 12600 14600 16600
Timestamp of the range measurment (ms)
Measured range
True range

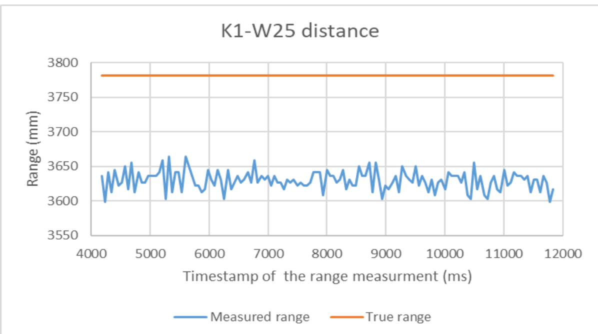

P4-W11 distance
Range (mm)
10400
10350
10300
10250
10200
10150
10100
10050
10000
5300 7300 9300 11300 13300 15300
Timestamp of the range measurment (ms)
Measured range
True range

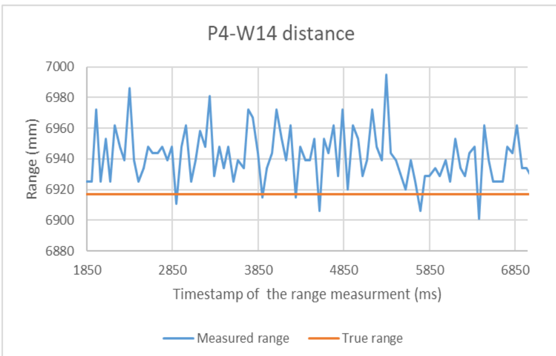

K1-W24 dstance
Range (mm)
5800
5700
5600
5500
5400
5300
5200
4700 5700 6700 7700 8700 9700 10700 11700 12700
Timestamp of the range measurment (ms)
Measured range
True range

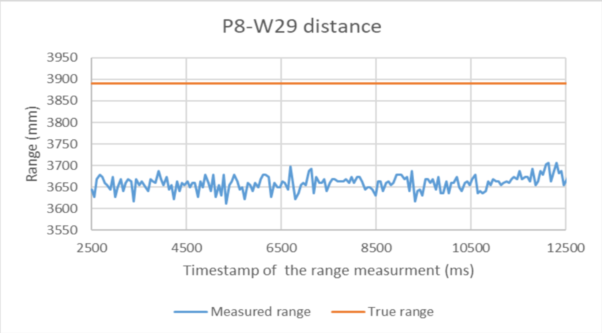

P4-W12 distance
Range (mm)
8940
8920
8900
8880
8860
8840
8820
8800
8780
8760
1850 3850 5850 7850 9850 11850
Timestamp of the range measurment (ms)
Measured range
True range

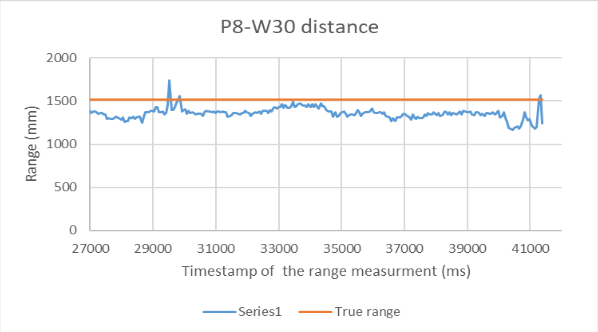

K1-W27 distance
Range (mm)
8400
8350
8300
8250
8200
8150
8100
8050
8000
3400 4400 5400 6400 7400 8400 9400 10400 11400 12400
Timestamp of the range measurment (ms)
Measured range
True range

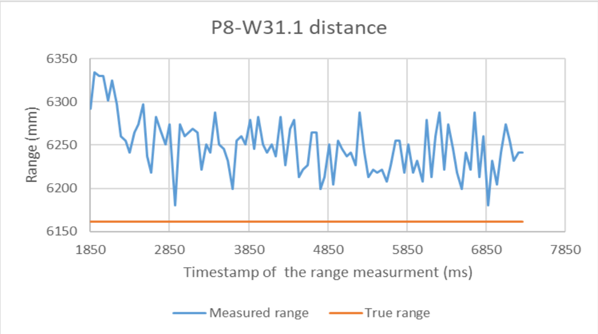

P4-W12 distance
Range (mm)
8940
8920
8900
8880
8860
8840
8820
8800
8780
8760
1850 3850 5850 7850 9850 11850
Timestamp of the range measurment (ms)
Measured range
True range

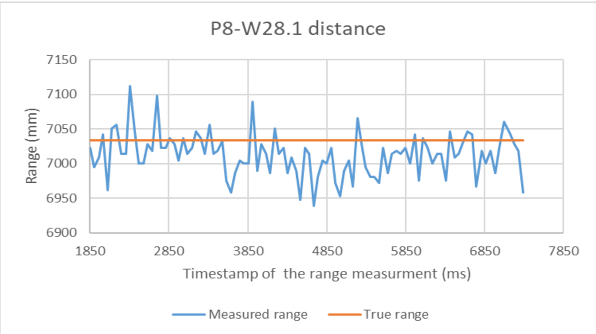

K1-W25 distance
Range (mm)
3800
3750
3700
3650
3600
3550
4000 5000 6000 7000 8000 9000 10000 11000 12000
Timestamp of the range measurment (ms)
Measured range
True range

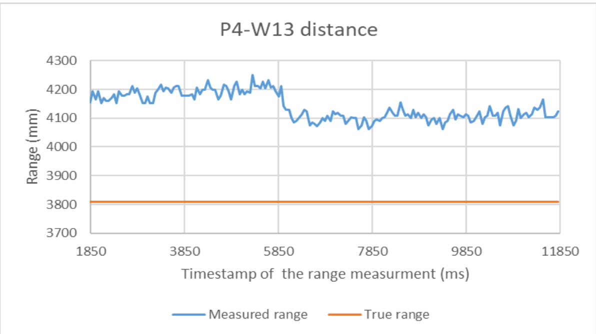

P4-W14 distance
Range (mm)
7000
6980
6960
6940
6920
6900
6880
1850 2850 3850 4850 5850 6850
Timestamp of the range measurment (ms)
Measured range
True range

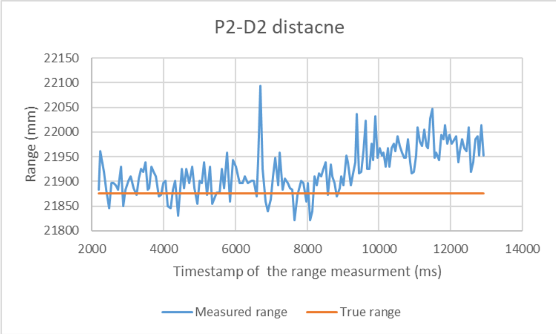

P8-W29 distance
Range (mm)
3950
3900
3850
3800
3750
3700
3650
3600
3550
2500
4500
6500
8500
10500
12500
Timestamp of the range measurment (ms)
Measured range
True range

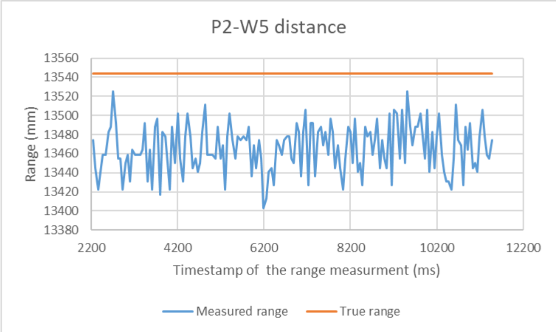

P8-W30 distance
Range (mm)
2000
1500
1000
500
0
27000
29000
31000
33000
35000
37000
39000
41000
Timestamp of the range measurment (ms)
Series1
True range

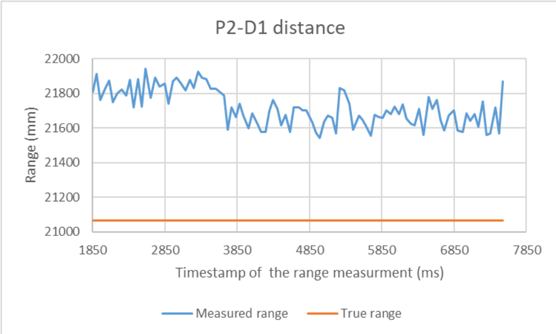

P8-W31.1 distance
Range (mm)
6350
6300
6250
6200
6150
1850
2850
3850
4850
5850
6850
7850
Timestamp of the range measurment (ms)
Measured range
True range


P8-W28.1 distance
Range (mm)
7150
7100
7050
7000
6950
6900
1850
2850
3850
4850
5850
6850
7850
Timestamp of the range measurment (ms)
Measured range
True range


P4-W13 distance
Range (mm)
4300
4200
4100
4000
3900
3800
3700
1850
3850
5850
7850
9850
11850
Timestamp of the range measurment (ms)
Measured range
True range

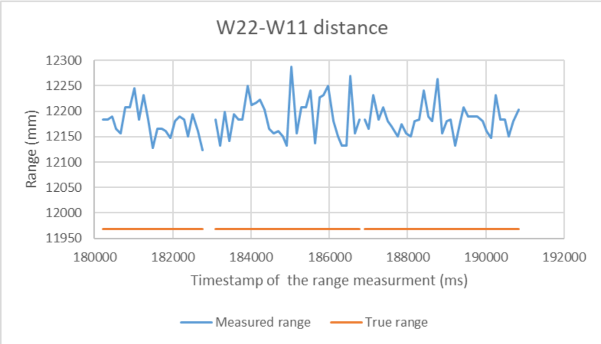

P2-D2 distacne
Range (mm)
22150
22100
22050
22000
21950
21900
21850
21800
2000
4000
6000
8000
10000
12000
14000
Timestamp of the range measurment (ms)
Measured range
True range

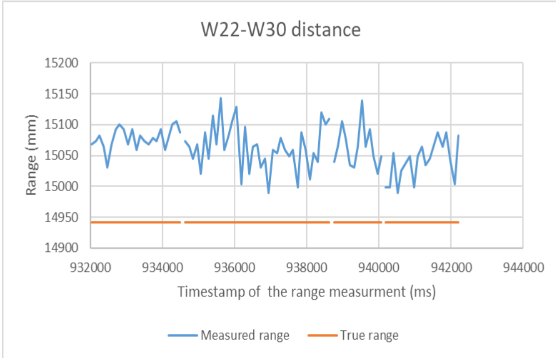

P2-W5 distance
Range (mm)
13560
13540
13520
13500
13480
13460
13440
13420
13400
13380
2200
4200
6200
8200
10200
12200
Timestamp of the range measurment (ms)
Measured range
True range

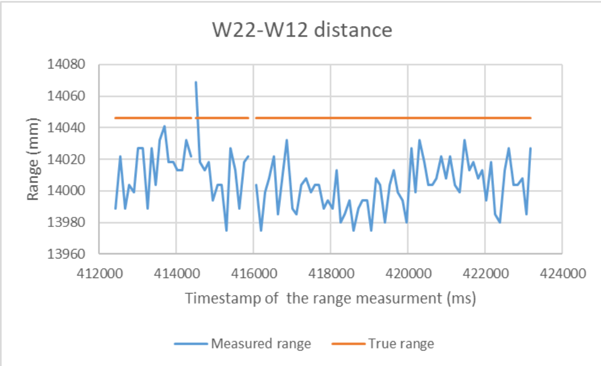

P2-D1 distance
Range (mm)
22000
21800
21600
21400
21200
21000
1850
2850
3850
4850
5850
6850
7850
Timestamp of the range measurment (ms)
Measured range
True range

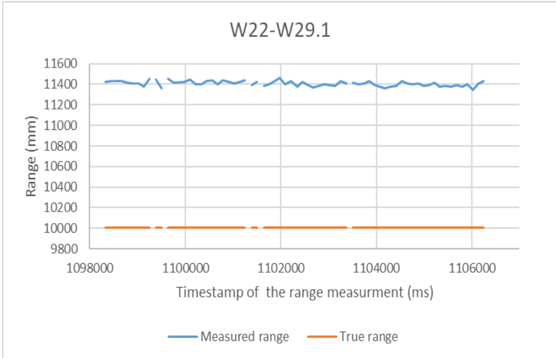
Distances drift in NLOS between anchors and tag

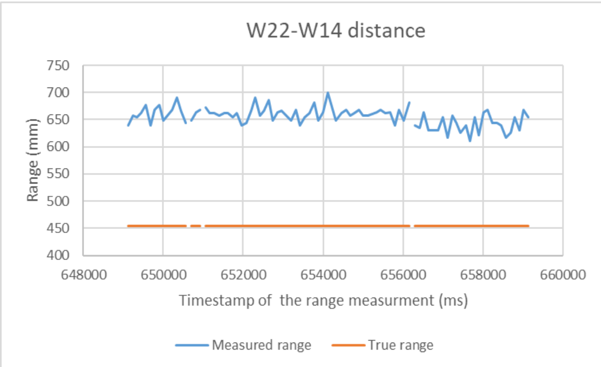
Space in the chart means that there was an error in during the measurement.

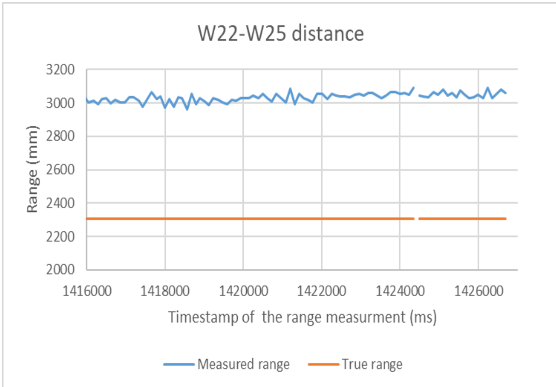


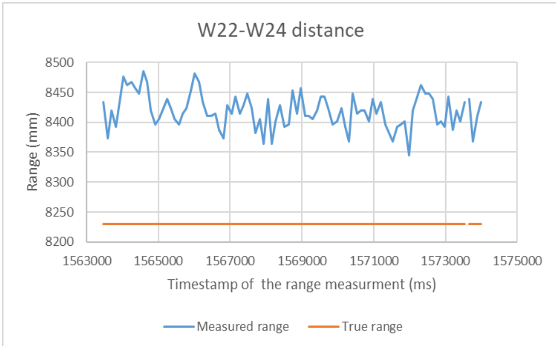


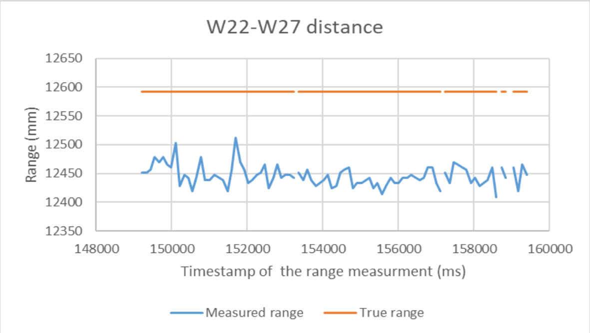


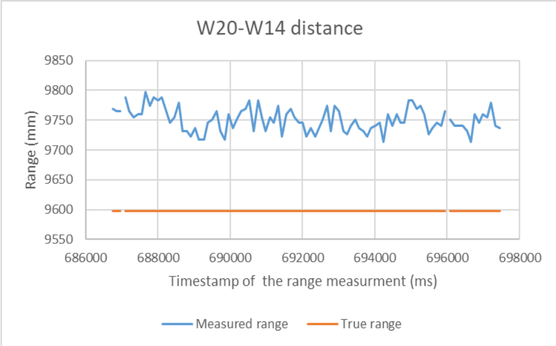


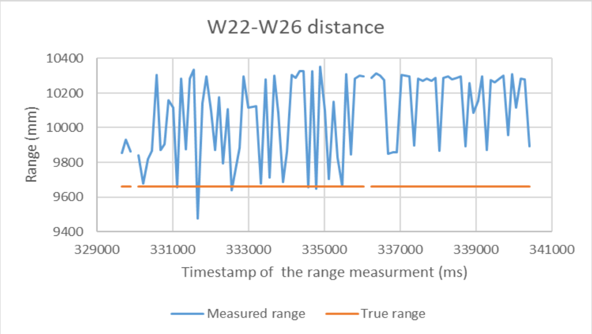


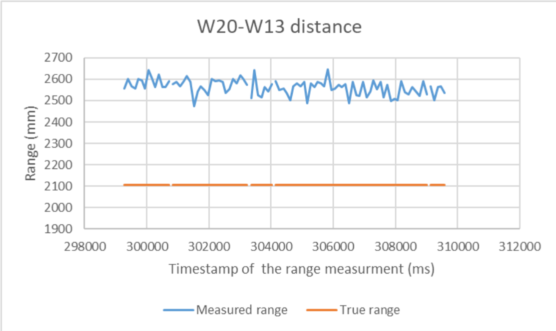


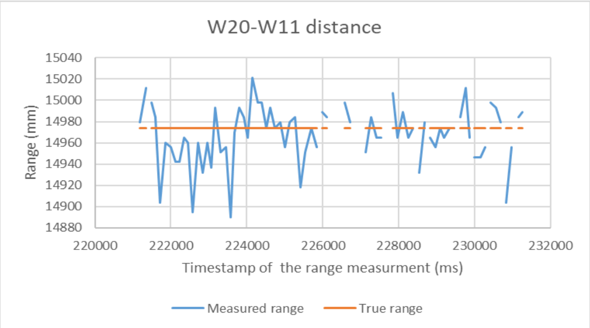


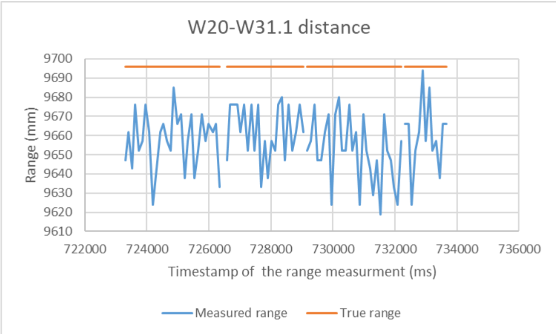

W22-W27 distance
Range (mm)
Timestamp of the range measurment (ms)
Measured range
True range

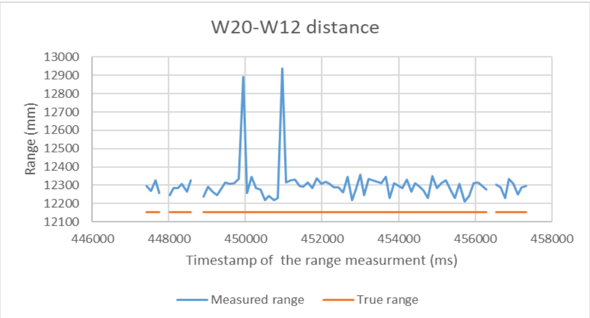

W20-W14 distance
Range (mm)
Timestamp of the range measurment (ms)
Measured range
True range

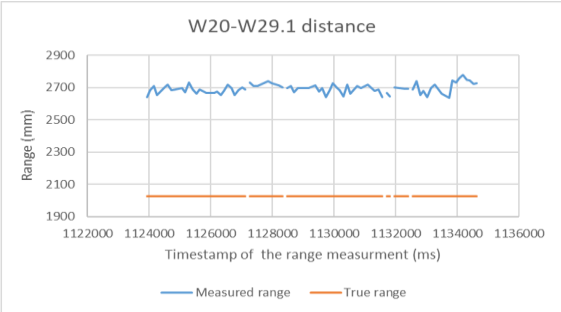

W22-W26 distance
Range (mm)
Timestamp of the range measurment (ms)
Measured range
True range

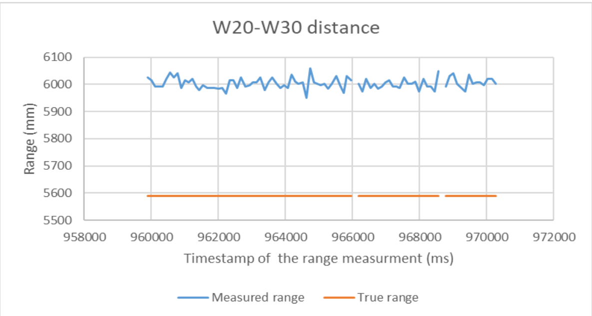

W20-W13 distance
Range (mm)
Timestamp of the range measurment (ms)
Measured range
True range

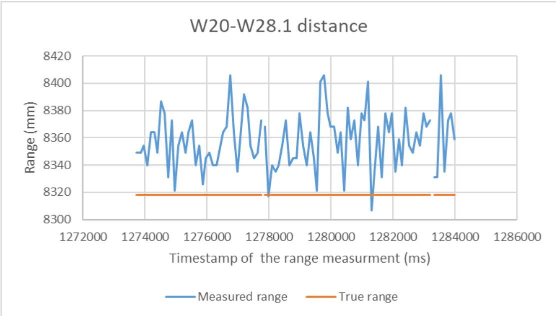

W20-W11 distance
Range (mm)
Timestamp of the range measurment (ms)
Measured range
True range

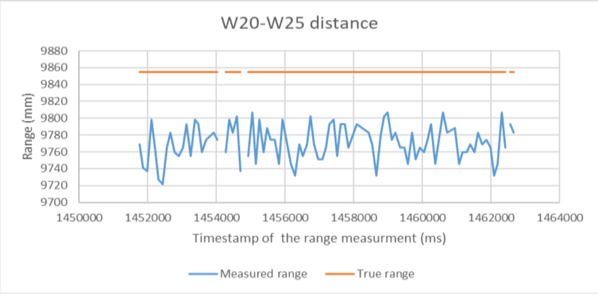

W20-W31.1 distance
Range (mm)
Timestamp of the range measurment (ms)
Measured range
True range

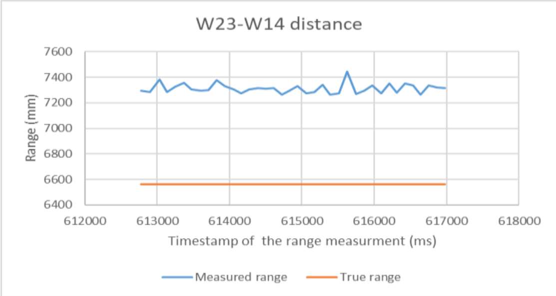

W20-W12 distance
Range (mm)
Timestamp of the range measurment (ms)
Measured range
True range

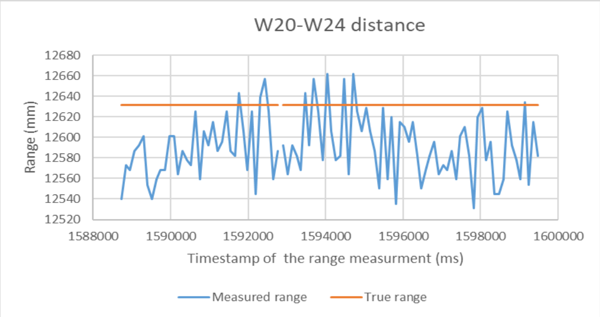

W20-W29.1 distance
Range (mm)
Timestamp of the range measurment (ms)
Measured range
True range

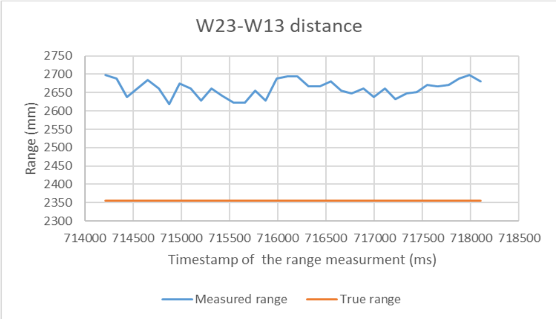

W20-W30 distance
Range (mm)
Timestamp of the range measurment (ms)
Measured range
True range

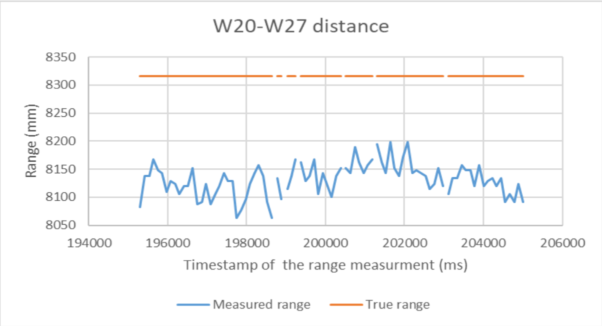

W20-W28.1 distance
Range (mm)
Timestamp of the range measurment (ms)
Measured range
True range

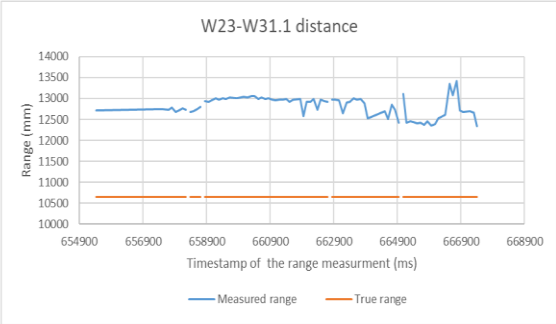

W20-W25 distance
Range (mm)
9880
9860
9840
9820
9800
9780
9760
9740
9720
9700
1450000
1452000
1454000
1456000
1458000
1460000
1462000
1464000
Timestamp of the range measurment (ms)
Measured range
True range


W23-W14 distance
Range (mm)
7600
7400
7200
7000
6800
6600
6400
612000
613000
614000
615000
616000
617000
618000
Timestamp of the range measurment (ms)
Measured range
True range

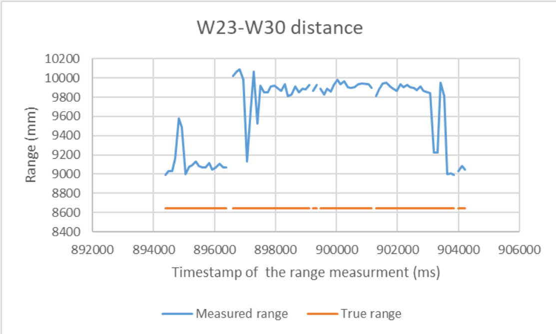

W20-W24 distance
Range (mm)
12680
12660
12640
12620
12600
12580
12560
12540
12520
1588000
1590000
1592000
1594000
1596000
1598000
1600000
Timestamp of the range measurment (ms)
Measured range
True range

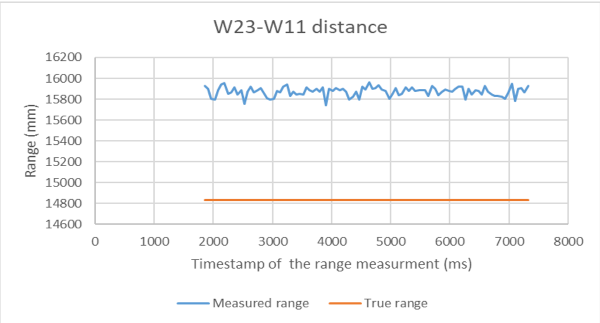

W23-W13 distance
Range (mm)
2750
2700
2650
2600
2550
2500
2450
2400
2350
2300
714000
714500
715000
715500
716000
716500
717000
717500
718000
718500
Timestamp of the range measurment (ms)
Measured range
True range

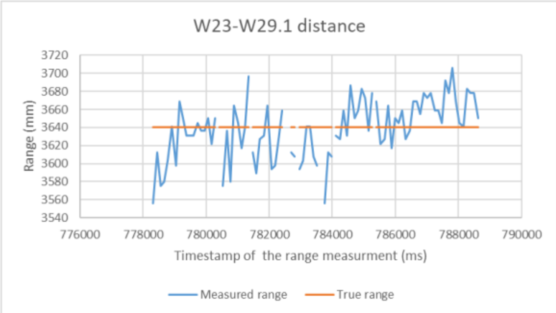

W20-W27 distance
Range (mm)
8350
8300
8250
8200
8150
8100
8050
194000
196000
198000
200000
202000
204000
206000
Timestamp of the range measurment (ms)
Measured range
True range

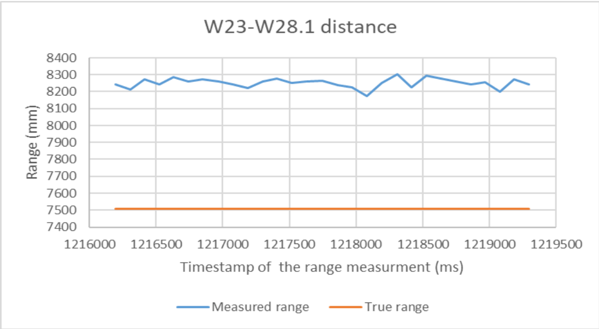

W23-W31.1 distance
Range (mm)
14000
13500
13000
12500
12000
11500
11000
10500
10000
654900
656900
658900
660900
662900
664900
666900
668900
Timestamp of the range measurment (ms)
Measured range
True range

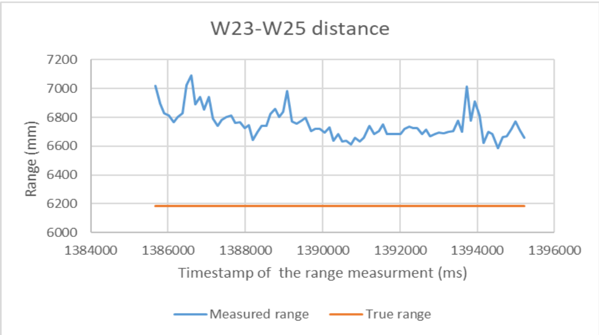

W20-W26 distance
Range (mm)
3000
2800
2600
2400
2200
2000
1800
360000
362000
364000
366000
368000
370000
372000
374000
Timestamp of the range measurment (ms)
Measured range
True range

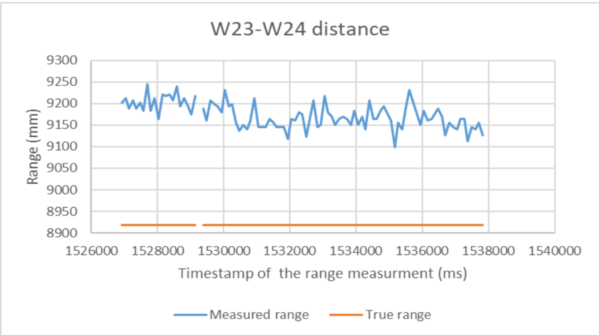

W23-W30 distance
Range (mm)
10200
10000
9800
9600
9400
9200
9000
8800
8600
8400
892000
894000
896000
898000
900000
902000
904000
906000
Timestamp of the range measurment (ms)
Measured range
True range

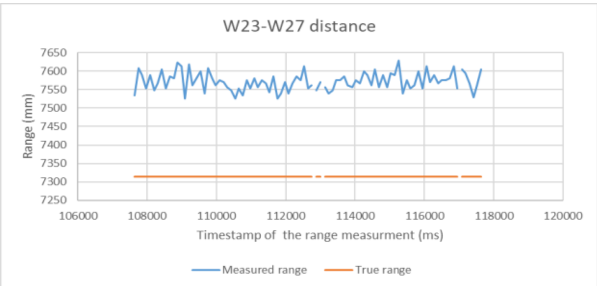

W23-W11 distance
Range (mm)
16200
16000
15800
15600
15400
15200
15000
14800
14600
0
1000
2000
3000
4000
5000
6000
7000
8000
Timestamp of the range measurment (ms)
Measured range
True range

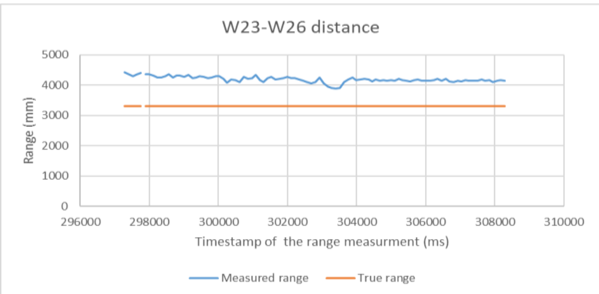

W23-W29.1 distance
Range (mm)
3720
3700
3680
3660
3640
3620
3600
3580
3560
3540
776000
778000
780000
782000
784000
786000
788000
790000
Timestamp of the range measurment (ms)
Measured range
True range

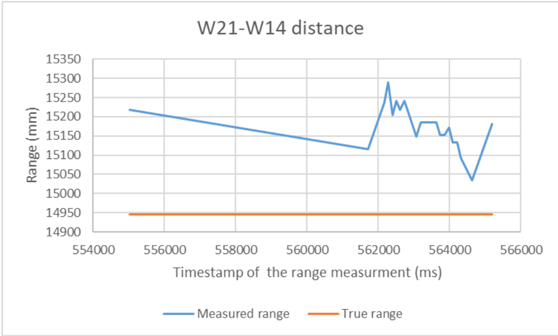

W23-W28.1 distance
8400 8300 8200 8100 8000 7900 7800 7700 7600 7500 7400
Range (mm)
1216000 1216500 1217000 1217500 1218000 1218500 1219000 1219500
Timestamp of the range measurment (ms)
Measured range
True range

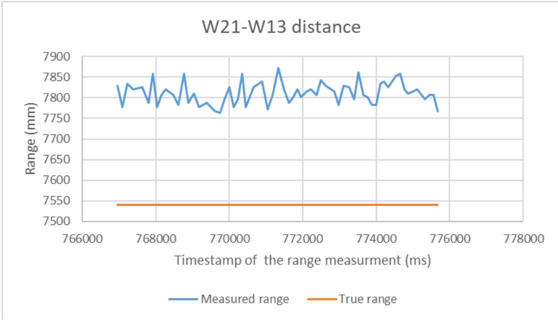

W23-W25 distance
7200 7000 6800 6600 6400 6200 6000
Range (mm)
1384000 1386000 1388000 1390000 1392000 1394000 1396000
Timestamp of the range measurment (ms)
Measured range
True range

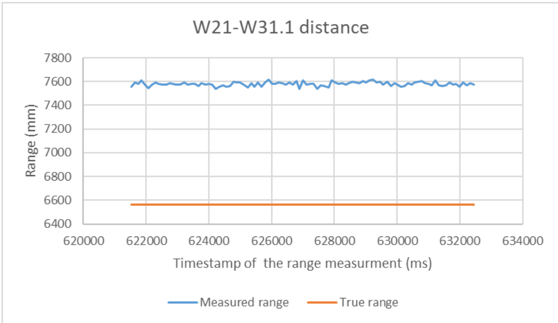

W23-W24 distance
9300 9250 9200 9150 9100 9050 9000 8950 8900
Range (mm)
1526000 1528000 1530000 1532000 1534000 1536000 1538000 1540000
Timestamp of the range measurment (ms)
Measured range
True range

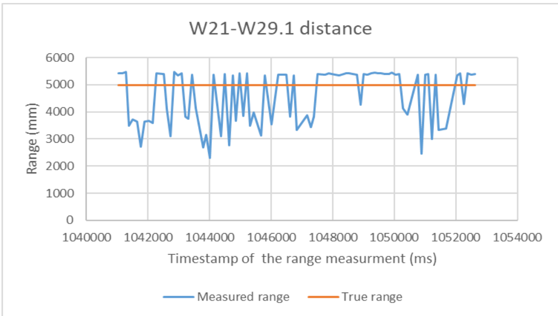

W23-W27 distance
7650 7600 7550 7500 7450 7400 7350 7300 7250
Range (mm)
106000 108000 110000 112000 114000 116000 118000 120000
Timestamp of the range measurment (ms)
Measured range
True range

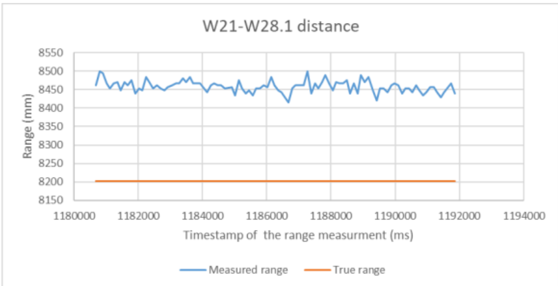

W23-W26 distance
5000 4000 3000 2000 1000 0
Range (mm)
296000 298000 300000 302000 304000 306000 308000 310000
Timestamp of the range measurment (ms)
Measured range
True range

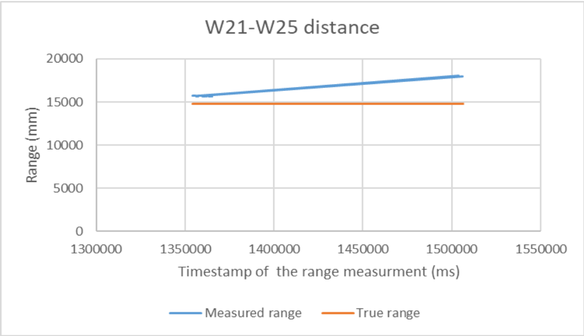

W21-W14 distance
15350 15300 15250 15200 15150 15100 15050 15000 14950 14900
Range (mm)
554000 556000 558000 560000 562000 564000 566000
Timestamp of the range measurment (ms)
Measured range
True range

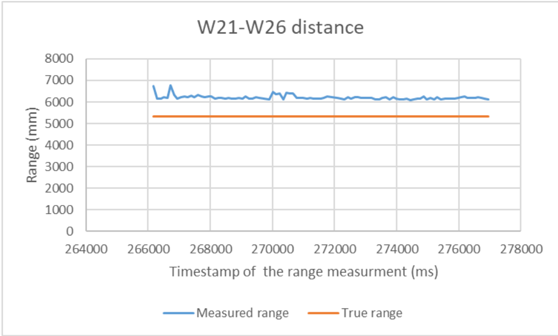

W21-W13 distance
7900 7850 7800 7750 7700 7650 7600 7550 7500
Range (mm)
766000 768000 770000 772000 774000 776000 778000
Timestamp of the range measurment (ms)
Measured range
True range

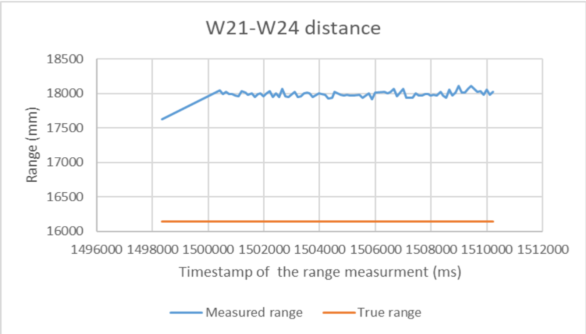

W21-W31.1 distance
7800 7600 7400 7200 7000 6800 6600 6400
Range (mm)
620000 622000 624000 626000 628000 630000 632000 634000
Timestamp of the range measurment (ms)
Measured range
True range

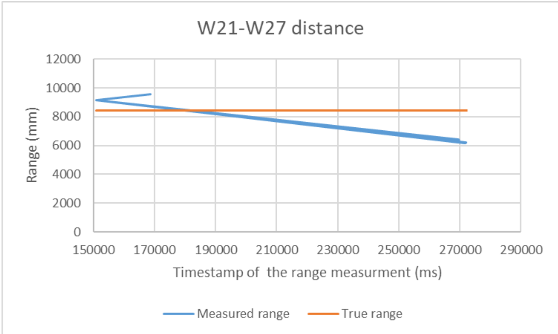

W21-W29.1 distance
6000 5000 4000 3000 2000 1000 0
Range (mm)
1040000 1042000 1044000 1046000 1048000 1050000 1052000 1054000
Timestamp of the range measurment (ms)
Measured range
True range


W21-W28.1 distance
8550 8500 8450 8400 8350 8300 8250 8200 8150
Range (mm)
1180000 1182000 1184000 1186000 1188000 1190000 1192000 1194000
Timestamp of the range measurment (ms)
Measured range
True range


W21-W25 distance
Range (mm)
20000
15000
10000
5000
0
1300000
1350000
1400000
1450000
1500000
1550000
Timestamp of the range measurment (ms)
Measured range
True range


W21-W26 distance
Range (mm)
8000
7000
6000
5000
4000
3000
2000
1000
0
264000
266000
268000
270000
272000
274000
276000
278000
Timestamp of the range measurment (ms)
Measured range
True range


W21-W24 distance
Range (mm)
18500
18000
17500
17000
16500
16000
1496000 1498000 1500000 1502000 1504000 1506000 1508000 1510000 1512000
Timestamp of the range measurment (ms)
Measured range
True range


W21-W27 distance
Range (mm)
12000
10000
8000
6000
4000
2000
0
150000
170000
190000
210000
230000
250000
270000
290000
Timestamp of the range measurment (ms)
Measured range
True range

0

APPENDIX 4

Arduino C++ code ready_to_range

```
/**
  The Pozyx ready to range tutorial (c) Pozyx Labs
  Please read the tutorial that accompanies this sketch: https://www.pozyx.
io/Documentation/Tutorials/ready_to_range/Arduino

  This demo requires two Pozyx devices and one Arduino. It demonstrates the
ranging capabilities and the functionality to
  to remotely control a Pozyx device. Place one of the Pozyx shields on the
Arduino and upload this sketch. Move around
  with the other Pozyx device.

  This demo measures the range between the two devices. The closer the devices
are to each other, the more LEDs will
  light up on both devices.
*/

#include <Pozyx.h>
#include<Pozyx_definitions.h>
#include <Wire.h>

////////////////////////////////////////////////
///////////////// PARAMETERS /////////////////
////////////////////////////////////////////////

uint16_t destination_id = 0x6745;     // the network id of the other pozyx
device: fill in the network id of the other device
signed int range_step_mm = 1000;      // every 1000mm in range, one LED less will
be giving light.

uint8_t ranging_protocol = POZYX_RANGE_PROTOCOL_PRECISION; // ranging protocol of
the Pozyx.

uint16_t remote_id = 0x6749;          // the network ID of the remote device
bool remote = true;                   // whether to use the given remote device
for ranging

////////////////////////////////////////////////

void setup(){
 Serial.begin(115200);

  if(Pozyx.begin() == POZYX_FAILURE){
    Serial.println("ERROR: Unable to connect to POZYX shield");
    Serial.println("Reset required");
    delay(100);
    abort();
  }
  // setting the remote_id back to NULL will use the local Pozyx
  if (!remote){
```

```
    remote_id = NULL;
  }
  Serial.println("------------POZYX RANGING V1.1------------");
  Serial.println("NOTES:");
  Serial.println("- Change the parameters:");
  Serial.println("\tdestination_id (target device)");
  Serial.println("\trange_step (mm)");
  Serial.println();
  Serial.println("- Approach target device to see range and");
  Serial.println("led control");
  Serial.println("------------POZYX RANGING V1.1------------");
  Serial.println();
  Serial.println("START Ranging:");

  // make sure the pozyx system has no control over the LEDs, we're the boss
  uint8_t led_config = 0x0;
  Pozyx.setLedConfig(led_config, remote_id);
  // do the same with the remote device
  Pozyx.setLedConfig(led_config, destination_id);
  // set the ranging protocol
  Pozyx.setRangingProtocol(ranging_protocol, remote_id);
}

void loop(){
  device_range_t range;
  int status = 0;

  // let's perform ranging with the destination
  if(!remote)
    status = Pozyx.doRanging(destination_id, &range);
  else
    status = Pozyx.doRemoteRanging(remote_id, destination_id, &range);

  if (status == POZYX_SUCCESS){
    Serial.print(range.timestamp);
    Serial.print("ms, ");
    Serial.print(range.distance);
    Serial.print("mm, ");
    Serial.print(range.RSS);
    Serial.println("dBm");

    // now control some LEDs; the closer the two devices are, the more LEDs will
be lit
    if (ledControl(range.distance) == POZYX_FAILURE){
      Serial.println("ERROR: setting (remote) leds");
    }
  }
  else{
    Serial.println("ERROR: ranging");
```

```
  }
}

int ledControl(uint32_t range){
  int status = POZYX_SUCCESS;
  // set the LEDs of the pozyx device
  status &= Pozyx.setLed(4, (range < range_step_mm), remote_id);
  status &= Pozyx.setLed(3, (range < 2*range_step_mm), remote_id);
  status &= Pozyx.setLed(2, (range < 3*range_step_mm), remote_id);
  status &= Pozyx.setLed(1, (range < 4*range_step_mm), remote_id);

  // set the LEDs of the destination pozyx device
  status &= Pozyx.setLed(4, (range < range_step_mm), destination_id);
  status &= Pozyx.setLed(3, (range < 2*range_step_mm), destination_id);
  status &= Pozyx.setLed(2, (range < 3*range_step_mm), destination_id);
  status &= Pozyx.setLed(1, (range < 4*range_step_mm), destination_id);

  // status will be zero if setting the LEDs failed somewhere along the way
  return status;
}
```