Ultra Wideband (UWB) Sensor Integration and Application in GPS-Compromised Environments

THESIS

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Abstract

The Global Positioning System (GPS) has been a reliable, accurate solution to most position and navigation problems for years. However, navigating and mapping in GPS-compromised environments still remains a problem. Even utilizing other Global Navigation Satellite Systems (GNSS), with an ever-increasing number of satellites, every day we encounter environments where there is limited or no access to a GNSS signal. Infrastructure and environmental factors can easily derogate and even obstruct the weak GPS/GNSS signals. It is because of these variables that an independent, repetitive solution is sought to measure and navigate positions. Ultra Wideband (UWB) technology has general advantages and the ability to be used in local environments where GPS coverage is poor or measurements are substandard.

A local UWB network system can be set up quickly, so that the position of a kinematic sensor can be tracked within the network area. The comparable frequency rate to GPS and No Line of Sight (NLOS) capabilities of UWB, make it ideal to collect data in GPS-compromised environments. These environments include indoor and outdoor areas where the weak GPS signal cannot penetrate or continually provide accurate measurements, such as under roof, through wall, in dense canopy, canyons, caves or mountainous areas. UWB sensors can measure ranges and communicate a variety of data by implementing short duration, pulsed radiofrequency (RF) waves, transmitted between sensors. By using the highest possible bandwidth, the signals are not easily degraded and
can even travel through wall and other objects, allowing for potential widespread application and uses in un-ideal navigation and NLOS environments. Through advancements in hardware and timing capabilities along with the opening of the frequency ranges by the federal government recently, UWB technology has recently emerged, to again be applied for navigation solutions.

This thesis presents the implementation and analysis of the UWB technology for positioning and tracking in indoor and outdoor scenarios where GPS is limited. UWB has the ability to be independent from or integrated with GPS, IMU, and other positioning sensors to solve navigation problems with accuracies on the scale of decimeters or smaller. Sensor performance validation included the timing calibration and analysis of a single ranging signal with various experimental setups and evaluations to be tested. The calibration results were then applied to sensors in a network to allow for optimal ranging accuracies in kinematic experiments.

Collecting kinematic data in an indoor scenario allowed for the assessment of the UWB performance in a laboratory environment where most variables, such as network setup and signal readings, were able to be accurately accounted for. An open sky outdoor test was conducted to compare the system’s solution to an optimal GPS solution. Finally, a GPS-compromised experiment was conducted to show the advantages of UWB in an environment where GPS cannot be relied on. With testing and analysis, it has been exhibited that UWB can be a suitable replacement for GPS. This thesis presents the theory and algorithms necessary to turn range measurements into an accurate navigation and position solutions, as well as the testing and results of numerous experiments.

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Dedication

This document is dedicated to my Family, without whom I would never accomplished this or much else. Thanks also to my friends, classmates, coworkers and others who have helped along the way. Finally, I would like to thank Katharine, who has been there helping and supporting for the entire trip.
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Fields of Study

Major Field: Civil Engineering
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List of Abbreviations

C/A.................................................................Coarse/Acquisition
CAT............................................................Channel Analysis Tool
CLOS.............................................................Clear Line of Sight
CORS.........................................................Continually Operating Reference System
CRE............................................................Coarse Range Estimate
DGPS..........................................................Differential Global Positioning Systems
EKF.............................................................Extended Kalman Filter
EPDF...........................................................Empirical Probability Density Function
FCC............................................................Federal Communication Commission
FRE............................................................Filtered Range Estimate
GPS............................................................Global Positioning System
GNSS.........................................................Global Navigation Satellite Systems
IMU............................................................Inertial Measurement Unit
KF.............................................................Kalman Filter
LS..............................................................Least Squares
MCS...........................................................Master Control Station
MLE.........................................................Maximum Likelihood Estimator
MRM..........................................................Monostatic Radar Module
NLOS.........................................................No Line of Sight
NOAA………………………………..National Oceanic and Atmospheric Administration
OHUN………………………………………………………Marysville Reference Station
OPUS…………………………………………………….Online Positioning User Service
P-code……………………………………………………………Precision Code
PNT…………………………………………..Positioning, Navigation and Timing
RCM……………………………………………………Ranging Communication Module
RF………………………………………………………………………..Radio Frequency
RMSE……………………………………………………………Root Mean Square Error
RMSE XY………………………………………….Root Mean Square Error in XY plane
RTK…………………………………………………………………Real Time Kinematic
SNR………………………………………………………………………..Signal to Noise
STD……………………………………………………………………Standard Deviation
STKR…………………………………………………………....Athens Reference Station
UWB……………………………………………………………………..Ultra Wideband
Chapter 1: Introduction

1.1. Background and Motivations

The Global Positioning System (GPS) has far outperformed its initial planned accuracies and become an integral part of everyday life and technology. Intended military uses have now been expanded to civil, commercial, and public users to help provide positioning, navigation, and timing (PNT) information throughout the world. Since GPS became fully operational in 1993, new algorithms and processing techniques have been and continue to be developed to improve accuracies from tens of meters to now sub-centimeter levels in clear line of sight (CLOS) environments.

As we become dependent on the high accuracy positioning data that GPS provides, an alternative redundant solution must be established, so that positioning and navigation data can be gathered in GPS-compromised environments and in the catastrophic event, if the global system is lost entirely. Ultra Wideband (UWB) radio frequency signals have proven to be an attractive alternative in these GPS-compromised local environments. The wide-bandwidth, pulsed signals produced by UWB systems are able to penetrate through objects, walls, canopies, etc., giving accurate range measurements where GPS cannot. These measurements can ensure the accuracy and availability of solutions needed by today’s various location-based and personal navigation applications.
UWB, while invented in the 1950’s, has recently begun a transition back to the forefront of PNT solutions with the deregulation of the Federal Communication Commission’s (FCC) rules. Radar, communication, precise ranging, through wall, and other capabilities of the technology gave the FCC the motivation to reconsider the ban on commercial and civil use of the systems. The large frequency range and various spectrums in which the systems operate in were open in 2002. To ensure there is no interference with existing signals, such as GPS, strict power restraints were introduced (Emami 2013). More importantly, the system is capable of effective localization in a local network arrangement. With multiple UWB units, the triangulation of a kinematic unit can be calculated with multiple ranging measurements, much like GPS (Küpper 2005). Note that the UWB systems can also operate indoor and in high multipath environments.

With the newly available systems, research, studies, and analysis on the implementations and capabilities of the UWB systems, priority has been given to assessing and to determining the capabilities of the technology. The motivation of this thesis is to show the accuracy, capability, and performance analysis of the UWB technology as an additional and/or substitute positioning solution to GPS in GPS-compromised local environments. By performing research and experiments using a set of Time Domain PulsON 410 UWB units, this investigation was able to explore the capabilities of the systems in indoor and outdoor environments with high multipath and NLOS constraints. Timing calibration procedures, positioning algorithms, and other post-processing techniques were implemented for kinematic positioning in both indoor and outdoor environments. The experimental results, comparisons, analysis, and
developed algorithms are all contributions made by this thesis to exhibit the abilities of UWB systems.
1.2. **Research Objective and Methods**

The objective of this research was to perform experiments in GPS-compromised environments to analyze the accuracy potential of the UWB system. The developed algorithms and techniques implemented are also presented. Experiments were performed in laboratory, open sky, and GPS-compromised environments. The accuracies of the system in areas where GPS was compromised or absent were then compared with the CLOS controlled laboratory and open sky experiments. The ideal CLOS experiments allowed for the comparison of the UWB kinematic calculations to centimeter-level accuracy GPS solutions for the outdoor experiments, and similar level accuracy total station measurements for the indoor experiments.

Sensor performance validation was also performed to ensure the accuracies of the individual units and their range measurements. In a high multipath indoor environment, analysis was performed with both CLOS and NLOS conditions. This analysis allowed for time synchronization of the units. Calibration procedures were also conducted and analyzed prior to all tests. The timing accuracy of the units is vital in making accurate range measurements. The amount of time for a signal to be sent, received and then back between two units is how the range measurement is calculated, and the accuracy of this timing must be precise to produce centimeter-level accuracy range measurements.

The implementation of UWB systems in emergency and natural disaster situations also demands the quick formation of ad-hoc networks. Speedy deployment and setup of a network with sufficient accuracy was also an objective of the experiments. Additionally, another objective of the kinematic collection was to process the data and obtain the highest level of accuracy. A goal of having a positional 2D error of less than
10cm when comparing to the ground truth data was set as a benchmark. By having the accurate CLOS solutions, the evaluation of UWB with no ground truth could then be assessed.

The development of unique and novel algorithmic solutions was also a research objective. The accuracies of the positioning measurements were improved by utilizing various algorithms in calculations. Analysis of static and kinematic data, laboratory and experimental collection, and newly developed processing algorithms, were all research objectives completed by this thesis.
1.3. Methodology

Methods used in this research varied between indoor and outdoor, laboratory and experimental, and static and kinematic collection of data, to complete the various objectives of the research. The numerous experimental collections, paired with differing processing algorithms, allowed for analysis of the UWB system. The system and its capabilities in NLOS experimental settings were compared to the poor GPS data along with the accurate CLOS experiments. This allowed for relative error analysis where ground truth was not as accurate in GPS-compromised kinematic tests. Table 1 shows the main experimental tests, location, and network dimensions.

<table>
<thead>
<tr>
<th>Date</th>
<th>Name</th>
<th>Location</th>
<th>Type</th>
<th>Dimensions</th>
<th>Runs</th>
</tr>
</thead>
<tbody>
<tr>
<td>November 15, 2015</td>
<td>November</td>
<td>west campus parking lot, OSU</td>
<td>kinematic, open sky</td>
<td>30 x 30m</td>
<td>1</td>
</tr>
<tr>
<td>December 2015</td>
<td>laboratory</td>
<td>laboratory in Hitchcock hall, CLOS/NLOS</td>
<td>kinematic, indoor laboratory</td>
<td>15 x 7m</td>
<td>2</td>
</tr>
<tr>
<td>November- Feb 2015</td>
<td>sensor performance validation</td>
<td>laboratory in Hitchcock hall, CLOS/NLOS</td>
<td>static, indoor/outdoor laboratory</td>
<td>15 x 7m</td>
<td>*1</td>
</tr>
<tr>
<td>January 21, 2015</td>
<td>open sky</td>
<td>west campus parking lot, OSU</td>
<td>open sky</td>
<td>30 x 30m</td>
<td>4</td>
</tr>
<tr>
<td>January 22, 2015</td>
<td>GPS-compromised</td>
<td>Wayne National Forest, Athens, OH</td>
<td>kinematic GPS-compromised</td>
<td>30 x 30m*2</td>
<td>6</td>
</tr>
</tbody>
</table>

Table 1. Experimental setup including the date, referenced name, location, type of test, network dimensions and number of processed runs/trajectories.

Note: numerous experiments and processed solutions were accomplished during all the tests.

*1Numerous static experiments were tested for each of the three different tests.

*2Due to environmental constraints, the dimensions are only approximately 30 x 30m and actual measurements shown in chapter 4.
The first testing completed was the validation of the sensors’ performance in an indoor setting with varying NLOS and CLOS setups. This testing allowed for verification and analysis of various static range measurements. The ability of the sensors to handle high multipath environments was also tested. The units gathered ranging data that was compared against measured ground truth. The setups varied with the units, measuring static data through differing materials, such as walls and doors, to test the penetration capability of the signal. CLOS measurements were also conducted with differing setups, including on/above ground and next to walls, to see how the units handled the multipath from being near surfaces. Validation of the units allowed for comparison to the manufacturer’s specifications, and for comparisons of different unit-pairs and setups including antenna ports, broadcasting and receiving setup, and other various settings and measurement types.

Network establishment and setup were first tested during the initial, kinematic, ‘November’, experiment performed. This testing used custom constructed UWB corner mounts at known positions, with one unit placed on a rover cart and collected ranging measurements, which allowed for the localization of the moving unit. The corner mounts were also designed to give a 2m elevation spacing between neighboring units. The spacing was designed to allow analysis of the movement in three dimensions (3D). System parameters, setup, and other variables such as UWB and GPS antenna position, data acquisition and storage, etc were accomplished during this first set of experiments. While not analyzed here, it was essential for quality data to be collected during the subsequent experimental collections by allowing for various problems, which were unforeseeable before experimentation, to be discovered and accounted for.
Open sky kinematic experiments were performed on January 21\textsuperscript{st}, 2015, allowing for highly accurate GPS data acquisition during the collection of calibration and kinematic data. Modeled after the November experiments, it used the same network setup and dimensions, but because of a limiting number of working units, only a 2D solution in the XY plane was possible. The corner station placement was measured with a total station prior to testing to ensure the geometry. Additionally, GPS static data was gathered to tie the local system globally. Several static calibration measurements were recorded throughout the testing square in a grid pattern. This was done to account for any potential multipath or signal degradation throughout the testing area. Numerous kinematic tests were performed within the network of the static units attached to the constructed mounts and the moving unit attached to the top of the SPIN Lab’s truck. The truck was also fitted with two GPS antennas and various Inertial Measurement Units (IMU) so that highly accurate ground truth data could be gathered and used for comparisons. This testing allowed for a baseline comparison of the UWB kinematic calculations in a large-scale environment on a moving vehicle, with highly accurate GPS data.

GPS-compromised kinematic experiments, were performed on January 22\textsuperscript{nd}, 2015, at a hilly, canopy-covered environment; this location was chosen because of the GPS-compromised environment it provided. The network corners were measured by a total station and calibration and kinematic data was gathered similarly to the open air test. The trees and hills provided the NLOS and GPS-compromised environment where UWB systems could enhance PNT measurements that GPS, IMU, and integrated solutions may not be able to handle. Analyzing this data allowed for the UWB system performance in
complex environments. The results demonstrated the advantage of UWB, showing that it could operate where the GPS signal was weak because of the rugged, canopy-covered environment.

After collection of laboratory and experimental data, processing of the measurements allowed for thorough analysis of the system in both static and kinematic situations. The measurements were statistically analyzed and compared with ground truth. The static validating tests showed the signal’s ability to travel through material and in high multipath environments. The configuration of the units was also studied. A review of the error and statistical calculations including root mean square error, standard deviation, etc., helped in deciding the network formation and performance capabilities of each unit and the system.

Using the geometry of the network, the position of the UWB unit can be localized within the grid using circle lateration principles. This localization calculation can then be improved by applying a least squares (LS) error estimation, which allows for finding the optimal linear estimated position based on the multiple range measurements (Küpper 2005). Applying a Kalman Filter may also smooth the data as it takes into account previous position estimations for predicted measurement positions. This means that erroneous measurements from one or multiple units and their impact to the projected trajectory can be limited. Integrating the other types of data with the UWB trajectory can also help to achieve better positioning performance. Using an Extended Kalman Filter with IMU and/or GPS data can potentially supply the most accurate trajectory for comparisons. An additional contribution of this research was the development of a methodology for processing kinematic data. By implementing algorithms and processing
techniques, a low 2D error of less than 10 cm was achieved in mapping the UWB trajectory. This low error is on par with high-quality GPS data, which has centimeter-level error and shows the capabilities and advantageous of the UWB system.
1.3. Overview

This thesis contains six chapters. Chapter 1 gives an overview of the research, backgrounds and motivations, research objectives, methodology for experimentation, processing and analysis. Chapter 2 outlines and explains the systems in use. The background and theory of GPS are discussed, as UWB is an ideal redundant solution to the global system. The principles of UWB and the integration of data using a Kalman filter are also discussed here. Chapter 3 discusses the validation of individual UWB units and focuses on individual range measurements in a laboratory setting, including testing CLOS, NLOS, such as through wall, along with other unit settings. Chapter 4 presents the network setup of multiple units, and the calibration of these units in experimental settings. The theories behind network and trajectory calculations are shown as well as the details of the ground truth collection and analysis. Chapter 5 presents the indoor and outdoor experimental results and analysis, including statistical evaluations. The final chapter completes the thesis with a conclusion of the research. It includes recommendations, future applications, and research that the author believes could also contribute and expand Ultra Wideband’s applications, abilities and knowledge.
Chapter 2: GPS and UWB Theory

Position, navigation, and timing of people and objects have become essential in the way we interact and travel throughout the world. Some of the main tools in completing these measurements are part of the Global Navigation Satellite Systems (GNSS). The NAVSTAR Global Positioning System (GPS) is the American contribution to GNSS and used extensively throughout this research. This global system uses triangulation to determine a unique position on the surface of the Earth. By knowing simultaneously the position of multiple satellites, their measured range from the receiver, and a reference system, the receiver is able to calculate a unique position.

UWB works with the same principles as GPS but on a local scale. By having a network of known units, the position of a static or moving unit can be localized. Both systems use the travel time of radio frequency (RF) waves to measure the distance between emitter and receiver. Both also operate with relatively frequency rates and are able to measure multiple times per second, thereby giving the ability to measure kinematic objects and object velocities with modest dynamics.

While GPS has far out-performed its initially expected uses, number of users, and accuracy, it is still challenged without complete visibility to at least four satellites, such as: indoors, near buildings, under tree canopies, or other confined environments. These areas make UWB a suitable companion for GPS in PNT solutions. Both systems are reviewed and discussed in this chapter.
2.1 Global Positioning System

This section is a short review on GPS and is not intended to cover the whole of one of the most globally used systems. It simply provides an overview in an attempt to show where the system could be assisted. GPS is a satellite-based radio-positioning and time-transfer system designed, financed, deployed, and operated by the United States Department of Defense. The all-weather system is available for use by anyone with a GPS receiver. It is made of three parts: the space segment, the control segment, and the user segment (Grejner-Brzezinska 2013/2014).

The space-based portion of the navigation system has had a total of 68 satellites launched, with 30 still in use. The system was designed with a full constellation of 24 satellites, 21 plus 3 extra satellites, in six orbital planes. They operate approximately 22,000km above earth in near circular orbits and have a period of 12 sidereal hours. The planes have an inclination of approximately 55° and are spaced at 60° intervals along the equator. The configuration and number of satellites was chosen to give visibility to 4 satellites everywhere on earth. A minimum of 4 satellites is needed to find a unique position (Grejner-Brzezinska 2013/2014).

Modeling the Earth is essential to calculate an accurate position from GPS. The Earth is not quite a sphere and is, therefore, modeled with an ellipsoid. This reference surface is realized by control points from a reference frame, creating a whole reference system commonly known as a geodetic datum. There have been many iterations of surfaces, frames, and systems. Some were either nominally created, some are more accurate than others, and some fit a specific region better. GPS uses the World Geodetic System revision 1984, commonly known as WGS84. The control segment is made of a
master control station (MCS), an alternate station, four ground antennas, and six monitoring stations (Jekeli 2013).

This research utilized numerous GPS antennas, receivers, and processing methods to create the most accurate GPS solutions possible. Static data was processed using the National Oceanic and Atmospheric Administration’s (NOAA) Online Positioning User Service (OPUS) software. Kinematic data was processed using the open source RTKLib toolkit created by T. Takasu.

2.1.1 General

GPS position is determined by the intersection of spheres with measured radii, as shown in Figure 2.1. Range measurements give us a distance or a sphere of possible points away from the object. Where these spheres or each range measurement intersect is where the receiver is located. As shown, three measurements can give a position. Note that a fourth measurement is needed to fix for the inaccurate quartz clock of the receiver to give a correct position (Grejner-Brzezinska 2013). GPS receivers can utilize three different types of measurements: pseudorange, carrier phase, and Doppler measurements. The accuracy of the pseudorange measurement can be as low as 20cm when using the P-code or can be as high as a few meters when using the C/A code. Pseudorange and carrier phase will be further discussed as they were utilized in the process and are the more popular measurements in high accuracy civilian applicatio Two Solutions
The pseudorange measurement is simply the geometric measurement of the time it takes the signal to go from the satellite to the receiver. The time between when the signal was sent and received multiplied with the speed of light gives the range. Included in this range is the clock error from the receiver clock, which is partially adjusted with additional satellites but still must be taken into account. Note that the additional error sources entering this range will be discussed later in section 2.1.4.

A carrier phase range measurement looks at the phase of the carrier signal. It is generated by comparing the receiver’s internal oscillator estimate with the satellite’s signal. The period of the carrier frequency is then multiplied by the speed of light to calculate the range of the waveform signal. The fractional carrier phase is the difference between the generated and observed signal. This fractional phase plus an unknown integer constant, known as the integer ambiguity, represents the number of full wavelength between the satellite and receiver, given the phase is observable. This integer is unknown until post processing because the number of cycles between the receiver and satellite cannot be observed, unlike the fractional phase. This ambiguity will be constant as long as the receiver can continuously monitor the satellite. Each loss of signal results in another integer ambiguity that must be fixed (Grejner-Brzezinska 2013).
A carrier phase positioning solution where the integer ambiguity is estimated is called a float solution. This solution is less accurate than a fixed solution and can vary from centimeters to meters but an exact error cannot be calculated. A fixed solution is a solution in which the integer ambiguity is known, can yield accuracies of as little as a few millimeters. A loss of reading or cycle slip may then introduce a new unknown ambiguity back into the calculations. A cycle slip is denoted by a sudden jump in the carrier phase observable. This error can come from multipath, blocking of the signal, receiver malfunction, or other distorting variables that are difficult to account for (Grejner-Brzezinska 2013).

2.1.2 Signal

Each satellite emits two signals: L1 (1575.42 MHz) and L2 (1227.60 MHz) microwave carrier signals. Note that an additional signal is being added with each new satellite, the L5 (1176.45 MHz) microwave carrier signal, so far implemented with two newer satellites. All signals are derived from the L band base frequency (10.23 MHz). Two range pseudorandom noise codes are superimposed on the carrier frequency: the Coarse/Acquisition (C/A) and the Precision (P-code). The C/A code is less precise, available for public use, and historically emitted from the L1 frequency. The new Block IIM satellites and subsequent satellites have begun to use the code on the L2 frequency as well. The P-code is emitted from both frequencies, but it is protected for military use (Grejner-Brzezinska 2013).

While observing a GPS signal, the detected signal can either be stored for post processing or can be calculated in real time, called Real Time Kinematic (RTK). This
investigation utilized the post processing approach for both static and kinematic measurements, using both OPUS and RTKLib processing solutions.

### 2.1.3 Calculations

GPS observables can be expressed with the following equations (Grejner-Brzezinska 2013):

\[ p_{i,1}^k = \rho_{i}^k + \frac{l_1^k}{f_1^2} + T_{i}^k + c(d t_i - d t^k) + b_{i,2} + M_{i,1}^k + e_{i,1}^k \]  

\[ p_{i,2}^k = \rho_{i}^k + \frac{l_2^k}{f_2^2} + T_{i}^k + c(d t_i - d t^k) + b_{i,3} + M_{i,1}^k + e_{i,2}^k \]  

\[ \phi_{i,1}^k = \rho_{i}^k + \frac{l_1^k}{f_1^2} + T_{i}^k + \lambda_1 N_{i,1}^k + c(d t_i - d t^k) + \lambda_1(\phi_{0,1}^k - \phi_{i,0,1}) + m_{i,1}^k + e_{i,1}^k \]  

\[ \phi_{i,2}^k = \rho_{i}^k + \frac{l_2^k}{f_2^2} + T_{i}^k + \lambda_2 N_{i,2}^k + c(d t_i - d t^k) + b_{i,1} + \lambda_2(\phi_{0,2}^k - \phi_{i,0,2}) + m_{i,2}^k + e_{i,2}^k \]  

\[ \rho_{i}^k = \left( (X_i^k - X_i)^2 + (Y_i^k - Y_i)^2 + (Z_i^k - Z_i)^2 \right)^{\frac{3}{2}} \]

where

- \( X_i, Y_i, Z_i \) - primary unknowns, the coordinates of the user (receiver)
- 1,2 - stand for frequency on L1 and L2, respectively
- \( i \) – denotes the receiver
- \( k \) - denotes the satellite
- \( p_{i,1}^k, p_{i,2}^k \) - pseudorange measurements between receiver \( i \) and satellite \( k \) for the L1 and L2
- \( \phi_{i,1}^k, \phi_{i,2}^k \) - carrier phase measurements between receiver \( i \) and satellite \( k \) for the L1 and L2
- \( \phi_{0,1}^k, \phi_{0,2}^k \) - initial fractional phases at the satellite \( k \) on the L1 and L2 frequencies, respectively
- \( N_{i,1}^k, N_{i,2}^k \) - integer ambiguities associated with the L1 and L2 carrier phase measurements
- \( \lambda_1, \lambda_2 \) - the wavelengths of the L1 and L2 phases. \( \lambda_1 \approx 19\ cm, \lambda_2 \approx 24\ cm \)
\( \rho_i^k \) - geometric distance between receiver i and satellite k.

\( \frac{t_i^k}{f_1^2}, \frac{t_i^k}{f_2^2} \) - ionosphere refraction on L1 and L2 frequencies.

\( T_i^k \) - tropospheric delay between receiver i and satellite k

\( dt_t \) - receiver clock errors

\( dt^k \) - k-th transmitter (satellite) clock error

\( f_1, f_2 \) - carrier frequencies

\( c \) - speed of light in vacuum

\( e_{i,1}^k, e_{i,2}^k, e_{i,1}^k, e_{i,2}^k \) - measurement noise for pseudoranges and carrier phase ranges

\( M_{i,1}^k, M_{i,2}^k, m_{i,1}^k, m_{i,2}^k \) - multipath error for pseudoranges and carrier phase ranges

\( b_{i,1} \) - interchannel bias between \( \phi_{i,1}^k \) and \( \phi_{i,2}^k \)

\( b_{i,2}, b_{i,3} \) - interchannel biases between \( \phi_{i,1}^k \) and \( P_{i,1}^k \), and \( \phi_{i,1}^k \) and \( P_{i,2}^k \)

These equations are not linear and must be linearized requiring a technique such as Taylor series expansion. Since normally there are more observations than unknowns, there is redundancy in the system, which can then be solved by the LS estimation technique or other estimation methods.

2.1.4 Error Source

The accuracy of GPS is anywhere from tens of meters to better then 1 cm if errors are mitigated, depending on design of the GPS receiver and the measurement techniques used (Grejner-Brzezinska 2013). Even with an open sky, there are many error sources that must be corrected in the GPS measurements: receiver bias, receiver clock, antenna phase center, satellite clock, atmospheric errors from the ionosphere and troposphere, and
multipath. Receiver bias is error inherent to the receiver; it is different between receivers and can even be different with the same receiver and different antennas. The low-grade quartz receiver clock is also a prime source of error, one that even the additional satellite measurements cannot fully correct. The antenna phase center is disturbed by variations at the point where the signal is measured. The satellite clock, while an extremely accurate atomic clock, must also be adjusted for. Atmospheric errors occur from the signal travelling through and around atmospheric particles such as water vapor, enlarging the range measurements. The ionosphere represents some of the more significant error sources but the troposphere contributes as well. Both must be corrected for. Multipath errors are the last source of errors and are caused by the signal reflecting off the surrounding environment, such as trees, buildings, and ground surfaces, resulting in multiple signals arriving to the antenna not directly from the satellite (Grejner-Brzezinska 2013/2014).

Mitigation of these errors must occur for an accurate GPS position to be calculated. Some of these errors can be removed and/or mitigated with posteriori information and modeling, while others are more difficult to account for. More uniform errors, meaning errors that are constant throughout the system for every GPS measurement (such as atmospheric errors), allow for better modeling mitigation techniques. Local or site-specific errors, such as multipath and antenna center, in contrast, must be adjusted and calibrated for by the user.

Precise orbit files, which contain the actual observed orbit, can help fix satellite clock error. The ionosphere can be corrected with a linear combination of the L1 and L2
signals and the smaller troposphere error can be modeled with known values. Table 2.1 shows typical error ranges associated with the different error types.

<table>
<thead>
<tr>
<th>Summary of GPS error sources (m)</th>
<th>No SA</th>
<th>SA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Satellite clocks</td>
<td>2</td>
<td>20</td>
</tr>
<tr>
<td>Orbit errors</td>
<td>2.1</td>
<td>20</td>
</tr>
<tr>
<td>Ionosphere</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Troposphere (model)</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Receiver noise</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Multipath</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

**Table 2.1 Typical error sources for GPS (Grejner-Brzezinska 2013).**

The main technique used to eliminate errors, and the one used by this study, is differential GPS (DGPS): Figure 2.2. Use of two readings by different GPS receivers at the same time allows for error reduction and/or elimination in clock errors, atmospheric errors, and noise.

**Figure 2.2 DGPS concept (Grejner-Brzezinska 2013)**

In DGPS, the only error sources not accounted for are site-specific, such as multipath and lack of sight to enough satellites. Multipath errors tend to be random yet can be mitigated with proper antenna location and use of choke ring antennas. When the weak GPS signal is blocked, there are no techniques during collection or post-processing
to get measurements. The only solution is to move until an open sky can be seen, which can be difficult in rural wooded areas and densely populated areas with buildings. This research focuses on kinematic collection in areas of high multipath and NLOS, where even with multiple high quality receivers, accuracies are still poor.
2.2 Ultra Wideband

Ultra Wideband sensors can measure ranges and communicate a variety of data with a short duration, pulsed RF signal. This signal should have the highest bandwidth while also keeping the average or center frequency as small as possible. UWB systems achieve this bandwidth by transmitting an impulse-like waveform. Such waveforms are inherently broadband. Fourier analysis shows that an ideal impulse, a signal of a given amplitude with an infinitesimally short duration, a Dirac delta, would provide infinite bandwidth (Emami 2013). While this is difficult to achieve and, in fact, not necessary, UWB signals employ this theory. As a result, transmissions are quite unlike traditional RF modulated sine waves. Instead they resemble a train of pulses. An example of an individual UWB pulse in both time and frequency domains is shown in Figure 2.3.

![Figure 2.3 UWB waveform in time domain (at left) and frequency domain (at right) (Time Domain 2015).](image)

By generating radio energy or pulses at a specific time, UWB has the ability to modulate the signal’s amplitude and, therefore, determine “time of flight,” which can then give ranging information between receiver and transmitter. The typical UWB measurement starts with the transmitter emitting a low energy, high bandwidth short pulse. This signal ‘interacts with’/’travels through’ the environment, and then the receiver detects it. Next, the process is repeated back to the transmitting unit. The CLOS
or direct signal reaches the receiver first, as it takes the shortest route between the two, while the other signals reflect off surfaces, and travel more, reaching the receiver later. Since the signal is pulsed and short, these overlapped signals are more easily distinguishable, unlike conventional RF signals. This property makes the signal more resistant to multipath and is shown in Figure 2.4.

![Figure 2.4 UWB pulsed signal vs. conventional RF signals (Time Domain 2015)](image)

UWB has numerous advantages when compared to the more common conventional/narrow band signals used in existing positioning estimators, such as WiFi. UWB signals are transmitted in non-sinusoidal carrier waves, while traditional systems differentiate signals by varying power level, frequency, or phase. UWB signals are more resistant to jamming, multipath, and loss of signal strength when traveling through walls and other objects because of this property (Opshaug 2007). The ease of delineation of pulsed signals make it easier to receive UWB signals and more resistant to multipath. These quick and resilient signals also make UWB ideal for applications where numerous ranging signals between multiple units are needed, like PNT problems.
Research into UWB technology, like many other modern day technologies, started as a result of the Cold War. In the 1940s and 1950s research work began on impulse radio and carrier-free or non-sinusoidal transceivers in an effort to improve radar. In both the US and USSR, advancements were made concurrently. Some of the first US contributors were Henning F. Harmuth, Gerald F. Ross, and others (Emami 2013).

In 2002, FCC regulations were changed to open the technology to the public. As a result, research and application advancements began. The FCC defined the UWB signal between 3.6 and 10.6 GHz bandwidth, with either 10dB bandwidth of the signal larger than 500 MHz, or its fraction bandwidth as at least 0.2. The fractional bandwidth being calculated by:

\[ B_f = \frac{2(f_H - f_L)}{(f_H + f_L)} \]

where
\( f_H, f_L \) - upper and lower 10 dB frequency of the power spectrum

The center frequency is calculated by

\[ Center \ Frequency = \frac{(f_L + f_H)}{2} \]

UWB is an ideal signal for a large channel capacity under the Shannon-Harley Theorem (Emami 2013). Which states that the channel capacity is proportional to the bandwidth multiplied with the log of the signal to noise ratio (SNR)

\[ C = B \ast \log_2 \left( 1 + \frac{S}{N} \right) \]

where
\( C \) - channel capacity, bits/s
\( B \) - bandwidth, Hz
$S$ -signal, W
$N$ -noise, W

With increasing bandwidth and power, the UWB signal is able to transmit a larger capacity and therefore more information very quickly. As the pulse is shortened the bandwidth increases. The relationship is linear between capacity and bandwidth, and logarithmic between capacity and SNR, growing much slower than the linear relationship. Lower SNR requires signal averaging which lowers the signal/symbol rate.

The FCC approved the bandwidth at low power outputs, and we now have commercial UWB products available for purchase today, such as Time Domain’s PulsON 410© units, used in this investigation.

### 2.2.1 Time Domain’s PulsOn 410

This research utilized a set of Time Domain PulsOn 410 UWB sensors: Figure 2.

5. Time Domain UWB systems rely on low duty cycle transmissions with coherent signal processing and typical repetition rates of 10 MHz. These UWB transmissions normally consist of a packet of between several thousand and a few hundred thousand coherently transmitted pulses. Because the transmissions are coherent, the signal energy can be spread over multiple pulses, thereby increasing the energy per bit and, consequently, SNR (Time Domain 2015).
Independent communication channels are established by pseudo-randomly encoding the phase, position, and/or repetition rate of the pulse train. Data can be added to the transmissions by further modulating either the phase and/or position of the pulses. The pseudo-random code and data are typically applied not to individual pulses but to blocks of many pulses. This approach has been implemented in the PulsON Ranging and Communications Module (RCM) (Time Domain 2015).

The P410 units transmit and receive UWB pulses. The pulses are transmitted between 3 and 5 GHz, have an RF bandwidth of 1.4 GHz, and a repetition rate of 10 MHz. Since these pulses are coherent, multiple pulses can be integrated to increase the signal, thus lowering SNR by 3 dB each time the integration rate is doubled (Time Domain 2015).

The range of the sensors is 30-60 m indoor and up to 354 m outdoor, with a pulse being able to transmit through walls. The accuracy for a CLOS is characterized by a bias of 2.1 cm with a standard deviation (1σ) of 2.3 cm. With NLOS, the bias cannot be estimated, as the attenuation of the signal varies through material but, in general, the standard deviation is 10 cm (Time Domain 2015).
2.2.2 Localization

Using multiple UWB units, the position of a single unit can be calculated. Once the ranges of at least three known stationary units are known in a network environment, the position w.r.t the network can be determined via circular lateration. The range measurements with their error terms can form a non-linear equation system. By linearizing the problem and using the estimates from the initial range measurements, a solution can be determined using the LS adjustment method (Küpper 2005, Koppanyi 2014).

2.2.3 Signal Mode

The supported solutions and applications created by the PulsON sensors can be divided into three groups: RCM, Monostatic Radar Module (MRM), and Channel Analysis Tool (CAT). For this research, only the RCM was used, which supports three different ranging solutions:

1. Two-way time-of-arrival (TW-ToA), termed Precision Range Measurement (PRM).
2. The received signal strength-based (RSS), providing Coarse Range Estimation (CRE).
3. The Kalman filtering-based solution, termed Filtered Range measurement (FRE).

The units also provide the estimated errors of these measurements.

The ranging model uses TW-ToF distance measurement; a packet of waves is sent from one UWB platform (the requester) to a second unit (the responder). The responder
then sends back a timed response. By knowing the speed of light, when the response of packet was requested, when it was received by the responder, when the response packet was sent back, and when the requester received it, it is possible to measure the range/distance between the two platforms. This TW-ToF is described in Eq. 2.9.

$$\hat{r}_{\text{prm}} = \frac{c}{2} (\tau_{rx}^{(1)} - \tau_{tx}^{(1)} - \tau_{\text{delay}})$$  

2.9

where

\( \hat{r}_{\text{prm}} \) - precision range measurement

\( \tau_{\text{delay}} \) - response time delay

\( \tau_{rx}^{(1)} \) - Time of Arrival (TOA) of the response reception measured by the requester node

\( \tau_{tx}^{(1)} \) - TOA of the request transmission measured using the clock of the responder node

\( c \) - speed of light in meter/second.

The strength of the signal or CRE allows for improvement of the PRM measurement by detecting signals from error sources like multipath, NLOS, and saturation situations. This is done by finding the earliest pulse component in the waveform, so no multipath signals are measured and the absolute maximum amplitude, \( A_{dp} \), in the direct path window is computed, Eq. 2.10.

$$A_{dp}(t) = \max(\text{abs}(w_{dp}))$$  

2.10

\( A_{dp} \) - absolute maximum amplitude of received signals

\( w_{dp} \) - received signal velocity

With each PRM of a neighboring node, \( j \), this node resets its calibration factor, \( K_0 \), by the multiple of PRM and \( A_{dp} \).

$$K_0^{(j)} = \hat{r}_{\text{prm}}(t_0)A_{dp}^{(j)}(t_0)$$  

2.11
$K_0^{(j)}$ -calibration factor

When also including the packets from other nodes, a separate range conversation is included to improve the measurement.

$$\hat{r}^{(j)}(t_k) = K_0^{(j)} / A_{dp}(t_k)$$  \hspace{1cm} 2.12

$\hat{r}_{cre}^{(j)}$ -new range measurement based on the amplitude

The FRE is the combination of both the PRM and CRE using a Kalman formulation with two state variables representing radial distance and velocity.

$$x_k = Fx_{k-1} + G\alpha$$  \hspace{1cm} 2.13

$$x_k = \begin{bmatrix} r_k \\ \dot{r}_k \end{bmatrix}, F = \begin{bmatrix} 1 & T \\ 0 & 1 \end{bmatrix}, G = \begin{bmatrix} T^2/2 \\ T \end{bmatrix}$$  \hspace{1cm} 2.14

$T$ -time between updates

$\alpha$ -acceleration term, is modeled as process noise.

$\sigma_{prm}$ -PRM noise term, which is derived with each PRM from the ring-up time of the scan.

$\sigma_{cre}$ -CRE noise term, which is determined empirically as a function of distance.

$r_k, \dot{r}_k$ -range measurements and calculated radial velocity

$F$ -state matrix update

$G$ -observation update

The diagonal elements of the covariance matrix, 2.15, provide an uncertainty metric of the range and radial velocities.

$$P_k = \begin{bmatrix} \text{var}(r_k) & \text{cov}(r_k, \dot{r}_k) \\ \text{cov}(r_k, \dot{r}_k) & \text{var}(\dot{r}_k) \end{bmatrix}$$  \hspace{1cm} 2.15

$P_k$ -covariance matrix of range measurements.
2.3 Kalman Filter

Filtering measurements from various collections methods allow for the integrations of measurements to help obtain a more accurate outcome. This can be seen in the traditional integration of the IMU and GPS measurements (as discussed later in section 2.3.2) but can also be implemented as a smoothing operator within one type of measurement. The filter used in this research was the Kalman Filter (KF), based on R.E Kalman’s famous paper published in 1960 (Kalman 1960).

The Kalman filter technique is able to optimally integrate accurate and inaccurate measurements while removing noise to provide an accurate and reliable solution for signals with Gaussian distributions. It uses a form of feedback control where previous measurements are compared with current and future measurements and, depending on settings and weighting, the most accurate measurement can be computed despite accuracy and precision deficits of the measurement data. This is accomplished by using a series of measurements over time, finding a posteriori estimate, which takes into account the previous measurements and is then generally more accurate than a single measurement. The algorithm is a two-step process, the time update (predicted/state) and measurement update (corrected/observation) equations/steps. The linear combination of the estimated position from previous measurements or state equation, with the predicted position from observation equations and statistics of the measurements, are used recursively to find an accurate solution. EKF, the extended version of KF, has been long used in navigation, as in many respects, it is ideal for PNT problems (Kalman 1960, Welch 2015).

The state equation is governed by the linear stochastic difference equation of the state estimate $x \in \mathbb{R}^n$ of a discrete-time controlled process. The algorithm of the discrete
Kalman filter is governed by the time update and filter measured equations listed below.

The time update or state equations are denoted by

\[
\begin{align*}
x_k &= \text{Ax}_{k-1} \\
P_k^- &= AP_{k-1}A^T + Q
\end{align*}
\]

where

\(x_k\) -the state vector, with previous epochs denoted by \(k - 1\)

\(A\) -nxn matrix relating the previous time step to the current

\(B\) -nx1 vector relating the input to the state

\(P_k^-, P_{k-1}\) -priori and posteriori covariance matrices

\(Q\) -cofactor matrix

The filter measurement update equations are:

\[
\begin{align*}
K_k &= P_k^-H^T(HP_k^-H^T + R)^{-1} \\
&= \frac{P_k^-H^T}{HP_k^-H^T + R} \\
\hat{x}_k &= \hat{x}_k^- + K(z_k - H\hat{x}_k^-) \\
P_k &= (1 - K_k H)P_k^-
\end{align*}
\]

where

\(K\) -nxm matrix, known as the Kalman gain factor

\((z_k - H\hat{x}_k^-)\) -is the residual

\(R\) -error covariance

\(H\) -the observation matrix

\(P\) -covariance matrix
With a measurement \( z \in \mathbb{R}^n \)

\[
z_k = H x_k + v_k
\]  

Equation 2.22

\( H \)-mxn matrix relates the state estimate to the measurement

\( v_k \)-measurement noise vector with Gaussian, zero mean noise

By changing the weighting of \( K \), we are able to influence the estimate’s ‘trust’ of either the state or predicted measurements (Welch 2015). In other words, we can rely on the state equation if the measurements are poor or vice versa if the state predictors are reliable. This filter is well suited for PNT problems, specifically for UWB integration in GPS-compromised environments. This is because with appropriate weight settings and measurement statistics, it can accurately integrate both measurements. When one becomes unreliable, as is prevalent in the environment, it can then be filtered out.

### 2.3.1 Discrete Kalman Filter for UWB

The Discrete Kalman Filter was first applied to UWB data to smooth the position estimates and get rid of outliers. These outliers were increased when the kinematic/rover unit was stationary because additional measurements, including multipath signals, were measured at that position. During kinematic movements these additional measurements were unable to be recorded and the weight of the predicted observations was able to handle outliers between varying positions. By deriving the velocity from the position data, the problem was able to be established and developed for the KF. This filter is described in the remaining paragraph and in the flowchart in Figure 2.6. The initial position and velocity estimates were obtained either from GPS or total station measurement and implemented in Eq. 2.16. These estimates were then inserted in the
predicted state equation, Eq. 2.17. The measurement noise covariance was then used with the statistics of the position estimation from the LS of the circular lateration equation. The process noise was set as the accuracy of the UWB units given from the manufacturer. With these two covariance matrices, the covariance of the state equations could be computed. The Kalman gain was then calculated, Eq. 2.18. The state update, Eq. 2.20, could then calculate the posterior measurement and the updated covariance matrix is finally calculated, Eq. 2.21 (Welch 2015). With these update estimates, the process could cycle through again with a new measurement. The accuracy of this filter is discussed in Chapter 5.

**Figure 2.6: Kalman Filter flowchart.**

### 2.3.2 GPS/IMU Integration

The basis for the Kalman filter integration for UWB and IMU data was modeled off of the Kalman filter integration of the GPS/IMU solution (Grejner-Brzezinska 1998). This integration uses GPS observations to fix for the inherent errors in the high data rate...
of the IMU measurements. This integration can be implemented loosely or tightly, depending on algorithm utilized. The autonomously operating IMU can gather data regardless of GPS availability. The GPS measurements do not accumulate errors. To some extent, UWB has similarity to both characteristics, as it has no drift and provides continuous solution. Both sensors share qualities and disadvantages with UWB, making the integration of the data together useful in various scenarios.

IMUs collect data at a high rate, recording acceleration and gyroscopic measurements in all axes. These independent units do not require infrastructure but, depending on their grade, may have large amounts of error and drift, which grow over time. IMU measurement errors include deterministic and stochastic errors. Deterministic errors are systemic, predictable, and usually fixed by the manufacturer, yet still must be monitored as they are environment dependent and typically include scale factor errors, misalignments, biases, etc. Stochastic errors are random, harder to fix, and include: correlated noise/bias, random drifts and quantization noise.

2.3.3 UWB/GPS and UWB/IMU Integrations

UWB can be seen as the intermediary sensor between GPS and IMU, as it has advantages and disadvantages from both. The global infrastructure of GPS is not needed but a local setup still is, making UWB only partially autonomous. It can operate through walls, under canopy, and indoors. It is also reasonably resistant to multipath and other environmental factors. The measurements do not drift or accumulate errors and, with correct initial setup, can have long-term accuracy. The data rate is comparable to GPS for making network measurements, which require multiple ranging measurements. UWB
has the ability to create accurate PNT solutions in scenarios where GPS is limited, and by integrating it, the most complete and accurate solution can be produced.

Similarly to the conventional GPS/IMU solution, UWB can be integrated with both GPS and IMU data. Both integrations have their own advantages and disadvantages due to the characteristics of the sensors, with a triple integration of all three, providing the most complete solution. Since this investigation targets GPS-compromised environments, only UWB/IMU solution was reasonable to compute. UWB observations can be as accurate as ‘good quality GPS’ and act in a similar manner, giving a good fix for the IMU data to achieve a low drift. The UWB/IMU solution provides good local data and can operate in areas where GPS cannot. Since these areas usually have high multipath, where even UWB signals can be disruptive, the IMU measurements still allow for bridging the gaps in UWB data and create a smooth solution. Areas with dense canopy can block signals temporally where the NLOS areas behind branches and trunks are not accounted for from all network nodes. Yet, UWB is able to quickly regain measurements when moved out of these sparse locations if the network geometry is good. This advantage means that the autonomous IMU measurements only operate for a short time and therefore limit the error accumulation.

The UWB/GPS solution would allow for a solution in a local or global coordinate system and can be tied together. This integration can be a good solution in applications where GPS availability is in a transition zone, like going from outside to inside a building. Both, UWB/IMU and UWB/GPS, integrations have their advantages and disadvantages, and with integration of all three into a UWB/IMU/GPS solution, the most accurate solution can be obtained. This combined solution will allow for the advantages
of all sensors to be utilized, limiting the disadvantages and making the highest accuracy, most complete solution.
Chapter 3: Sensor Performance Validation

By validating sensor performance, the specifications given by the manufacturer can be confirmed, along with determining the practically available highest accuracy of the UWB ranging measurements under various scenarios. Tests were performed in a variety of situations, including both CLOS and NLOS. The ranges between the units, environmental conditions, materials of travel-through, and height setup were all varied to analyze the performance potential of possible real life situations and to help when forming networks.

Collecting and analyzing static measurements allowed for the assessment of the precision of range measurements. The range measurement is the capability of the transmitting unit to send a signal, have it recognized and processed by a receiving unit, and then for the this to be repeated back to the original transmitting unit. Since these actions are unit pair-specific, the units were swapped to help give guidance in later network testing. This allowed the best rover unit to be selected and the best measurement units to be placed at crucial geometric positions.

This chapter discusses the sensor performance validation, including supporting analysis, experimental setups and results of numerous experiments. By looking at experimental data, the success rates of successfully completed measurements verse attempted measurement and accuracies of the PulsON 410 pairwise UWB units can be compared to each other and the manufacturer’s specifications, listed below in Table 3.1.
This chapter also discusses timing calibration and synchronization. Both individual unit and joint calibration theories are introduced, along with time synchronization of the units with PC and GPS time. The final part of the chapter discusses estimation methods used in determining the correct static range measurement.
3.1 Methods and Concept

By analyzing the statistics and histogram plots of multiple static UWB range measurements, the accuracy of the range measurements can be assessed. For example, by taking 500 to 10,000 measurements at a time, the statistics of the collected ranges can be compared to each other and to the ground truth. To analyze the ranging performance, varying CLOS and NLOS setups were tested, including:

- **Test A**: Through wall penetration through hard materials, including a door, tree, brick, drywall, and cinder walls.
- **Test B**: Long range measurement outdoors.
- **Test C**: Long and short range measurements indoor, on and above ground, various unit configuration.

As discussed in Chapter 2, the PulsOn 410 units provide three different ranging measurements: PRM, CRE, and FRE. PRM and FRE are analyzed in the through wall tests, and CRE is not. This is because the signal strength, which generates the CRE measurement, does not work correctly when penetrating materials (Time Domain 2015). The resulting measurements are simply PRM measurements and are not adjusted because the direct signal amplitude is not available. The Kalman based filter FRE measurement was also analyzed to see if it can yield better solutions in the experimental setups.

To receive accurate results, different pairs of units and setups were analyzed. During testing, it was discovered that some pairs measured differently and had noticeably varying errors. Besides the usual variations in manufactured systems, it is likely that the units may have lost calibration and accuracy through use, transportation, setup and/or storage. Error can be attributed to one or both units, and it is difficult to accurately
attribute to a specific unit. Testing revealed poor performance both by individual UWB units and UWB pairs. In addition, variables of the setup may affect range measurements. This information can be used to help with network setup, using the optimal setup under given conditions. Putting the best nodes in essential network geometry positions and using the best unit for collection can help ensure the best data collection in kinematic use.

Discarding the poor pairs, there was still a lot of variation within measurements, which is attributable to multipath and environmental noise. Noise in the indoor environment included other high frequency emitters, such as WiFi, radios and other electrical components that omit a signal. Environmental noise is so common that even a component within the UWB unit, the analog digital converter, emits noise (Time Domain 2015). There is no filter to mitigate the environmental noise and the only preventative step to lower noise is by placing units and the signal paths away from emitters.

3.1.1 Interpretation

For data interpretation, a combination of relative and absolute histograms was created. The relative histogram allowed for adjustable frequencies/bin sizes so that the data could be displayed in a normal distribution. The absolute frequency is normalized by the total number of measurements and allows for the calculation of the probability density function, which describes the relative likelihood of a given measurement. This then allowed for the peak empirical probability density function (EPDF) to be plotted; that is, the most likely measurement given a normal distribution with regard to the bin size. The ground truth, calculated mean, the EPDF, and the EDPF’s peak, are displayed to help interpret the data.
Statistical evaluations used in the analysis of the data include the root mean squared error (RMSE), the standard deviation (STD), the variance (VAR) and the mean and max difference from ground truth. The RMSE describes the difference between the estimated range values and the ground truth. This is done by looking at the square root of the sum of the squared residuals. The STD measures the variation of the data. The variance is included to show the tendency of the ranging data to over or underestimate values compared to the ground truth measurements. Assuming that the true value should be close to the mean, large outliers were removed to allow for ease of interpretation and calculation. Depending on the data a certain portion of the measurements were deemed outliers due to multipath and other interference and were removed. For the through wall tests this was 40% and CLOS was set at 10%. The figures and tables are displayed in section 3.1.3.

### 3.1.2 Experimental Tests

Test A measured the penetration of the signal through three different walls, a solid door, and a tree, at short range. Table 3.2 shows the outcomes through various materials and each material’s ground truth.

<table>
<thead>
<tr>
<th>&quot;Through wall&quot; material</th>
<th>Thickness (m)</th>
<th>Ground truth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cinder block wall</td>
<td>0.87</td>
<td>1.78</td>
</tr>
<tr>
<td>Bick and composite material wall</td>
<td>0.24</td>
<td>1.28</td>
</tr>
<tr>
<td>Standard drywall</td>
<td>0.15</td>
<td>2.00</td>
</tr>
<tr>
<td>Solid wood door-closed</td>
<td>0.05</td>
<td>2.44</td>
</tr>
<tr>
<td>Solid wood door-open</td>
<td>0 (used for calibration)</td>
<td>2.44</td>
</tr>
<tr>
<td>Artificial tree</td>
<td>0.05 branch thickness, 0.6 circumference</td>
<td>3.10</td>
</tr>
</tbody>
</table>

*Table 3.2 Test A, wall type, thickness and ground truth distance (m).*
Test A allowed for analysis of the through wall penetration capability of the signal through multiple materials. These results were compared with the manufacturer’s specifications listed in Table 3.1. The bias for each material was also compared. Penetration of the signal was tested but since the test was indoors, the effect of multipath from numerous surfaces and noise from the electrical components in the vicinity was also measured.

Test B investigated the long range CLOS measurements in an outdoor environment. This lower multipath environment allowed for analysis of the strength of the signal at 10m intervals between 10m and 100m by measuring the success rate and the accuracy associated with each distance.

Test C acquired long range CLOS measurements in an indoor environment. This test allowed for the analysis of multipath and noise in an indoor environment. Both on and above ground unit setups were tested to determine if the signal had trouble near surfaces. The tests are shown in Figure 3.1.
Figure 3. 1 CLOS outdoor environment(i) NLOS through tree(ii) NLOS through cinder block wall
(iii) NLOS through dry wall(iv) CLOS indoor environment(v)
3.2 Results

The results from Tests A, B, and C show the various signal anomalies observed in the experiment data. Test A demonstrates that material type and thickness affect the signal’s penetration ability. Test B demonstrates that signal strength decreases over longer ranges. Test C demonstrates that the placement of the unit affects signal quality and that on floor/ground units are subject to more multipath than units above ground. The additional indoor testing shows that antenna and unit settings make little difference on the accuracy of the measurements. When correcting with calibration measurements, the unit pairs don’t really matter, as all give low variations in CLOS low multipath situations. The remainder of this subsection discusses the analysis of the results.

3.2.1 Test A: NLOS (Through wall)

As expected and displayed in Figure 3.2, the through wall path introduced large biases as the signal was attenuated traveling through the material. For the cinder block wall, measurements suffered an extremely large bias of over 100% of the ground truth. However, the measurements displayed little influence from multipath, and this resulted in small measurement variations. The large bias can be negated with calibration and since there is very settle variation in the results, this is evidence that the measurements are dependable/repeatable. The resulting Mean and EPDF max peak had about the same offset from ground truth, around 30cm, because of the limited variation. Both sets of measurements, PRM and FRE, were similar.
Figure 3. 2 PRM measurements (i) and FRE measurements (ii) histograms for the through cinder block wall (0.87m thickness) static collection, ground truth at 1.78m.

For the brick wall, variation in the measurements was noted, as well as an increase in bias, shown in Figure 3. 3. The variation in measurements can be attributed to many variables, including the differing materials, the path of signal travel, thinner thickness of material, geometry of the walls, etc. The FRE measurement also displays two distinct large peaks, while the PRM measurements displayed more of a normal distribution. In the FRE graph, the first peak seems to be the EKF estimating a correction of the measurements causing a more accurate EPDF peak. The second peak displays the opposite influence from the EKF and the bias is increased. Together, both peaks in the FRE graph result in a larger bias but more correct peak EPDF than seen in the PRM graph.
Figure 3. 3 PRM measurement (i) and FRE measurement (ii) histograms for the through brick wall (0.24m thick) static collection, ground truth of 1.28m.

The drywall test showed lower variation and bias, attributed to the material’s thinner width and lower density of the material; Figure 3. 4. For indoor through wall applications, drywall yields the most successfully completed measurements and the lowest error as expected from the lower signal attenuation.

Figure 3. 4 PRM measurement (i) and FRE measurement (ii) histograms for the through dry wall (0.24m thick) static collection, ground truth of 1.28m.

The through door measurements displayed a negative bias. The attenuation of the signal was low enough that it was not offset by the intrinsic/calibration bias of the two
units; Figure 3.5. The closed door measurements display similar tendencies that are shown in the open door graphs, with a slightly higher bias.

Figure 3.5 PRM measurement (i,iii) and FRE measurement (ii,iv) histograms for the through door static collection, ground truth of 2.44m (closed door (i,ii) and open door (iii,iv)).

Unlike the brick wall measurement, the FRE measurement for the drywall test, displayed more of a normal distribution, and the PRM measurements have multiple peaks. This is expected, as the later FRE measurements should be corrected with previous measurements, and resulted in the averaging of the later measurements. The PRM records both direct and multipath measurements with no correction, so multiple peaks can occur. The multipath could result from through door measurements or possibly going under the door.
This negative delay is also apparent in the same setup with the open door. With this setup, a simple calibration of the unit can occur, with the first peak measurement corrected to match the ground truth. Since with CLOS, the shortest measurement is the direct path. Still in the open door setup, multipath influences the measurement and three distinct peaks are apparent in the PRM measurements. The FRE measurements display a more normal distribution of measurements, with the mean and peak EPDF similar to the closed door outcome.

The bias is smaller for the thinner walls and door, displaying less attenuation of signal. This is consistent with observations of wall thickness (Time Domain 2015). Material type also displays an effect, as the drywall and door display very little bias.

The through tree tests display small bias and variation because of the relative lack of branches for the signal to travel through and around: Figure 3. 6. A similar tree setup was also tested during the laboratory calibration and kinematic trajectories discussed in Chapters 4 and 5.
iii) iv) Figure 3. 6 PRM measurement (i) and FRE measurement (ii) histograms for the through tree static collection, ground truth 3.1m.
3.2.2 Test B: CLOS (Outdoor Environment)

Outdoor testing allowed for testing of the strength of the unobstructed signal. By testing static measurements approximately every 10m up to 100m, the strength of the signal and accuracy of the ranging measurement as a function of the range was accomplished.

By comparing the shortest and longest range measurements, bias and variation were shown to increase with distance; Figure 3.7. Analysis of the CRE measurement shows that it is still the same as the PRM, meaning no adjustment was made due to strength of the signal.
Figure 3. 7 CRE/PRM measurements (i,iii) and FRE measurements (ii,iv) histograms for the CLOS outdoor environment static collection, ground truth of 7.8m (i,ii) and ground truth of 98.6m (iii,iv).

The number of readings for the static test had to be kept low due to constant interruptions from pedestrians walking through the area: only 500 static ranges were taken. The decreasing measurement success rates are displayed in Figure 3. 8. A trend line was added to help give an estimate of reading success with increasing distance. The success rate of measurements is still high but the RMSE of the measurements does increase, as shown in the neighboring graph.
3.2.3 Test C: CLOS (Indoor Environment)

Similar to the outdoor tests, the shorter range measurements were computed more often, despite multipath. The accuracy of the indoor measurements was similar for both shorter and longer ranges. The antenna used did not make a significant impact on the measurement; however, location on or above ground did. PRM and CRE measurements were almost the same and more accurate than the FRE measurement, which increased the mean and variation. The location of the units on the floor increased the error because of multipath reflection from the close surface; Figure 3. 9.
The long range indoor measurements displayed larger errors and fewer complete measurements. This is likely due to the combination of noise and multipath. The placement of the units caused a particularly interesting effect; the floor units were actually incredibly accurate with extremely low bias and variation. This could be due to the perfect placement and amplification of the signal or, more likely, poorly measured ground truth; Figure 3.10.
Table 3. 3 shows the patterns discussed in the figure analysis. The ground truth was measured with a combination of a total station and measurement tape. The outdoor tests were measured and marked with a total station, giving the ground truth an error of 2 cm. The indoor tests were done with a measuring tape, giving a slightly larger error range of 5 cm. Room geometry affected through wall ground truth, so an error budget of 10 to 20 cm was applied.
<table>
<thead>
<tr>
<th>Test</th>
<th>Ground truth (cm)</th>
<th>RMSE PRM (cm)</th>
<th>RMSE FRE (cm)</th>
<th>STD PRM (cm)</th>
<th>STD FRE (cm)</th>
<th>Mean PRM (cm)</th>
<th>Mean FRE (cm)</th>
<th>Mean difference PRM (cm)</th>
<th>Mean difference FRE (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NLOS cinder block</td>
<td>178</td>
<td>29</td>
<td>30</td>
<td>3</td>
<td>1</td>
<td>208</td>
<td>208</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>NLOS brick wall</td>
<td>128</td>
<td>56</td>
<td>67</td>
<td>45</td>
<td>37</td>
<td>161</td>
<td>184</td>
<td>33</td>
<td>56</td>
</tr>
<tr>
<td>NLOS door (closed)</td>
<td>244</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>6</td>
<td>241</td>
<td>241</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>NLOS door (open)</td>
<td>244</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>243</td>
<td>243</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>NLOS drywall</td>
<td>200</td>
<td>7</td>
<td>7</td>
<td>1</td>
<td>1</td>
<td>202</td>
<td>204</td>
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<td>NLOS artificial tree</td>
<td>310</td>
<td>4</td>
<td>4</td>
<td>2</td>
<td>1</td>
<td>314</td>
<td>314</td>
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<td>4</td>
</tr>
<tr>
<td>CLOS outdoor short 7m</td>
<td>780</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>7830</td>
<td>7830</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>CLOS outdoor long 100m</td>
<td>9860</td>
<td>16</td>
<td>11</td>
<td>12</td>
<td>2</td>
<td>9869</td>
<td>9869</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>CLOS indoor short 23m</td>
<td>2338</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>3</td>
<td>2337</td>
<td>2337</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>(above ground)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CLOS indoor short 23m</td>
<td>2338</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>2341</td>
<td>2341</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>(floor)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CLOS indoor long 45m</td>
<td>4585</td>
<td>3</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>4586</td>
<td>4586</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>(above ground)</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CLOS indoor long 45m</td>
<td>4585</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>4586</td>
<td>4586</td>
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</tbody>
</table>

Table 3. Metrics for the various validation tests, including NLOS, outdoor CLOS and Indoor CLOS. The ground truth, root mean square errors, standard deviations, mean and absolute mean differences are displayed.
3.3 Calibration and Synchronization

As discussed above, the calibration of the units is necessary for accurate ranging measurements. Time Domain does provide software to calibrate the units and write the calibration parameters to the flash drive of the units. This is useful for laboratory settings, but when setting up in-field tests, additional calibration measurements should be taken, as the time delay can easily change. The time delay from both units must be adjusted for calibration of the range measurements to be completed. One method is to find the delay of each unit individually. The other is to find the combination of delay from both (Koppanyi 2015). The individual sensor calibration (Eq. 3.1) and the joint calibration model (Eq. 3.2) are given as:

\[
d_{A,B} = \hat{d}_{A,B} + f_A(\hat{d}_{A,B}) + f_B(\hat{d}_{A,B})
\]

\[
d_{A,B} = \hat{d}_{A,B} + f_{AB}(\hat{d}_{A,B})
\]

where

\[\hat{d}_{A,B}\] - range measurement between stations A, B,

\[f_A, f_B\] - individual unit calibration functions

\[f_{AB}\] - joint calibration function

\[d_{A,B}\] - corrected range measurement

Depending on the environment, the calibration models can be constant, linear or higher order polynomials as a function of distance. Only the joint calibration model was used during this research, and the results and analysis from the kinematic tests are shown in Chapter 4.
Time synchronization between the UWB units, PC, and GPS is essential for correct integration and position calculations. The UWB measurements are made with PC timestamps. Since the time-tagging to GPS sub-second timing failed during data acquisition, a work-around was implemented and interpolation of the PC times were made to get 1 second time-tag resolution.
3.4 Estimation

To estimate coordinates from multiple measurements, an estimation method is needed to calculate position. Former research by the SPIN lab, see Koppanyi (2014), discusses and compares the use of two estimation methods, the LS and Maximum Likelihood estimators (MLE). One of the most common estimation methods, the LS, finds the minimum sum of squared residuals. The LS is usually a fairly robust and good estimation method, but is sensitive to outliers (discussed later in section 4.1.4). The large influence of multipath increases the number of outliers, so an additional method is needed for static measurement estimation. The MLE is a good estimator for the UWB application because of its robustness. The MLE is defined as

\[
\max_{x,y} \prod_{i,j} f_{i,j}(x_i, y_i, x_j, y_j) \tag{3.3}
\]

where

\( f_{i,j} \) - probability density function

This function requires the PDF, which may be calculated, if the data is available as with the histograms above, or it can be estimated. Estimating the probability is difficult and was solved in static collection with kernel density estimation. This requires the setting of appropriate bandwidth, which becomes a problem with varying datasets. The paper establishes a good MLE algorithm and results, showing it to be more accurate than LS. However, its uniform unit setup and static recording does not make it applicable for kinematic recordings or areas of changing multipath, as both require change PDFs.
Chapter 4: Network Establishment & Calibration

Easily deployed, accurate network formation helps to facilitate accurate trajectory calculations, and is a main goal of this research. The use of numerous experimental setups allows for the analysis of the accuracies of the calculated UWB trajectories and the networks used to form them. These accuracies, processing techniques and differing network formations can be compared and analyzed within three different experimental collection environments: laboratory, open sky outdoor, and GPS-compromised outdoor.

A field calibration method was developed using two calibration techniques to ensure that the most accurate ranging measurements are calculated for the particular environment. This chapter discusses the setup of each test, the post-processing of data and the collection and accuracies of the ground truth. The developed techniques, processing algorithms and the experimental setup are discussed in this Chapter. The results are analyzed in Chapter 5.
4.1 Network

Establishing a network of UWB units allows for the localization and tracking of an unknown static or kinematic unit, referred to as the rover unit. The use of the network in emergency situations demands quick and accurate setup. Ad-hoc deployment and setup were sought, so that the network can be quickly adapted to specific site environments and constraints. As long as geometry of the network is good with regard to the rover unit, then the shape of the network can vary. Determining the positions of static network units is essential to establishing network geometry.

Establishing a network requires finding the optimal location and positioning of the static units. This can be done in a variety of ways by measuring points with tape, a total station, or by collecting static GPS or UWB data during deployment. For post-processing of the data, these measurements can be made priori, during or after the test. For real-time applications these measurements must be made priori to the test.

For the laboratory and GPS-compromised environments, the measurements of the unit locations were found with a Leica total station, giving local coordinates errors of sub millimeter levels. For the open sky test, GPS measurements from antennas on poles with UWB units were used, giving a 3D accuracy of 2cm.

As discussed in Chapter 3, having the UWB units placed above ground lowered the impact of multipath. The placement of the units above ground was accomplished using poles. This allowed for the elevation adjustment and placement of multiple units securely above ground to adjust for the environment. The 8ft poles allowed for a 2 meter separation between units, so that a ‘fair’ geometry could be established in the z axis as well. Adjusting positions were drilled every 20cm so setup height could be varied.
top was fitted to hold a GPS antenna, thus allowing good static data acquisition. Adjusting screws allowed the leveling of the pole on uneven surfaces. Figure 4. 1 displays one of the poles, used in outdoor tests.

![Network pole. The GPS antenna height is 2.44m, the separation between units is 2m, and the red square shows the leveling adjusting screws.](image)

4.1.1 Ad-hoc Setup

Quick deployment of the system is needed in GPS-compromised environments where time is of the essence, such as emergency situations. In a typical emergency scenario after showing up to a location where there is NLOS to GPS, the units are quickly placed without prior measurements of their locations, while making sure they are spread throughout the area. In these scenarios, the network is then responsible for determining positions based on measurements between units. The November testing found this technique produced low accuracies without prior calibration of the units to one another.
In non-emergency situations, static GPS data should be collected at each static unit to estimate the accurate network geometry.

4.1.2 Circular Lateration

Using at least three ranging measurements from three known positions, the location of the rover unit may be calculated. With more measurements this position can be optimized and better determined. The 2D case is depicted in Figure 4.2. The three known stations are labeled Stations 1, 2 and 3, with the solid line circles representing the range measurement from each. The dotted line represents the error range or standard deviation of each measurement. Since this signal has no directional component, three measurements are needed to find a unique point where the three range circles intersect.

![Figure 4.2](image)

*Figure 4.2 The principle of circular lateration with the three known stations listed, their individual range measurement to the rover unit marked by the solid circles, error boundaries of the measurement shown in the dotted line, and the intersection showing the localized position.*
The first three measurements can give an initial estimate of the position. Additional measurements and their statistics can be optimized with an estimation method. We used the LS estimation; the most commonly used and widely accepted approach.

4.1.3 Geometry

The geometry of the network is important because if it is sufficiently poor or the error is sufficiently large, a reliable solution is not possible. This case is depicted in Figure 4.3, demonstrating the existence of two possible solutions.

Figure 4.3 Ambiguous solution, when the error of one measurement is too large, or the geometry of the system is poor, or both.

With construction of the corner nodes, 3D data collection attempts were made; unfortunately, due to the decreased number of working units and resulting poor geometry, this goal could not be realized. Only 2D data positioning in the X,Y plane could be accomplished.

4.1.4 Least Squares Estimator
The LS was determined to be the most appropriate estimation method for optimizing kinematic data. LS minimizes the sum of the squared residuals of every equation and can give a solution to less redundant problems, like kinematic measurements. Static measurements, as discussed in 3.4, have more redundancy and the MLE should be used. LS does not handle outliers well but the bandwidth and PDF estimation are not required as with the MLE. Multipath was limited in the kinematic testing by appropriate placement of the units. The LS is denoted by:

\[
\min_{x,y} \sum_{i,j,k} v_{i,j,k}^2 (x_i, y_i, x_j, y_j, d_{i,j})
\]

4.1

Where \(v_{i,j}\) is the sum of squared residuals, \((x_i, y_i)\) is the positions of each rover unit, \((x_j, y_j)\) is the position of the station units and \(d_{i,j}\) is the range measurement between the two positions. These measurements are then optimized by fitting the estimates to lower the residuals until a certain number of iterations is met or the internal accuracy falls below a threshold limit. Since no reference solution was available, the relative or internal accuracy metric was evaluated with the posteriori reference standard deviation (Cepek 2015),

\[
m_0 = \sqrt{\frac{v^T v}{r}},
\]

where \(A\) is the design matrix, \(r = \dim(A^T A) - \text{rank}(A^T A)\) is the degree of freedom of the network, and \(v\) is the vector of residuals. These statistics were then used to indicate the quality of the estimate when integrating with the other datasets (Schaffrin 2015).

4.1.5 Geometry from velocity

The velocity of each localized position was used to estimate the timing delay between each range measurement of a specific position. This delay, while as small as the
frequency or time between measurements, must be fixed as each ranging measurement adds timing delays until the constraints are met and the trajectory can be calculated. The constraints are the number of measurements and internal accuracy. This delay and subsequent ranging error is shown in Figure 4.4.

![Figure 4.4](image)

**Figure 4.4** The schematic for the error introduced by rover motion and the subsequent fixed solution for the timing delay created by velocity. The red line represents the trajectory and the red dots represent the calculated trajectory positions, the striped red dot shows the incorrect solution without adjustment. The solid blue, green, yellow and orange lines represent the range measurements and when they were taken. The dotted line represents the adjustment for the geometry from velocity from the previous positions and time of measurement.

The blue dotted line represents the adjusted range, \( \hat{d}_{A,R} \), between the rover and station A. This new range is derived using the previous positions and timing information to obtain the current velocity of the rover and adjust the original range measurement, \( d_{A,R} \).

\[
\hat{d}_{A,R} = d_{A,R} + (x^{i-1} - x^{i-2})/dt \tag{4.2}
\]

Where \( x^{i-1} \) and \( x^{i-2} \) are the two previous positions, and \( dt \) is the function of time, including the time between positions over the frequency or time between measurements. Finding the velocity in all directions is calculated by finding the change in movement over time. The frequency delay must be adjusted for by using the UWB frequency and
number of measurements taken before the trajectory calculation. The striped red dot represents the incorrect calculated position if these variables are not adjusted. The red dot labeled $x$ is the adjusted position.

4.1.6 Integration

The outdoor tests included UWB, GPS and IMU sensors, allowing for the most accurate solution to be computed. Since GPS data was poor, the integration of GPS with the other two was not computed, as discussed in 2.3.3. Multiple IMU’s were onboard during testing but this research only used only the tactical grade HG1700. By integrating the IMU and UWB, an accurate solution in GPS-compromised environment, with sporadic NLOS temporarily stopping UWB localization, should be possible. It was for this reason that the novel integration was attempted.
4.2 Calibration

A field calibration was also developed to help obtain the most accurate ranging data. Static measurements were used to derive calibration models in post-processing to help fix ranging error. The calibration allowed for inherent errors from the units to be accounted for as well as errors accumulated by the UWB units from transportation, setup, and the specific environment. The method used for this research was a grid calibration procedure that allowed for range measurements to be taken throughout the entire testing area. This allowed for adjustment based on distances to account for the environment and any multipath, bias or other errors introduced. By accounting for these error sources, the optimal ranging measurements were obtained by applying a calibration model.

The developed calibration models included: simple, average, linear and polynomial. The simple model meant no adjustment was applied. The average model used the average error for all measurements to adjust. The remaining linear and polynomial models used the ranging measurements versus distance as a function.

4.2.1 Grid Calibration

The grid calibration method takes static readings at positions in a grid-like layout throughout the testing area. This allows for the collection of ground truth and numerous measurements to fix the timing delay (see section 3.3). In the laboratory testing the ground truth was captured by total station. For the outdoor tests, GPS static data was used to calculate the position. The grid layout for the open sky test is presented in Figure 4.5. In general, the pattern may vary as the environment allows, but good distribution of points is essential; the grid pattern is not necessary.
4.2.2 Average Model

The average calibration method used the average time delay calculated for each calibration point, applied to the range measurements. This method does not account for distance and used a threshold for corrections. The threshold kept large biases from incorrect calibration points, from entering the assumed small, constant time calibration adjustment. This model allowed for the calibration of the slight delay created through transportation and setup.

$$\hat{d}_{A,R} = d_{A,R} + \bar{x}$$

4.3

The newly adjusted range measurement, $\hat{d}_{A,R}$, is simply derived by adding the average calibration distance, $\bar{x}$, to the original measured range, $d_{A,R}$.
4.2.3 Linear Model

The linear adjustment model uses the range of each calibration measurement to create a linear model of adjustment versus range. This model allowed for calibration as the signal grows weaker for longer distances.

\[ \hat{d}_{A,R} = d_{A,R} + f_L(d_{A,R}) \]  

4.4

Where \( f_L(d_{A,R}) \) is the linear function created from the grid calibration point measurements.

4.2.4 Polynomial Model

The polynomial calibration takes into account the distance for calibration but allows for higher-order models to be created. From the sensor performance validation in Chapter 3, there is some evidence that the UWB signals may not be linear. The longer ranges do not have the same interference and multiple reading problems that the shorter ranges sometimes display, so a polynomial model was examined for the data.

\[ \hat{d}_{A,R} = d_{A,R} + f_P(d_{A,R}) \]  

4.5

Where \( f_P(d_{A,R}) \) is the polynomial function created from the grid calibration point measurements. All the models improve with increased number of calibration measurements, but this model in particular benefits from more measurements to ensure it is not underdetermined.
4.3 Experimental Setup

To test the accuracy of the calculated trajectory, three different experiments were performed. The first setup test was an indoor laboratory setting to help establish optimal accuracy expectations and collection techniques. This setup also tested the system in an indoor environment, where obviously GPS was absent. The second setup test was an open sky outdoor test, allowing for comparison to highly accurate GPS ground truth of a dynamic rover unit. The third and final test was in a GPS-compromised outdoor environment. Images of these tests are displayed in Figure 4.6.
Figure 4. 6 Images taken throughout the three testing sites. A and B display the laboratory, C shows the open sky test, D shows the UWB and GPS sensors for both outdoor tests, and E & F show the GPS-compromised testing environment. The red squares indicate UWB location on the vehicle and pushcart.
4.3.1 Laboratory

Laboratory testing commenced in the Camera Calibration Facility located in the basement of Bolz Hall on the OSU campus. The open space allowed for network establishment without having to disassemble between tests. Numerous calibration and kinematic experiments were repeated. Block-like movements were performed to simulate an office cubical environment and to allow for easy lever-arm adjustments. Tree interference was also simulated by placing an artificial tree in front of one corner to see how NLOS would affect the accuracy.

Calibration

The laboratory calibration models are displayed in Figure 4. 8. This smaller, indoor network saw large errors during calibration, meaning poor calibration adjustments. This can be attributed to large multipath, interference, and poor lever-arm measurements, shown in Figure 4. 7.

Figure 4. 7 Laboratory lever-arm. Antenna center is UWB center, the total station measure from the reflector above.
Figure 4.8 Models created from laboratory calibration. The Green line is the average difference, the red is the linear model, and the blue is the polynomial model. The blue circles show the range difference at each grid point.

As seen in Figure 4.8, the linear or average model seems to be the most appropriate fit, although all are questionable because of the large amount of variations. The static collection, as shown in Chapter 3, seems to be highly affected by multipath. Analysis of the kinematic collections and applications of the models are found in Chapter 5.

The 2nd order error surfaces displayed in Figure 4.9 show the improvement of the linear calibration (right) compared with the no-model surface (left). The models improved the error surfaces from over a meter to a few centimeters.
4.3.2 Open Sky

The open sky test allowed for the performance analysis of the UWB where GPS coverage is ideal. This test allowed for the comparison of UWB in this ideal environment with high quality ground truth and gave a good baseline to the optimal accuracy achievable by the system. The open area also provided testing of the system’s ability to handle mild-dynamic movement, as the vehicle was able to turn quickly and travel at moderate rates of speed both within and outside the grid.

Calibration

Open sky calibration gathered good ground truth data from GPS measurements. All grid points had successful measurements to each unit. This allowed for good
calibration models to be created and applied to the data. Figure 4. 10 displays the low bias, high accuracy calibration performed in the open sky environment. The highest bias is with Unit 101, centering around 20cm; but, the variation of the measurements were low meaning the calibration was accurate. The lower variation for all units in the open sky calibration, when compared to the laboratory calibration is due to the lack of multipath and interference, better lever-arm measurements, and because longer distances are more optimal for the UWB measurements.

Figure 4. 10 Models created from calibration in open sky testing. The green line is the average difference, the red is the linear model, and the blue is the polynomial model. The blue circles show the range differences at each grid point.
The decreased residuals, shown in Figure 4.10, are witnessed in the 2nd order error surface, Figure 4.11, with only slight deviations from the no-model model. Since the calibration was so accurate, the decrease in the surface error is small to the eye when looking at the half meter scale. This is expected, as the open area should not have drastic errors introduced anywhere.

![Figure 4.11 2nd order error surface fitted to the residuals at grid points for the open sky test. The red star is the node being modeled and the blue circles are the grid points. The no-model model is displayed to the left and the polynomial model is displayed to the right.](image)

### 4.3.4 GPS-Compromised

The GPS-compromised testing was performed to show the advantage of UWB in areas where GPS has difficulty operating. The poor ground truth gathered during these tests meant that only relative comparison could be performed. The decrease in accuracies was limited for UWB compared to GPS. In the forested area trees and other obstacles created areas where a UWB signals were poor and positioning was difficult.
With grid calibration the processing and positioning calculations could then be adjusted accordingly, even with NLOS.

Calibration

The calibration of GPS-compromised testing was not as successful as the open sky testing. The lack of good ground truth made the calibration of the collected grid points difficult and sometimes impossible. The sporadic GPS fixed solution had to be reprocessed numerous times to obtain the lowest level of error, but was still high. The NLOS of some positions made calibration from these points to certain corner units not possible. For example, through tree calibration adjustments could not be performed.

Only eight points were able to be calibrated and from those points, depending on the corner unit, as little as 3 to 4 points were usable for calibration model creation, as they provided errors of less than 10cm. Tree branches and NLOS from the vehicle body caused the calibrations to be made through various materials, thus dramatically increasing error and adjustment. Since this NLOS was not constant throughout the trajectory, fixing for these positions would increase the error over the majority of the trajectory which do not have these circumstances. It was for these reasons that the calibration threshold of 10cm was set, so that the models would not adjust for the NLOS condition.

The threshold limited the number of points and, therefore, the ability of the models to fix for the environment. The polynomial and linear models were poor due to the small number of points, and were forgone. Only the no-model and average model
were used for the comparison of the solution, as the large error of the other two were obvious. With additional research, the implementation of an algorithm to fix for areas with NLOS and obstruction will allow for the complete calibration. This was not attempted as these areas were limited in the kinematic trajectory, with at least three network units able to give good range measurements. This adjustment meant calibration similar to the through wall measurements in Chapter 3. In future applications and studies of the system, this should be corrected but for this processing, it was determined that a 3 unit solution and/or distance stipulations from the last point was sufficient.

Figure 4.12 shows the sporadic point distribution, which results partly from NLOS and multipath but is also attributed to poor GPS ground truth. As this testing was specifically performed in a GPS-compromised environment, a better collection method of ground truth, such as from a total station, should have been performed. This was a lack of data and could not be adjusted in post processing. Instead, the high quality of the open sky calibration from the previous day permitted it to be used in situ. This meant that units were still well calibrated, but calibrating for the multipath and NLOS from the environment could not be performed.
Figure 4. 12 Models created from calibration in GPS-compromised testing. The green line is the average difference, the red is the linear model, and the blue is the polynomial model. The blue circles show the distance of each grid point.

Figure 4. 13 shows the 2nd order error surfaces of both the no-model and average model. Both are quite poor from the limited number of points used for calibration and poor ground truth.
Figure 4. 2nd order error surface fitted to the residuals at grid points for the GPS-compromised tests. The red star is the node being modeled and the blue circles are the grid points. The no-model model is displayed to the left and the average model is displayed to the right.
4.4 Ground Truth

Ground truth is important in validating the accuracies of UWB. Ground truth was a combination of total station measurements and GPS, depending on the particular environment. System authentication was done in both the laboratory and open sky settings, by comparing the UWB solution to highly accurate ground truth. The lack of or poor quality GPS in both the laboratory and GPS-compromised settings showed the advantages of UWB.

4.4.1 Laboratory

Ground truth collection for the laboratory experiments was performed by a Leica total station with a 3D error of 0.25mm (Leica 2014). This method gave extremely low errors but had the disadvantage of also having a low frequency rate of collection. To make up for the low frequency rate, the kinematic movements were done slowly, so enough ground truth points could be collected and compared.

The pattern of collection was made with deliberate right turns. This allowed the lever-arm between the laser sight and the UWB to be applied accurately without adjustment for non 90 orientations, as discussed in section 4.3.1. The slow movements were offset by decimating the data to emulate walking speeds. Figure 4.14 displays the ground truth for the corner units, grid points, and kinematic trajectories including the NLOS tree test. Additional error of the lever-arm offset, measured by hand and changing direction, depending on push cart orientation, gave an error estimate of 5cm. This
estimate included both orientation and hand measurement errors. This accuracy was the same for kinematic and calibration point measurements. Since the UWB antennas were able to be measured directly, the accuracies of their location were the same as the optimal accuracy of the total station, 0.25mm.

Figure 4. 14 Corner units, grid points and ground truth trajectories for the block kinematic CLOS collection in orange circles and for the NLOS tree collection in the blue asterisks.

Additional calibration and ground truth data for the laboratory testing can be seen in Appendix A.

4.4.2 Open Sky Test

The accuracies for the static corner GPS receivers were centimeter-level for the rapid static solution provided by OPUS. With the addition of the lever-arm to the UWB
units, measured with tape, a 3D error of 2cm was expected. The GPS errors provided from OPUS are provided in Table 4.1.

<table>
<thead>
<tr>
<th>Corner</th>
<th>X (m)</th>
<th>Y (m)</th>
<th>Z (m)</th>
<th>3D (m)</th>
<th>Quality Index</th>
<th>Normalized RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>NE_corner-NovAtel</td>
<td>0.004</td>
<td>0.012</td>
<td>0.010</td>
<td>0.016</td>
<td>18.98/0.76</td>
<td>0.369</td>
</tr>
<tr>
<td>NW_corner-Topcon</td>
<td>0.004</td>
<td>0.016</td>
<td>0.012</td>
<td>0.020</td>
<td>18.94/3.34</td>
<td>0.37</td>
</tr>
<tr>
<td>SE_corner-Trimble2</td>
<td>0.005</td>
<td>0.015</td>
<td>0.011</td>
<td>0.019</td>
<td>17.09/5.37</td>
<td>0.374</td>
</tr>
<tr>
<td>SW_corner-Trimble1</td>
<td>0.005</td>
<td>0.012</td>
<td>0.009</td>
<td>0.016</td>
<td>18.25/14.63</td>
<td>0.375</td>
</tr>
</tbody>
</table>

*Table 4.1 Accuracies of each corner pole GPS receiver and antenna.*

The error for X, Y, Z and 3D are included to show the estimated error in all directions. The quality indicator is the ratio of RMS values associated with the best and second best candidate sets. To be valid, the quality indicator, should be greater than 1, and 3 for higher precision (Mead 2015). All met that requirement. The unit-less quantity of Normalized RMS is included to reference the standard deviation of the measurement. A value greater than 1 indicates noise (Pearson 2015), which none of static measurements have.

The accuracies for the static solution provided by RTKLib were below 2cm. These measurements were made for the calibration grid points from the front GPS antenna on the van. The lever-arm between the UWB and the antenna was applied using AIMS-PRO (Jozkow 2015). The fixed solution, several minute collections, the grid
points, showed the repeatability of the solution, allowing the given error from RTKLib to be trusted. The error for the grid point GPS solution was still centimeter-level.

The error term calculated by RTKLib is usually low and should be multiplied by a factor of up to 5, depending on variables, to give a more reliable estimate, dependent on variables (Jozkow 2015). Since there was static data before and after each kinematic trajectory indicating a good solution and a fixed solution for the all points, a factor of 2 was used to estimate the error. This gave the kinematic solution an extremely low 3D error of 2cm, calculated throughout testing. This solution was 100% fixed throughout and provided high quality ground truth to give a good estimate of the UWB accuracy.

Figure 4. 15 shows the GPS trajectory throughout the entire test. This trajectory was broken up and analyzed for four different kinematic collections.

*Figure 4. 15 GPS solution for the open sky experiment. The green trajectory was the kinematic solution from the front antenna attached to the van, the red pins are the grid point calibration positions, and the red triangles are the OPUS solution for the corner antennas. The local reference station chosen and labeled was the northwest corner.*
The local reference station used was the Continually Operating Reference System (CORS) Marysville (OHUN). For the kinematic solution, the northwest station, labeled NW_TopCon, was used as the local base station. Additional figures expanding on the accuracy, position, velocity and satellite coverage of the solution can be found in Appendix B.

4.4.3 GPS-compromised

The corner nodes and trees within the testing grid were measured with the total station, giving them the subcentimeter-level error found in the laboratory testing. These measurements were more accurate than the open sky test because the lever-arm was not measured by hand. As discussed above, the accuracy of the grid measurements was 10cm for the points able to be measured. The kinematic solution had a range of accuracies, as the ability to maintain and fix the number ambiguities changed throughout the test. Figure 4.16 shows the GPS data for the entire test, as well has the corner GPS receivers on a satellite image.
The local reference station used was the CORS Athens (STKR). For the kinematic solution the northeast station, labeled NE_Trimble1, was used as the local base station. Additional figures expanding on the accuracy, position, velocity and satellite coverage of the solution can be found in Appendix C. A 3D plot of the corner UWB units, GPS antenna and tree locations within the network is depicted in Figure 4.17.
The inability of the signal to remain fixed increased errors as the testing proceeded. Note that the receiver was able to fix ambiguities on the road before entering the test area. As the time between fixed solutions and open sky increased, so did the error. This is seen in the average 3D errors displayed in Table 4. 2.

<table>
<thead>
<tr>
<th>Trajectory</th>
<th>Time</th>
<th>3D error (m)</th>
<th>Fixed %</th>
<th>Float %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>02:59.4</td>
<td>4.31</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>01:23.8</td>
<td>7.53</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>02:25.7</td>
<td>15.27</td>
<td>1.2</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>09:45.4</td>
<td>60.25</td>
<td>12.5</td>
<td>5.1</td>
</tr>
<tr>
<td>5</td>
<td>02:40.8</td>
<td>33.11</td>
<td>15.2</td>
<td>3</td>
</tr>
<tr>
<td>6</td>
<td>22:40.5</td>
<td>26.47</td>
<td>9.9</td>
<td>1</td>
</tr>
<tr>
<td>Calibration</td>
<td>25:35.0</td>
<td>3.99</td>
<td>32</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 4. 2 Average 3D error, the fixed percentage of measurements and the float percentage of measurements during the kinematic trajectories and calibration. All measurements fixed or float were DGPS measurements.
The increased percentage of fixed solutions seen in the later trajectories can be attributed to better satellite coverage at the time of recording, but does not correlate with an increase of accuracy. With the increased fixed measurements, an increase in the high-error float solutions also occurred.

The large error in GPS shows the disadvantages, in canopy-covered areas, of relying solely on the global solution. This error increases irrespective of time or position, as seen in the table where, in the same general area, errors changed drastically, even with some fixed solutions. UWB becomes an appealing solution in these covered areas where it is difficult to trust GPS.

4.4.4 Error Estimation

By applying error propagation laws, the lowest error for the network can be estimated. This estimation does not take into account any other variables that can affect the accuracy, simply a model of the range and lever-arm errors. This method only allows for the estimation of the geometry error as a linear function. Without additional research it is not possible to create an adjusted model. This elementary analysis was taken to find the optimal error based on the geometry of the network by including the range and lever-arm error.

By assuming independent variables, the estimation of the total error from geometry becomes:

\[ \sigma_T = \sqrt{\sigma_R^2 + \sigma_{LA}^2} \]
where

$\sigma_T$ - total accuracy of the network  

$\sigma_R$ - range measurement accuracy  

$\sigma_{LA}$ - lever-arm accuracy  

Applied to the entire network, the error estimation can be completed. As the center of the network includes 1) the largest error from all measurements and 2) does not include the incorrect decreasing error seen closer to the corners, optimal error estimation of the network was achieved. For the laboratory testing with a geometry of 7 by 15m, this was calculated as 7cm. This is shown in Figure 4.18.

![Error Estimation for Laboratory Testing](image)

*Figure 4.18 Optimal error estimation for laboratory testing.*

For the larger 30 by 30m grid, the optimal error was calculated as 5cm. These values give a tentative target accuracy to achieve, as shown in Figure 4.19.
Figure 4. 19 Optimal error estimation for outdoor 30x30m network.
Chapter 5: Results

Analysis of the tests shows the optimal achievable accuracy of the UWB system in indoor laboratory and open sky outdoor environments. By comparing UWB kinematic trajectories with ground truth, including GPS and total station measurements, the accuracies of the system can be estimated in ideal collection environments. These accuracies can then be inferred in the GPS-compromised environments, and juxtaposition between the UWB and GPS trajectories in these areas can occur, showing the advantages of the UWB solution. UWB has demonstrated 2D accuracies below 10cm in all environments and outperforms GPS in NLOS, canopy-covered environments, and indoor environments. As a highly accurate and suitable GPS replacement for local applications, UWB has demonstrated the ability to successfully fulfill the goals of this research.
5.1 Laboratory Testing

The laboratory testing shows the ability of the network to be operated indoors, with high multipath and interference throughout. Results mentioned in Chapter 3 demonstrated the ability of the sensors to work through wall; and, while this test could not add that extra stipulation due to environmental limitations, a NLOS through artificial tree was able to simulate later testing. The acquiring of accurate signals indoor was difficult even in CLOS. The accuracies of the movements are displayed in Table 5.1, showing relatively high errors for the laboratory setting.

<table>
<thead>
<tr>
<th>Model</th>
<th>RMSE(cm)</th>
<th>STD(cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
<td>Y</td>
</tr>
<tr>
<td>Block</td>
<td>6.7</td>
<td>9.8</td>
</tr>
<tr>
<td>Block KF</td>
<td>6.5</td>
<td>9.2</td>
</tr>
<tr>
<td>Tree</td>
<td>11.6</td>
<td>14.9</td>
</tr>
<tr>
<td>Tree KF</td>
<td>11.6</td>
<td>14.8</td>
</tr>
</tbody>
</table>

Table 5.1 Accuracies of the laboratory testing, including the RMSE, and standard deviation, when compared with total station measurements.

These errors excluded large outliers, and shifts by the average bias, reducing the margin for error. The excluding of large outliers was done by setting a threshold of distance between the calculated position and the previous position. Incorrect positions were not included and biases were subtracted from each leg of the block movement, as the exact lever-arm was unable to be accounted for. While these errors are reasonable, they are still larger than the residual of the network calculations which are on a scale of 5cm at optimal geometry, see section 4.4.4.
This larger error is attributed to several different reasons, including the accuracy of the level-arm adjustments, see section 4.3.1. There was an orientation error based on the geometry of the measurements and the inability to move completely straight, but the larger average error of the lever-arm was able to be negated. Additional errors come from poor calibration of the system in the basement, the multipath and interference. The multipath and interference caused large errors in both the CLOS and NLOS calibration. These errors continued for the kinematic collection.

The kinematic block trajectory displayed in Figure 5.1 shows the calculated UWB trajectory and the corresponding matching total stations positions. The corner unit stations were kept in the same location for both calibration and other testing.

![Ground Trajectory Block Movement](image)

*Figure 5.1 The kinematic block trajectory for the laboratory experiment.*
Figure 5. 2 shows the difference from ground truth on both axes. The grouping of data at constant rates points to incorrect lever-arm offsets. This is seen explicitly between measurement 1000 and 1300 in both axes. The incorrect calculations from multipath, due to the indoor environment, are obvious, as they jump far from the trajectory in both figures. They are the result of the errors listed above.

![Graph showing differences between UWB and ground truth trajectories in X and Y coordinates.]

*Figure 5. 2 The differences with respect to both axes from ground truth measurements for the kinematic block trajectory.*

**NLOS Analysis**

Using the artificial tree as a NLOS obstacle for one node raised the error of the UWB calculations. This is noticeable in the NLOS trajectory in Figure 5. 3 and numerically in Table 5. 1. The increase in large outliers is obvious and shows how the
correct geometry and measurements from only one node are important in the LS adjustment.

Figure 5. 3 Kinematic NLOS tree trajectory laboratory environment

The results of the laboratory testing show lower than 10cm error for indoor trajectory calculations, even with high multipath, interference, and slow collection rates. With better ground truth collection measurements and lever-arm adjustments, this error can be lowered even further when comparing. The NLOS capabilities are displayed in the artificial tree but through wall testing could show the additional advantages.
5.2 Open Sky Testing

The open sky experimental collection displayed a low RMSE of the XY plane (RMSE XY) error for kinematic collection for the four tests in the 30m by 30m grid. The error analysis for trajectory 1 is shown in

<table>
<thead>
<tr>
<th>Open sky trajectory 1</th>
<th>RMSE(m)</th>
<th>STD(m)</th>
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<td></td>
<td>X</td>
<td>Y</td>
</tr>
<tr>
<td>Simple</td>
<td>10.0</td>
<td>13.0</td>
</tr>
<tr>
<td>Simple KF</td>
<td>8.4</td>
<td>10.6</td>
</tr>
<tr>
<td>Simple, KF, Velocity</td>
<td>7.6</td>
<td>8.9</td>
</tr>
<tr>
<td>Average</td>
<td>5.6</td>
<td>5.8</td>
</tr>
<tr>
<td>Linear</td>
<td>5.8</td>
<td>6.0</td>
</tr>
<tr>
<td>Polynomial</td>
<td>6.2</td>
<td>6.3</td>
</tr>
</tbody>
</table>

Table 5.2. The improvement made by the Kalman filter was around 2cm for the RMSE XY. The improvement of the geometry from velocity was over a centimeter in combination with the Kalman filter for the same measurement. These improvements lowered the error well below the 10cm goal for the open sky tests.

All the additional calibration models further improved the trajectory measurements. The average model lowered the RMSE XY error to 5.7 cm. The linear and polynomial models lowered the error to around the same level, 5.8 and 6.2 cm, respectively. The standard deviation was approximately the same as the RMSE, indicating that the predicted model and actual measurements are about the same.
Open sky trajectory 1

<table>
<thead>
<tr>
<th>Model</th>
<th>RMSE(m)</th>
<th>STD(m)</th>
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<tbody>
<tr>
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<td>X</td>
<td>Y</td>
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<tr>
<td>Simple</td>
<td>10.0</td>
<td>13.0</td>
</tr>
<tr>
<td>Simple KF</td>
<td>8.4</td>
<td>10.6</td>
</tr>
<tr>
<td>Simple, KF, Velocity</td>
<td>7.6</td>
<td>8.9</td>
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<tr>
<td>Polynomial</td>
<td>6.2</td>
<td>6.3</td>
</tr>
</tbody>
</table>

Table 5. 2 Errors for the different models of open sky trajectory 1 compared to high accuracy GPS. The simple model indicates no model adjustment from calibration Kalman filter or geometry from velocity adjustments. The KF indicates the Kalman filter correction with no geometry from velocity adjustments. The remaining models, including simple KF Velocity are all corrected with the Kalman filter and geometry from velocity adjustments.

Trajectory 1 in Figure 5. 4, shows the accuracy of the UWB trajectories. Even at high-resolution, the small scale portion, outlined in red, showing the difference between the ground and UWB measurements are still difficult to see. The additional trajectory figures are displayed in Appendix B.
The smoothing of the Kalman filter is shown in Figure 5. 5, where the residuals are smaller. The advantage of the Kalman filter is noticeable even on the small scale, especially at measurement epoch 100 on the X axis. This is where the turn outside the grid boundaries occurs, and where the Kalman filter is able to correctly predict and weight the measurements further outside, as the ground truth indicates. The large outliers are also mitigated, as seen with the UWB solution, leaving the plot range on the Y coordinate at measurement epochs 300-400.

Figure 5. 4 Open sky trajectory 1, average model. The ground truth, UWB trajectory, KF UWB trajectory, and the corner units are all marked. The outcrop portion shows the section in red at a higher resolution to show the difference in trajectories.
Using UWB as a replacement for GPS demands that the system works reliably for long periods of time and distances, within and near the network. For all trajectories, the ability of the system to successfully complete these objectives and demonstrate the repeatability of the accuracies of the first trajectory, are displayed in Table 5.3.

<table>
<thead>
<tr>
<th>Trajectory</th>
<th>Time</th>
<th>Length(cm)</th>
<th>RMSE(cm)</th>
<th>STD(cm)</th>
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<td>283.8</td>
<td>5.7</td>
<td>5.52</td>
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<td>6:10</td>
<td>788.7</td>
<td>7.94</td>
<td>7.95</td>
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<tr>
<td>3</td>
<td>3:11</td>
<td>166.5</td>
<td>6.42</td>
<td>5.74</td>
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<td>4</td>
<td>7:26</td>
<td>842.7</td>
<td>7.32</td>
<td>7.47</td>
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</table>

Table 5.3 Time, length, RMSE for XY plane, and standard deviation for all trajectory collected during the open sky environment.

Accuracy statistics are slightly higher for the later trajectories, as these trajectories were sometimes farther outside the network but were nearly the same as in trajectory 1. The long runtimes, showed the ability of UWB to maintain measurements for extended periods of time.
Figure 5. 7 shows the longest time and distance of trajectory 4. This figure shows the ability of the system to work at long distances and outside the network, as a portion of the trajectory travels nearly 35m outside the grid. This made measurements from two of the stations well over 70m, yet both were able to be completed. Kalman filter correction is also noticeable during this same portion.

![Ground trajectory 4 (UWB antenna position), model: Polynomial](image)

*Figure 5. 7 Open sky trajectory 4, polynomial model. The ground truth, UWB trajectory, KF UWB trajectory, and the corner units are all marked.*

In the open sky experiment, the improvement from model correction is notable, but the difference is not large between them and depends on the geometry of the trajectory. Accuracy is also noticeably increased with the Kalman filter and with geometry from velocity corrections.
5.3 GPS-Compromised Outdoor Testing

The GPS-compromised experiment showed the same high accuracies that the open sky tests were able to confirm with ground truth. While comparison of these tests could not be directly derived with ground truth, after reviewing the testing layout, numerous trajectories, and comparisons, the UWB measurements were indeed much more accurate than GPS. With the accuracy of GPS degraded between and during trajectories, the advantage is seen in the trajectory figures.

Table 5.4 shows the comparison models of trajectory 1 to GPS. This is the lowest error of all the trajectories, with a 3D error of 4.3cm. As the mentioned in Chapter 4, the ground truth for calibration of the GPS-compromised experiment was not of high enough accuracy to complete an accurate calibration of the network. This meant that only the no-model and average model were implemented.

<table>
<thead>
<tr>
<th>GPS-compromised trajectory 1</th>
<th>RMSE</th>
<th>STD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>X</td>
<td>Y</td>
</tr>
<tr>
<td>Simple</td>
<td>10.1</td>
<td>9.5</td>
</tr>
<tr>
<td>Simple KF</td>
<td>9.8</td>
<td>9.9</td>
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<td>Simple, KF, velocity</td>
<td>8.2</td>
<td>11.3</td>
</tr>
<tr>
<td>Average</td>
<td>10.1</td>
<td>13.3</td>
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<tr>
<td>Linear</td>
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<td>NA</td>
</tr>
<tr>
<td>Polynomial</td>
<td></td>
<td>NA</td>
</tr>
</tbody>
</table>

Table 5.4 Errors for the GPS-compromised trajectories 1 compared to GPS. The simple model indicates no model adjustment from calibration Kalman filter or geometry from velocity adjustments. The KF indicates the Kalman filter correction with no geometry from velocity adjustments. The remaining models, including Simple KF Velocity are all corrected with the Kalman filter and geometry from velocity adjustments.
Figure 5. 8 shows trajectory 1 with an outcrop illustrating the difference between the GPS and UWB solution. The outcrop specifically shows quick oscillating movements that a vehicle is unlikely to make. This is mostly the result of non-smooth or lagging GPS solution. The Kalman smoothed trajectory represents the more accurate solution. The GPS solution is DGPS and the most accurate of all the trajectories, but the UWB solution is still more accurate. This is made more evident in the remaining trajectories.

![Ground trajectory 1 (UWB antenna position), model: Simple](image)

*Figure 5. 8 GPS-compromised trajectory 1, simple (no) model. The ground truth, UWB trajectory, KF UWB trajectory, and the corner units are all marked. The outcrop portion shows the section in red at a higher resolution to show the difference in trajectories and the poor GPS solution.*

The differences between the Kalman filter smoothed solution and UWB solution show no real indication on which is more accurate, as they are so similar, see Figure 5. 9. Without better ground truth, a determination cannot be made which is better. In the
remaining trajectories, the Kalman filter is calculated to be less accurate than the UWB solution as the GPS jumps in measurements. This is not conducive to real life movements and indicates the lower error of the Kalman filter as shown in the open sky tests.

![Graphs showing X and Y coordinate differences with respect to ground truth](image)

*Figure 5.9 Difference from ground truth with respect to both axes for both the UWB (cyan) and KF UWB (green) solutions, shown in Figure 5.8.*

As the accuracy of GPS decreased throughout testing, the ability to compare GPS to UWB also decreased. This made it more difficult to define which trajectory was more accurate, but it was still clear that the UWB solution was more accurate than GPS in the canopy environment. This was shown by the repeating trajectories being mapped accurately throughout the experiment. The UWB solution was able to maintain
measurements throughout extremely long trajectories, while the GPS lost reasonable measurement accuracies as shown in trajectory 6, in Table 5. 5.

<table>
<thead>
<tr>
<th>Trajectory</th>
<th>Time</th>
<th>Length</th>
<th>RMSE</th>
<th>STD</th>
<th>Bias</th>
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</thead>
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<td>7.62</td>
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<td>3</td>
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<td>8.34</td>
<td>0.69</td>
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<tr>
<td>4</td>
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<td>546.4</td>
<td>9.89</td>
<td>9.31</td>
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<tr>
<td>5</td>
<td>2:40</td>
<td>157.5</td>
<td>15.25</td>
<td>14.49</td>
<td>2.28</td>
</tr>
<tr>
<td>6</td>
<td>22:40</td>
<td>1296.4</td>
<td>NA</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5. 5 Time, length, RMSE for XY plane, standard deviation and bias for all trajectories collected during the GPS-compromised experiments.

Two of the remaining trajectories, shown in Figure 5. 10, outline the large error of GPS and the ability of UWB to maintain high accuracy throughout testing.
Movement was limited by the vehicle’s turning rate, trees, and other environmental features blocking the way, making the trajectory of the vehicle identical for each trajectory. Though comparisons of all the trajectories, it was evident where GPS was incorrect and where UWB was able to repeat the same movements that the environment allowed. This allowed for additional proof that the UWB trajectory was indeed more accurate.

In summary, the UWB solution was shown to be more accurate even with poor a field calibration. The solution was also able to hold over time, while GPS was degraded.
with lack of connection to satellites. The additional trajectories are shown in Appendix C.
5.4 Integrated Solution

The integrated solution of UWB and IMU was unsuccessful due to the poor time synchronization of the UWB during the tests. The integer timing of the UWB measurements and the localization with measurements at different times meant that the high frequency IMU data was unable to be accurately integrated. This is evident by the curves of the two solutions not aligning as shown in Figure 5.11 and Figure 5.12. They mirror each other, but the UWB/IMU solution is delayed.

With a fixed orientation offset and timing data, the integrated solution should become more accurate. This cannot be completed with any post processing techniques.
Figure 5. 12 GPS-compromised trajectory 1, simple (no) model. The KF UWB trajectory, and the integrated IMU/GPS are all marked.
Chapter 6: Conclusion and Recommendations

6.1 Conclusion

The primary goal of this research was accomplished, by assessing UWB as a suitable replacement for GPS, in areas where there is high multipath, no open sky, or other limiting factors that make the use of the global system highly inaccurate or impossible. UWB can accurately position and navigate in almost any local environment through use of procedures to establish a network, validate sensors, and ample testing. The goals of network deployment and establishment, operation in laboratory, under canopy, NLOS environments, development of processing algorithms and trajectory 2D errors of below 10cm were all met.

An overview of GPS and UWB allowed for the comparison of the systems. By looking at the history, basics of operation, calculations and error sources, the advantages, disadvantages, and areas where each system may benefit the other was shown. With the addition of IMU sensors, the potential to accurately position, with only centimeter-level error, almost anywhere in a local environment is possible.

Sensor validation of the units allowed for analyzing the manufacturer’s specifications and demonstrated the ability of the sensors to operate in indoor and NLOS
applications. These experiments showed how accurately the sensors could operate indoors. Varying setups, including different ranges, environments, UWB sensor placement and obstacle materials were all subject to testing. Testing results along with calibration and time synchronization procedures and measurement estimation methods, were all discussed and analyzed.

Establishment of a network by numerous units allowed for the localization of sensors. Procedures, calibration, collection methods and processing techniques were developed for this research. Three separate environments: laboratory, open sky and GPS-compromised were each tested and discussed. Combinations of all three environments allowed for conducting similar analysis and comparison in many types of positioning problem and environments. Numerous processing techniques with specific procedures were also developed to compare the experimental data.

Analysis of these tests showed the accuracy and abilities of UWB under varying circumstances. For laboratory testing, 2D accuracies of 9 cm were achieved. While these estimates suffered from large amounts of interference and slow collection, post-processing of data allowed for increased accuracy.

The open sky outdoor test showed the true capability of the system when compared to a centimeter-level GPS solution. Mounted on a moving vehicle, the UWB system was able to maintain accurate measurements for all tests, with only 5-7cm of errors. This test showed the true accuracy of the system when used in a real-life scenario.
Comparing the solution of substandard GPS data with the GPS-compromised UWB trajectories showed the advantage of UWB in GPS-compromised environments. In the canopy-covered hills of Wayne National Forest, the system was tested in an area where GPS is practically useless. The UWB system successfully showed its capabilities and accuracy in the NLOS environment. Accuracies, while not able to be calculated, were estimated to be similar, by a relative comparison, to the open sky tests.

With additional analysis and research, the use of UWB will likely increase and help obtain accurate solutions to various positioning navigation and timing problems. UWB technology has many uses, as it can link GPS with areas that could not be accurately mapped previously while maintaining a low error. The contribution of this thesis is its’ discussion and presentation of the abilities of the UWB technology, as well as solutions to increase accuracy.
6.2 Recommendations & Future Applications

People spend most of their lives indoors. Positioning technology can have myriads of applications indoors but must be accomplished without reliance on GPS and other traditional navigation solutions. The ability of UWB to operate in NLOS environments, such as indoors, is an exciting and appealing way to solve positioning problems. As UWB begins its’ integration into PNT solutions, it is becoming possible to map almost any local location in the world. With additional research and algorithmic developments, the use of these sensors indoors and in NLOS environments can be accomplished accurately, with either permanent or temporary network setups.

While UWB use indoor is already prevalent, positioning performance may be improved with the design of the environment considered so that varying interferences can addressed. Prior knowledge of values associated with various structures and materials will allow for better calibration. This research begins this process. Additional studies will add to the knowledge base, further improving applications. UWB can be the perfect substitution to GPS in indoor environments. Its’ through wall ability makes additional positioning applications almost limitless. The UWB signal’s ability to transmit accurate timing information and communication data also makes it possible to provide solutions to problems outside of positioning and navigation.

Additional research is needed to develop a truly ad-hoc network. While this thesis is a step in that direction, faster and easier setup is always desirable. By developing techniques and units for independent collections and communications,
additional problems may be solved as the potential abilities of the networks to be used can be increased.

The author recommends additional indoor laboratory testing. The laboratory settings displayed large errors, which could be reduced with more analysis and better collection. The addition of a robotic total station with a higher frequency will increase the ability to simulate real-life movements, as well as decrease the error in collection from multiple readings. Additional NLOS experiments should also be performed to determine the achievable accuracies when calibrating for various surfaces in kinematic applications.

The poor ground truth for calibration in the GPS-compromised testing made implementation of the models impossible. Accurate measurement of ground truth will allow the calibration of the measurements based on the environment. New procedures for measuring the lever-arm should be developed, including addition of an IMU to account for orientation. Additional improvements to the high accuracy solution will come from increasing the accuracy of the ground truth.

Clock synchronization is of vital importance for the next set of testing and analysis. The current integer time solution resulted in poor integration with IMU. Accuracy will increase by time tagging measurements with GPS time.

UWB has the ability to link indoor or NLOS environments with outdoor GPS positioning. These NLOS environments, while once difficult to map, allow for navigation behind walls, trees, and other objects. The development of ad-hoc or
permanent units for network establishment will make localization possible. Much like the cell-phone infrastructure, UWB has the ability to position at centimeter-level accuracy. Its integration into PNT solutions will continue to develop as additional research and development are commenced.
References


Koppanyi, Z.: TimeDomain PulsON P410 Units Overview, implementations and materials. 2014 (cit. on p. 3).


Appendix A: Basement

Figure A.1 Shows the histogram measurements for laboratory calibration, rover unit 103, corner unit 105.

Figure A.2 Shows the histogram measurements for laboratory calibration, rover unit 103, corner unit 100.
Figure A. 3 Shows the histogram measurements for laboratory calibration, rover unit 103, corner unit 107.

Figure A. 4 Shows the histogram measurements for laboratory calibration, rover unit 103, corner unit 101.
Table A. 1 Displays the calibration data for the laboratory testing.

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<th>Pt#</th>
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<th>UWB Mean (m)</th>
<th>UWB Median (m)</th>
<th>Mean Difference (m)</th>
<th>Median Difference (m)</th>
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Figure A. 5 Displays the 2^{nd} order error surface fitted to the residuals at grid points with no model adjustment. The red star is the node being modeled and the blue circles are the grid points.

Figure A. 6 Displays the 2^{nd} order error surface fitted to the residuals at grid points with the average model adjustment. The red star is the node being modeled and the blue circles are the grid points.
Figure A.7 Displays the 2nd order error surface fitted to the residuals at grid points with the linear model adjustment. The red star is the node being modeled and the blue circles are the grid points.

Figure A.8 Displays the 2nd order error surface fitted to the residuals at grid points with the polynomial model adjustment. The red star is the node being modeled and the blue circles are the grid points.
Appendix B: Open sky

Figure B. 1 Shows the histogram measurements for open sky calibration, rover unit 103, corner unit 107.

Figure B. 2 Shows the histogram measurements for open sky calibration, rover unit 103, corner unit 101.

123
Figure B. 3 Shows the histogram measurements for open sky calibration, rover unit 103, corner unit 106.

Figure B. 4 Shows the histogram measurements for open sky calibration, rover unit 103, corner unit 105
Table B.1 Displays the calibration data for the open sky testing

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Table B.1 Displays the calibration data for the open sky testing
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Figure B. 8 Displays the 2nd order error surface fitted to the residuals at grid points with the polynomial model adjustment. The red star is the node being modeled and the blue circles are the grid points.
Figure B. 9 Shows the position of the GPS solution from RTKLib for the open sky test. These static positions were used in the calibration.

Figure B. 10 Shows the residuals of the GPS solution from RTKLib for the calibration portion.
Figure B. 11 Shows the GPS solution from RTKLib for kinematic trajectory 1.

Figure B. 12 Shows the velocity from the GPS solution generated by RTKLib for kinematic trajectory 1.
Figure B. 13 Shows the residuals from GPS RTKLib solution for kinematic trajectory 1.

Figure B. 14 Shows the open sky trajectory 2, no model adjustment. The ground truth, UWB trajectory, KF UWB trajectory, and the corner units are all marked.
Figure B. 15 Shows the open sky trajectory 3, no model adjustment. The ground truth, UWB trajectory, KF UWB trajectory, and the corner units are all marked.

Figure B. 16 Shows the open sky trajectory 3, no model adjustment. The ground truth, UWB trajectory, KF UWB trajectory, and the corner units are all marked.
Appendix C: GPS-Compromised

Figure C. 1 Shows the histogram measurements for open GPS-compromised calibration, rover unit 103, corner unit 107

Figure C. 2 Shows the histogram measurements for open GPS-compromised calibration, rover unit 103, corner unit 101
Figure C. 3 Shows the histogram measurements for open GPS-compromised calibration, rover unit 103, corner unit 106

Figure C. 4 Shows the histogram measurements for open GPS-compromised calibration, rover unit 103, corner unit 105
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Table C.1 Displays the calibration data for the GPS-compromised testing.
Figure C. 5 Displays the 2nd order error surface fitted to the residuals at grid points with no model adjustment. The red star is the node being modeled and the blue circles are the grid points.

Figure C. 6 Displays the 2nd order error surface fitted to the residuals at grid points with polynomial model adjustment. The red star is the node being modeled and the blue circles are the grid points.
Figure C. 7 Displays the 2nd order error surface fitted to the residuals at grid points with linear model adjustment. The red star is the node being modeled and the blue circles are the grid points.

Figure C. 8 Displays the 2nd order error surface fitted to the residuals at grid points with average model adjustment. The red star is the node being modeled and the blue circles are the grid points.
Figure C. 9 Shows the GPS RTKLib solution for the GPS-Calibration with only 32% Fixed

Figure C. 10 Shows the satellite visibility for the GPS-compromised test.
Figure C. 11 Shows the SNR and multipath for the GPS-compromised test

Figure C. 12 Shows the number of satellites and the solution able to be calculated for the GPS-compromised test.
Figure C. 13 Shows the GPS-compromised trajectory 2, no model adjustment. The ground truth, UWB trajectory, KF UWB trajectory, and the corner units are all marked.

Figure C. 14 Shows the GPS-compromised trajectory 3, no model adjustment. The ground truth, UWB trajectory, KF UWB trajectory, and the corner units are all marked.
Figure C. 15 Shows the open sky trajectory 4, no model adjustment. The ground truth, UWB trajectory, KF UWB trajectory, and the corner units are all marked.

Figure C. 16 Shows the open sky trajectory 5, no model adjustment. The ground truth, UWB trajectory, KF UWB trajectory, and the corner units are all marked.
Figure C. 17 Shows the open sky trajectory 6, no model adjustment. The ground truth, UWB trajectory, KF UWB trajectory, and the corner units are all marked.