Evidential Problems with GPS Accuracy: Device Testing

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Declaration

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which to a substantial extent has been accepted for the qualification of any other degree or diploma of a University or other institution of higher learning, except where due acknowledgement is made in the acknowledgements.

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David Huang

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Abstract

In the last few decades there has been an exceptional growth in the use of the GPS (Global Positioning System). The usage of GPS navigation has escalated from the military area and commercialised for civilian use. Since the Selective Availability was turned off in the year 2000, the accuracy of civilian GPS has improved from 100 meters to 20 meters. In the last decade, several improvements to the GPS have been implemented, including new signals for civil use and better accuracy and integrity for all users. As a result, the GPS applications are now widespread in aviation, rail, marine, and particularly in passenger cars and personal handheld devices.

This research builds on research reported in relevant publications and focuses on the immediate variables external to a GPS device such as cloud cover, weather, obstructions, split signals and user preferences, and tests the accuracy of three GPS devices.

The testing was conducted in three types of weather conditions (sunny, cloudy and rainy) and four environmental conditions were selected (tree canopies area, a suburban area, a city street with tall buildings and an indoor environment). Based on the literature reviewed these represented a 100% tree canopy, a varied percentage of canopy open and a closed canopy. The proposed testing methods therefore measure the travelled distance for each device in each weather and canopy combination, to analyse the accuracy and evaluate the possible factors that influence the accuracy.

The research project showed that the environmental conditions, GPS technique employed and the speed of movement all influence the GPS accuracy. These results confirm the results found in the literature regarding the impact of different canopy types on GPS accuracy. The findings of this study have implications for the way a digital investigator must audit and report evidence extracted from GPS devices. Future research is also required to further explore other factors that are found to influence GPS accuracy by other studies. Findings from such research will further the understanding of GPS

accuracy in digital forensic investigations and will improve the presentation of GPS related evidence in courts.

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List of Abbreviations

3D	3 Dimensional
AGPS	Assisted Global Positioning System
AIS	Automatic Identification System
CA	Control Antennas
CBD	Central Business District
CPU	Central Processor Unit
DGPS	Differential Global Positioning System
DR	Dead Reckoning
DTM	Digital Terrain Models
GB	Giga Byte
GIS	Geography Information System
GLONASS	Global Navigation Satellite System (Russia)
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
IMO	International Marine Organization
INS	Inertial Navigation System
IRNSS	Indian Regional Navigation Satellite System
ITS	Intelligent Transportation Systems
LCD	Liquid Crystal Display
MCS	Master Control Station
MD5	Message Digest 5
MicroSD	Micro Secure Digital
MMGPS	Map Match Global Positioning System

MS	Monitor Station
NANU	Notice Advisories to Navstar Users
NAVSTAR	Navigation Satellite Timing and Ranging
OMMGPS	Odometer Map Match Global Positioning System
PC	Personal Computer
PDA	Personal Digital Assistant
PPS	Precise Positioning System
PTC	Positive Train Control
QZSS	Quasi-Zenith Satellite System
RMS	Root Mean Square
RINEX	Receiver Independent Exchange Format
SD	Standard Deviation
SIP	Signal Interruption Probability
SPSS	Statistical Package for the Social Sciences
TDARDS	Truth Data Acquisition, Recording and Display System
USB	Universal Serial Bus
UTC	Coordinated Universal Time
VCR	Video Camera Recorder
WAAS	Wide Area Augmentation System

Chapter 1 : INTRODUCTION

1.0 BACKGROUND

Global Positioning System (GPS) is a system of devices that uses satellite readings to determine a receiver's geocentric coordinates (gps.gov, 2012). Due to the commercialisation of the technology it has been widely adopted for many different business and private activities. It has also become more affordable, easier to use and generally available in everything from cameras to mobile phones. In the field of digital forensics, GPS applications have been used widely and with great success for helping investigators to solve various crimes. Investigators know that GPS data provides a good estimation of date, time and location but also that many variables influence the accuracy. The purpose of this research is to identify in the relevant scientific literature the factors influencing GPS accuracy and then to test some of these factors in field trials to better understand the challenges faced by investigators analysing evidence from GPS.

In digital forensics examiners have focused on collecting the digital evidence from traditional media such as personal computers. With the ubiquity of consumer-grade GPS, examiners are required to understand more about how to extract evidence from GPS devices, where the potential data might be stored in the device and the challenges when analysing such data. Importantly, the physical limitations of the GPS applications and other external factors not only affect the accuracy of collected data, but also influence the forensic investigation viability. From the issues raised it becomes apparent that we need to explore and evaluate the factors and conditions that contribute to the accuracy of GPS data.

1.1 PROBLEM DEFINITION

Due to the increasing popularity of GPS applications, it isn't surprising that GPS applications have used more prevalent for criminal activities. There are many available literature sources that discuss the challenges of gathering digital evidence from GPS devices. For example, the research paper from Jones, Sutherland and Tryfonas (2008) elaborates on the various forensic tools that can retrieve and analyse information presented by the GPS, as well as the challenges involved in the process of extracting evidence. The evolution of GPS devices is continuous and therefore technical challenges and variations in design will cause further problems for law enforcement officials (Chen, 2013). Strawn (2009) details what types of evidence should be collected from GPS devices and how to ensure the evidence can be legally admissible in court.

The expertise presented in literature regarding how data can be extracted from GPS devices is valuable. However, from the forensic investigation perspective the big question is the accuracy of date, time, and location data and which or what variables came into play and influenced the evidence in the particular circumstances. The accuracy of GPS can range from 50cm to 150m and the variation in refresh rates can alter the accuracy of time stamps. These are only some of the issues that may affect evidence matching. Hence, a great concern for tracking estimates is the integrity and accuracy of the collected data. A question raised by previous researchers is how to measure the accuracy of GPS data stored the device. Unfortunately, there is little research work available that discusses the potential factors that affect the accuracy of the GPS data. This is because it is assumed (as shown in Chapters 2 and 3) the mathematical models presented will adequately compensate for variations and the concern of accuracy is an elementary problem. For example, a GPS in a car does not have to be accurate to 1m and probably 15m is functionally sufficient in normal driving conditions. However, for forensic purposes 1m accuracy is likely to be the upper limit. As a result there is a definite gap in the literature in terms of the forensic implications of the GPS-tracking data accuracy.

Two studies further elaborate on this problem. Al-Kuwari and Wolthusen (2009) surveyed the types of localization and tracking techniques used in the logic of GPS. They also worked out the forensic implications and calculated the impact of variability on the accuracy of data. Another similar study has been presented by Vodhanel (2011) who discuss a number of possible factors that influence GPS accuracy. They list environmental conditions, line to signal and device capability (e.g. refresh rates and so on). In order to evaluate the forensic viability, they also suggest mathematical and experimental approaches to determine the accuracy of the collected GPS data.

Nevertheless, there are a number of factors that affect accuracy at the same time and additional knowledge regarding how these factors impact the accuracy is required.

Understanding of the reliability of GPS information and accuracy is extremely important for a forensic examiner and it is necessary to be aware of the barriers that would affect the accuracy. Currently the accuracy level of the data that is extracted from GPS devices is determined largely subjectively and there is no standardized procedure or even specific approaches for determining the level of data accuracy. The aim of this thesis is to offer a comprehensive perspective on a variety of factors that might affect the accuracy level of GPS data and to unpack causal factors that depend on many interacting variables. It is an opportunity to test assumptions that underlie the assumed stability of GPS data. The field tests will focus on comparing three GPS devices two of which are similar and the third one is different. Establishing a system for reliable real-time monitoring is not only important, but also the data collected and the limitations that are revealed have an important impact on the interpretation of time location measures as evidence.

1.2 MOTIVATION

The problem statement for the selected research topic, namely GPS data accuracy, has been presented in the above section. This section explains the motivation for choosing the research topic and briefly discusses how the GPS analysis is becoming more prevalent in the field of digital forensics. A further concern is raised that there is a lack of guidance available for forensics examiners to determine the accuracy level of the digital evidences that may be collected from GPS devices.

1.2.1 GPS and Forensics

Nowadays, the commonest digital storage device for forensic investigators to collect digital evidence is traditional media such as computer hard drives. However, technology has been continually evolving and digital fingerprints are being held in different types of devices such as Smart phone, GPS and so on. Predictably, since the GPS navigation technology has spread from military usage to civil usage, GPS devices have become more and more common in current digital examinations. Recently, research related to the methods of extracting digital evidence from GPS devices has attracted much attention and discussions. Moreover, previous studies have found that GPS has numerous possible random and systematic errors that influence data accuracy. However, currently available literature does not provide detailed knowledge regarding how these existing GPS errors affect the data accuracy and how we can reduce the errors to increase the accuracy level. Therefore, the lack of previous work has highlighted the need for further understanding of the factors that affect GPS accuracy.

1.2.2 Challenges of collecting digital evidence from GPS

With the advancements of the GPS technology, GPS applications not only store navigational data, but also contain evidentiary data such as personal information, positioning data and track logs. Some GPS devices contain video and image files. This information provides digital evidence or some invaluable leads for an investigation. Nevertheless, performing a forensic examination on GPS devices differs from dealing with traditional personal computers (PC) in various important ways and the design of these devices presents challenges for the examiner during a digital forensic investigation.

Firstly, GPS vary in areas of hardware components, communication approaches and operating systems, as well as file storage methods. Accordingly, acquiring digital evidence from GPS requires particular forensic procedures and technology, as well as professional knowledge of GPS devices. Additionally, although a great deal of useful data can be harvested from GPS devices as digital evidence, it is also recognized that the investigators need to ensure the integrity and availability of the collected evidence. GPS must be determined forensically sound on different levels. All steps taken for investigation of GPS devices must have certain controls to ensure the evidences gathered are valid for law enforcement. However, this is a difficult task since the accuracy level of GPS data is impacted by a wide variety of factors. Their impact, however, is only considered in very general terms in literature. Further knowledge in the area will not only help forensic examiners but will improve the explanation of errors in any digital forensic report. Summing up, due to the increased popularity of GPS applications, there is a need to investigate how GPS works forensically and what factors will impact the GPS accuracy. As a result, a better understanding of analysing data present on the GPS for the investigators can be provided.

1.2.3 Lack of existing research in this problem area

Although GPS navigation is not a new technology, the factors that affect GPS accuracy have not widely studied by the researchers. There is a lot of literature on GPS devices and about the issues related to gathering evidence from them. However, most of this research is focused on gathering data from storage on a device. In terms of GPS technology there is little information on the forensic viability of GPS data in a tracking context. Since the cost of hardware has been decreasing and consumer-grade GPS devices have become ubiquitous, there are important implications for evidence collection. Accuracy in terms of time/position identification is a major issue for tracking moving objects such as vehicles, people and location on maps (such as Google images). It is therefore of great interest to extend the research area related to GPS accuracy and find out the relationship between the accuracy and the external factors.

1.3 RESEARCH QUESTION AND METHODOLOGY

As outlined in the above section, this thesis discusses the GPS (Global Positioning Systems) and the accuracy of GPS for evidential measures. In addition, the process of conducting a forensic examination on GPS devices will be evaluated theoretically based on the knowledge gained from the literature review; also, the issues that have a potential to affect the GPS accuracy are highlighted for discussion. Specialized procedures and software for retrieving and analysing digital evidence from GPS have been discussed and developed by pervious researchers, but most studies were based on the assumption that the GPS data was accurate. There is therefore, an obvious need for better understanding of what factors affect measurement of the accuracy of GPS data the most. Consequently, the main research question that has been developed for this project is: *How accurate is a GPS device over the test period?*

The approach for this project will be focusing of system testing. The basic idea is to test each device in similar conditions and to measure a sample of the contributing factors to accuracy, variable by variable. Hevner and Chatterjee (2010) fine- tuned this approach that was introduced in an earlier paper written in 2004 by Hevner, March, Park and Ram. The seven guidelines proposed in their paper will form the basis and direction of my research and they are the following: design as an artefact, problem relevance, design evaluation, research contributions, research rigor, design as a search process, communication of research. With these guidelines in mind, my research will initially take the form of an exhaustive literature review in order to provide the background and context. This will not only help me to design my GPS measurement system, but also provide background for generating and understanding the relevant metrics mentioned in the literature review.

1.4 RESEARCH FINDINGS

The research findings show that the selected GPS devices were influenced by a number of factors in the immediate surroundings and by the way the user was using the device. These findings are not surprising given the literature reviewed in chapters 2 and 3. For example Hasegawa and Yoshimura (2005) showed the effects of canopy cover on the accuracy of GPS data. The test results obtained in my study confirm the factors. The testing was conducted at walking speeds but the movement of the device and between different canopy covers suggests that the accuracy of a car GPS can be substantially influenced by the environment in which it is used. A GPS would be travelling at far greater speeds and changing between different canopies on a regular basis. Consequently what may be recorded in the GPS logs reflects environmental conditions as well as the carefully designed mathematical models for measurement. The local environmental variations are contributing factors that a digital investigator must hope to understand and to explain in his/her digital forensic report.

1.5 STRUCTURE OF THE THESIS

The thesis begins with a formalities section that includes the research abstract, acknowledgements and a table of contents. This is followed by lists of abbreviations, figures and tables. These matters along with the Reference section at the end provide organisation and access to the research.

Chapter 1 outlines the selected research topic, its justification and related background information on GPS accuracy. It briefly introduces the existing approaches for collecting digital evidence from GPS devices and the use of GPS technology in the forensic investigation area. The chapter also identifies the motivation driver for this study and elaborates on the structure of the thesis.

Chapter 2 presents a critical literature review and defines the current state of GPS technology, the studies related to accuracy of GPS measurement and the applications of the technology. This chapter provides an overview of existing GPS measurement and location tracking technology, and a review of the ideal conditions for GPS performance. Moreover, it elaborates on the concepts and working process of GPS; the sources of potential GPS errors have also been highlighted. This is followed by an outline of major factors that could affect the level of accuracy of GPS measurement and how each of these factors will influence the accuracy of measurements. It concludes with a review of the issues and problems identified in GPS measurements.

Chapter 3 develops and specifies the research methodologies used to conduct the testing of the GPS accuracy and to analyse how the external factors affect the accuracy. At the beginning of this chapter, a review of five relevant research papers is made with the aim of learning from others how to do this type of research. The research questions and associated hypotheses for each question are then formulated on the basis of the gathered information from the previous studies that relate to the same problem area and the comprehensive literature review in Chapter 2. In addition, the proposed research guidelines suggest an examination of the GPS devices with multiple test scenarios. The theoretical knowledge and recommendations presented in previously conducted studies provide guidance for establishing the testing methodologies and key approaches and tools that should be used for the testing. The testing methods proposed here are consisted of four specific stages and each research question will be answered through the analysis of the testing results. The proposed equipment, data requirements and expected testing outputs of each testing stage are also discussed. The chapter concludes with a discussion of the limitations of the proposed research methodology.

The research outcomes from each of the four GPS accuracy testing phases specified in Chapter 3 are reported in Chapter 4. Chapter 4 starts with a section that determines the variations made to the proposed data requirements. According to the actual circumstances, various changes may be applied to the proposed testing approaches and this is reported. Next, the outcomes from each independent stage of testing are reported and analysed to evaluate the implemented testing design and to determine the GPS accuracy. The findings are visually represented and summarized in graphical form. The chapter concludes with a summary of the main factors found to affect the GPS accuracy.

Chapter 5 discusses the research findings for each test stage. Firstly, the six hypotheses are tested by using the research findings presented in Chapter 4 and then revised, followed by a more intensive discussion aimed at answering each of the research questions. In order to provide a further understanding of the test outcomes, the gathered data is processed and summarised in tables. Secondly, each of the factors identified as influencing the GPS accuracy is discussed along with a detailed analysis of how these factors affect the accuracy. The last section in this chapter offers some suggestions on how to use the research findings for potentially improving the GPS accuracy.

Chapter 6 concludes the thesis by reflecting on the main findings and recommending further research topics and areas.

Chapter 2 : LITERATURE REVIEW

2.0 INTRODUCTION

The primary objective of Chapter 2 is to critically review the existing literature that is relevant to the GPS and to the accuracy of GPS for evidential measures. The concepts of GPS, the working process of GPS, and the issues that have the potential to affect the accuracy of GPS measurements are all reviewed in this chapter. Based on the knowledge derived from the literature review, the next step is to analyse how the level of accuracy of GPS measurements relates to the digital forensic investigations.

The literature review is not only focused on the current research, but will also identify the potential problems that affect the accuracy of the GPS. This chapter is divided into five main sections. Section 2.1 presents the definition of GPS and defines the interaction between satellites and the GPS devices. Sections 2.2 to 2.4 discuss the GPS devices that are commonly used by the public, the measurement of the GPS accuracy and elaborate on the precision of the currently used devices. Finally, all the issues and problems related to the accuracy of GPS that are presented in the literature review are identified and are discussed in section 2.5. Section 2.5 is the foundation of this research as it identifies problem areas that have potential for research.

2.1 GPS DEFINITION

When investigating the accuracy of GPS devices, the primary task is to explore GPS and outline a boundary for such devices. Base on the output of the primary task, the GPS devices for testing will be selected. The following section will identify the definitions of GPS provided by other researchers. It will investigate the influence of GPS devices on different industries in which they are implemented. The investigation of GPS devices' accuracy will be also discussed along with GPS architecture.

2.1.1 Background

A GPS-enabled device uses satellite readings to determine a receiver's geocentric coordinates. The coordinates are related to the centre of the earth, and the information will be read by a number of satellites, that is optimally at least 4 satellites (GPS.gov, 2012).

Generally, the GPS is defined as a group of satellites in the earth orbit that transmit precise signals, to allow GPS receivers to calculate and display the accurate location, time information and speed to the users (about.com, 2012).

Table 2.1: Summary of Satellites (Wikipedia, 2012)

Block	Launch Period	Satellite launches				Currently in orbit and healthy
		Suc-cess	Fail-ure	In prep-aration	Plan-ned	
I	1978–1985	10	1	0	0	0
II	1989–1990	9	0	0	0	0
IIA	1990–1997	19	0	0	0	10
IIR	1997–2004	12	1	0	0	12
IIR-M	2005–2009	8	0	0	0	7
IIF	2010–	2	0	10	0	2
IIIA	2014–	0	0	0	12	0
IIIB	Theoretical	0	0	0	8	0
IIIC	Theoretical	0	0	0	16	0
Total		60	2	10	36	31
(Last update: 24 May 2010)						

The GPS receivers capture the signals from three or more satellites, and then triangulate the obtained data and pinpoint the users' location. In this way, the timing message, precise orbit information, the system health and the rough orbit of all satellites will be transmitted between the satellite and the GPS receivers. In the last 40 years, there were 60 satellites launched successfully, as shown in Table 2.1. Currently there are 31 satellites still in orbit and operating (about.com, 2012).

2.1.2 System Architecture for GPS

Global Positioning System is a satellite based navigation system that can provide the exact location and time of an object at any place on the earth in different weather conditions. The basic concept of the GPS technology involves the transmission of signals by satellites that contain the time at which the message was transmitted by the satellite, the orbital information, the general system health and the rough orbits of all GPS satellites (roseindia.net, 2012). In order to run the GPS properly, a highly advanced architecture of GPS has been developed that includes three different segments, namely space segment, control segment and user segment (GPS.gov, 2012). Figure 2.1 illustrates how the three different segments work with each other. These GPS segments are introduced in the following sub-sections.

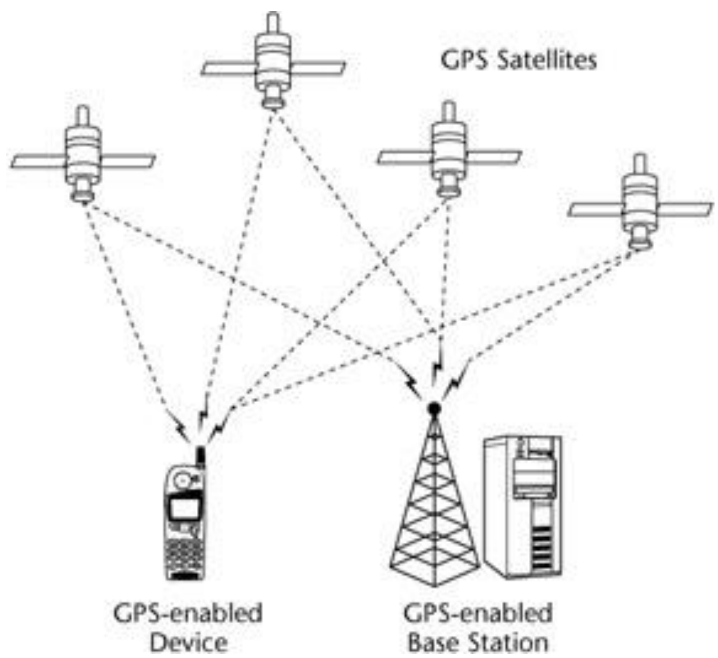

Figure 2.1: GPS Architecture (eTutorials, 2012)

The GPS satellites transmit signals from space that are received by the data receivers on the earth and are then used to calculate the three-dimensional location (latitude, longitude and altitude) of the object along with time. In the architectural framework of GPS, the space segment consists of 24 operational satellites and three more satellites along with the payload adapters to the boosters required to launch them into orbit. These satellites are placed in the medium earth orbit. The control segment consists of a master control station, alternate master control station, a host of dedicated, shared ground antennas and monitor stations. The user segment constitutes thousands of military users and millions of commercial and civilian users; the military users use the GPS Precise Positioning Service while the others use the GPS Standard Positioning Service (roseindia.net, 2012).

2.1.2.1 Space Segment

The GPS satellites are moving in an orbit around the earth with a speed of 3.9km per second and have a circulation time of 12 hours sidereal time, corresponding to 11.58 hours in earth time (kowoma.de, 2008). So how do we determine the orbit for the GPS satellites?

GPS satellites fly in medium earth orbit at an altitude of approximately 20200 km, and each of them circles the earth two times a day. The satellites in the GPS constellation are organized into six equally spaced orbital planes surrounding the earth. Each orbital plan contains four slots occupied by baseline satellites. As a matter of fact, the 24 slots are needed to ensure there are at least four satellites that can be viewed from virtually any point on the planet (GPS.gov, 2012).

According to Chinese Astronomy and Astrophysics, the satellite-borne GPS receivers are carried out by more low earth orbit satellites, and the precise orbit determination of low earth orbit satellites is a result of the satellite-borne GPS. The satellite-borne GPS precise orbit determination accuracy is based on the GPS ephemeris accuracies and the clock error (Wu, Peng, 2009).

The GPS constellation that travels around the orbit is a mix of new and legacy satellites (GPS.gov, 2012). The current GPS satellites include Block IIA, Block IIR, Block IIR (M), and Block IIF.

- **GPS Block IIA**

  GPS Block IIA is the advanced version for the second generation GPS satellites. The first production IIA satellite was launched in November 1990 and the last one was launched in November 1997, in total of 19 satellites. At June 2012, there are 10 Block IIA satellites remain in the GPS constellation (GPS.gov, 2012).

- **GPS Block IIR**

GPS Block IIR is the replacement for the Block II/ IIA series satellites as these satellites are degraded or exceed their intended life cycle. The first Block IIR satellite was launched successfully in July 1997, and the last one was launched in November 2004. In June 2012, there were 12 Block IIR satellites remain in the GPS constellation (GPS.gov, 2012).

- **GPS Block IIR(M)**

The Block IIR (M) (M stands for modernized) series satellites are the upgraded version of the IIR series satellites; the new military and new civil GPS signals are added with this generation of spacecraft. The first Block IIR (M) series satellite was launched in September 2005, and as of June 2012, there were seven healthy Block IIR (M) satellites in the GPS constellation (GPS.gov. 2012).

- **GPS Block IIF**

The IIF series GPS satellites is the advanced version of the IIR (M) series satellites, with added third civil signal in a frequency protected for safety-of-life transportation. The IIF series is reported to have a longer life expectancy and a higher accuracy requirement. The Block IIF satellites will have a higher accuracy, better signal strength and the good quality of GPS services. The IIF series include a total of 12 satellites and the first satellite was launched in May 2010. In June 2012 there were 2 operational IIF operating in the GPS constellation (GPS.gov, 2012).

- **GPS Block III**

The Block III is the newest block of GPS satellites and currently under deployment. The Block III satellites will provide more powerful signals to enhance signal reliability, accuracy and integrity (GPS.gov, 2012).

2.1.2.2 Control Segment

The GPS control segment includes a global network of ground facilities used for tracking the GPS satellites, monitoring the transmissions, performing analyses, and sending commands and data to the constellation (GPS.gov, 2012). Currently the control segment consists of a master control station in Colorado, USA, an alternative master control station in California, USA, 12 command and control antennas, and 16 monitoring sites around the world (GPS.gov, 2012).

- **Master Control Station**

  The master control station is responsible for generating and uploading the navigation messages and ensures the health and accuracy of the satellite constellation. It also monitors the navigation messages and system integrity. The space operators use the master control station to maintain the satellites. If one of the satellites fails, the MCS can relocate the satellite and optimize the GPS constellation (GPS.gov, 2012).

- **Monitor Station**

  The main purpose of the monitor stations is to collect atmospheric data, range measurements and navigation signals, and to send the information back to the master control station to ensure the health and accuracy of the GPS satellites.

- **Control Antennas**

  The ground antennas are used for communicating with the GPS satellites for commanding and controlling. The antennas transmit navigation data and processor program load, and collect telemetry. They also support the normal command transmissions to the satellites (GPS.gov, 2012).

  The multibillion-dollar GPS modernization program is an on-going project that aims to upgrade the GPS space and control segment, in order to improve the GPS performance and accuracy, including the new civilian and military signals. The GPS modernization program also introduces the modern technologies all the way through the space and control segment to improve the overall GPS performance (GPS.gov, 2012).

2.1.2.3 User Segment

The GPS is an essential element of the Information structure just like the Internet. The open, free and reliable nature of the GPS has led to the development of thousands of application tools that affect modern society. The GPS products have crossed different industries, such as agriculture, environment, rail, marine, survey and mapping, aviation, rail, road and highways (GPS.gov, 2012). Some major communication networks, financial markets, banking systems are heavily dependent on the precise time synchronization of GPS. The GPS is critical to national security, the applications are widely spread into the military operations, and nearly all the military assets are equipped with GPS-enabled devices (GPS.gov, 2012).

2.1.3 Other GPS

There are also different types of satellite navigation systems that are used and developed by other countries and regions. The following section will discuss the details of some of these navigation systems.

- **GLONASS**

  Global Navigation Satellite System (GLONASS) is a radio based satellite navigation systems that is operated by the Russian Government. The GLONASS is based on a group of active satellites that continuously transmit code signals in two frequency bands, which are received by users anywhere around the earth to identify their position and velocity in real time. This navigation system uses the same principle in data transmission and positioning methods as the GPS which is owned and operated by the US government (Wikipedia.com).

  The GLONASS space segment consists of 21 satellites in three orbital planes, with three on-orbit spares. The first GLONASS satellites were launched into the orbit in 1982, but the deployment of the full constellation of satellites was not completed until late 1995/ early 1996. The GLONASS system was officially declared operational on September 1993 (Wikipedia.com).

- **Beidou**

  Beidou Navigation Satellite System is a project set up by China to develop an independent satellite navigation system; it includes two generations - Beidou-1 and Beidou-2 (beidou.gov.cn, 2010).

  Beidou-1 is officially called Beidou Satellite Navigation Experimental System, which includes three satellites (two satellites for operation and one for backup) and provides limited coverage and applications. It has offered navigation services mainly for customers in China and their neighbouring regions since the year 2000.

  Beidou-2 is the second generation of the system known as Compass, which will be a global navigation system and consists of 35 satellites (beidou.gov.cn, 2010).

Beidou-2 has become operational for China in December 2011, with 10 satellites currently in use. The system is planned to offer services to Asia Pacific customers by the end of 2012 and to provide services to global customers on its completion by 2020 (Spaceflightnow.com, 2010).

- **Galileo**

Galileo is a satellite navigation system being developed by the European Union and the European Space Agency. The main reason for developing Galileo is to provide the high precision positioning/navigation system that the European nations can rely on, and to be independent from the USA GPS, Russian GLONASS and Chinese Beidou satellite navigation systems. Galileo is the fourth satellite navigation system can be used by the general public.

The Galileo project is Europe's proposed state-of-art satellite navigation system. The fully deployed system will include 30 satellites and the associated ground facilities, but the first two satellites were already launched in October 2011. Galileo will be interoperable with the US GPS and the Russian GLONASS (Europa.eu, 2012). Precision, availability and coverage will be the three main features of the Galileo system as described below:

- ✓ Precision

  In a combined use of GPS-Galileo system, the higher number of available satellites will offer higher precision to the users. Six to eight Galileo satellites will be visible in most locations, and by combining their signals with the GPS signal, an object position will be determined up to within a few centimetres (europa.eu, 2012).

- ✓ Availability

  With a higher number of satellites available to the users, there would be a higher availability of the service/signal to the high-rise cities, where the buildings might block signals from satellites that are low on the horizon (europa.eu, 2012).

- ✓ Coverage

Galileo will offer better coverage than the GPS at high latitudes, because of the location and the inclination of the satellite. This feature will particularly benefit Northern Europe (europa.eu, 2012).

- **IRNSS**

The Indian Regional Navigation Satellite System (IRNSS) is a regional navigation system that is developed by the Indian Space Research Organization, and is under the Indian government's control (livemint.com, 2007). IRNSS will provide standard Global Positioning Services to civilians, and also provide the same services to military in an encryption mode. The first satellite of the constellation is expected to launch during 2012 – 2013, and the full constellation is planned to be completed around 2014; a total of seven satellites will be delivered to form the satellite navigation system (rediff.com, 2002). The system is intended to provide position accuracy of better than 20 meters all throughout India and within a region extending approximately 2000 km around it (livemint.com, 2007).

- QZSS

The Quasi-Zenith Satellite system (QZSS) is a proposed by Japan regional time transfer system and Satellite Based Augmentation System for GPS, and its signal can only be received within Japan. The first satellite was launched in September 2010, and full operational constellation is expected by 2013 and will include a total of three satellites (jaxa.jp, 2010).

QZSS can enhance GPS services in two different ways: availability enhancement, that is to improve the availability of GPS signals; the second one is to enhance the performance, increase the accuracy and reliability of GPS-derived navigation solution (jaxa.jp, 2010).

2.2 GPS DEVICES

The GPS devices receive GPS signals in order to determine the device's location on the earth. They passively receive the satellite signals and don't transmit signals; they require an unobstructed view of the sky, so they can only be used effectively outdoors (pocketgpsworld.com, 2011). When the GPS signal is received, these devices can provide longitude and altitude information, so their users know what location they are at. GPS operations depend on a very accurate time reference, which is provided by atomic clocks on board the satellites.

Each GPS satellite transmits data that indicates the location and the current time. All GPS satellites synchronize operations so that these repeating signals are transmitted at the same instant. The GPS signals move at the speed of light and arrive at different GPS receivers at slightly different times because some satellites are further away than others. The distance to the GPS satellites can be determined by estimating the amount of time it takes for their signals to reach the receiver. When the receiver estimates the distance to at least four GPS satellites, it can calculate its position in three dimensions (pocketgpsworld.com, 2011).

There are at least 24 operational GPS satellites at all times plus a number of spares. The satellites, operated by the US Department of Defence, orbit with a period of 12 hours at a height of about 11,500 miles traveling at 9,000mph; ground stations are used to track each satellite's orbit precisely. The accuracy of a position determined with GPS depends on the type of receiver. Most consumer GPS units have an accuracy of about +/- 10 meters. Other types of receivers use a method called Differential GPS (DGPS) to obtain much higher accuracy. DGPS requires an additional receiver fixed at a known location nearby. Observations made by the stationary receiver are used to correct positions recorded by the roving units, producing an accuracy greater than 1 meter.

GPS devices are mainly used in marine, military, aviation and for civil applications. Different types of GPS devices exist on the market for public use or are used in the military. The following subsection will discuss how these devices display the location and their advantages and disadvantages.

2.2.1 Military GPS

The NAVSTAR (Navigation Satellite Timing and Ranging) global positioning system is a US Department of Defence system of 24 satellites that provide navigation information to both civilian and military users around the world (Kaplan & Hegarty, 2006). The PPS (Precise Positioning System) is an extremely accurate military positioning, velocity and timing system service. The military equipment provides accurate data at less than 25m feet vertically and 20m horizontally, with a 200 nanosecond UCT accuracy (Kaplan & Hegarty, 2006).

The GPS devices provide navigation, tracking, bomb and missile guidance, rescue, and map update and facility management to the military services. For a long time the military used to use the night skies to determine their direction, but this was often impossible, especially in unfamiliar territory. During the 1990 Gulf war and 1999 Kargil conflict, the necessity for the troops to know their position was clearly highlighted. While initially only 1000 GPS receivers were issued for the Gulf war, at the end of the war nearly 9000 handheld devices were used (GPS: A military perspective). The GPS receivers also proved its value in the Kargil conflict, the special force team used the GPS to locate and destroy the vital enemy installations, to occupy the gun positions, as well as to track and plan convoy movements effectively.

The US army develops a GPS Truth Data Acquisition, Recording and Display System (TDARDS) (GPS: A military perspective). This tracking system uses up-to-date GPS data and computer technology to provide highly accurate and real-time position information. This system is highly modular and can be modified to meet any special needs of tracking applications very easily. Modern weapons use GPS to input targeting and guide the direction; the GPS receivers can constantly calculate the weapon's location (bomb, missile) while in flight and adjust the direction in order to hit the target. Rescue is another valuable usage of GPS. The US army integrates the GPS receivers into the communication radio so the search and rescue of a crew member would be much faster and more efficient. Updating maps is another important feature for the military GPS, because the modern mapping products are able to locate the target locations more accurately.

2.2.2 Public Used GPS

GPS is widely used by civilians and is widespread in different industries, including aviation, environment, rail, public state and disaster recovery, agriculture, surveying and mapping, road and highways, timing and so on. This sub-section will discuss how GPS-enabled devices are used in these industries.

- **Aviation**

The GPS aircraft tracking system is installed on aircrafts to report the positions via the satellite or the cellular network. The information is accessed via web-based mapping interface. Both the historical and the current information can be viewed from there. The GPS aircraft tracking system reports bearing, speed, altitude and aircraft-specific information. The reporting interval can vary from one minute to fifteen minutes.

GPS is used in aviation to improve safety, accountability and situational awareness. Safety is referring to some emergency situation that happened to the aircraft, e.g. if the aircraft went down; the position information and aircraft's altitude information from the GPS would reduce the search time and speed up the rescue process. The aviation GPS-enabled devices are able to help aircraft operators to access historical information for each aircraft that was saved by the pilots, and possibly save hundreds of thousands dollars in maintenance and repair. The aircraft GPS can track the aircrafts remotely via the application on smart phones, or receive emails about certain events. It can also improve the operational efficiency for identifying the aircraft arrival times and some unexpected events, and plan for the aircraft early arrival.

- **Agriculture**

In the past it was very difficult for farmers to correlate the production techniques and the crop yields with the land variability. This would limit their capability to develop the most effective plant treatment and to enhance their productivity. When the precise agriculture combining the GPS and GIS (Geography Information System) was introduced to this industry, the situation changed, reducing expenses, producing a higher yield and improving the productivity of the farming industry.

With the help of GPS, GIS and remote sensing, farmers get the information required for improving the land and water use, and gain addition benefit from the information. The location information collected by GPS receivers is used for mapping field boundaries, road, and irrigation system and problem areas such as weed and disease (gps.gov, 2012). The accuracy of GPS enables farmers to draw out the areas with precise field acreage, road locations and distances between points of interest. The United State committed to implementing the second or third civil signal on GPS satellites, which would enhance the quality and efficiency of agriculture operations in the future (gps.gov, 2012).

- **Environment**

The GPS is also able to help authorities gather accurate and timely information for the earth's environment so they can make better decisions.

The data collection system can provide descriptive information and the item's accurate positional data, which would cover many kilometres of terrain. The data collected by GPS would be imported to GIS applications, so the government environment analysts would analyse the data together with other information and create a complete understanding of the situation (gps.gov, 2012). With the aid of GPS technology, the strategy planners can evaluate an area's wildlife, terrain and human infrastructure.

The GPS can also be used to understand and forecast the changes in the environment. With the integration of GPS measurements into functional method implemented by the meteorologist, the atmosphere's water content can be identified in order to improve the accuracy of weather forecast. GPS applications can also be used to track the movement and spread of oil spills. In earthquake areas, the GPS plays an important role in researching the earthquake and enables rescuers to search the victims.

- **Rail**

The GPS-based devices integrated into the rail systems can be used to track the movements of locomotives or trains, and the wayside equipment in real time. Combined with other communication systems, sensors and computers, the GPS can improve the rail safety, security and operational effectiveness (gps.gov, 2012). The GPS technology helps to reduce accidents and delays, as well as to reduce operation costs, while increasing the customer satisfaction.

Positive Train Control (PTC) system has been implemented in several countries to prevent train collision, derailment and passage through switches in the wrong position (gps.gov, 2012). PTC combines with real time location tracking and control systems to monitor and control train movement. The rail system also benefit the GPS technology; give more accurate information on train arrival, allows the automation of track inspection systems work much faster to detect more defects than human, to improve the safety and save money.

- **Surveying and mapping**

The GPS provides highly accurate surveying and mapping data to the skilled professionals that ensures cost savings and efficiency. It is much faster than the traditional methods, reducing the amount of equipment and labour required. GPS surveying is not bound by constrains such as line-of-sight visibility between the survey stations (gps.gov, 2012). The stations can be deployed at a greater distance from each other, and can operate anywhere with a good view of the sky, rather than being confined to remote hilltops as the traditional technique required. Land surveyors can carry GPS in backpacks or mount them on vehicles to allow fast and accurate data collection, which is also a great improvement compared to the traditional mapping.

- **Public safety and disaster recovery**

Time is a critical component of a successful rescue mission. The GPS can help rescuers to find the precise location of landmarks, buildings, emergency service resources and disaster relief sites, which would minimise rescue time and save more lives.

Another vital area of disaster relief is the management of wildfire. Aircraft equipped with GPS and infrared sensors can be used to identify the fire boundaries and the hot spots. The fire map will be transmitted to a portable computer at the fire-fighters' camp within a few minutes. The GPS also plays an important role in assisting rescuers to save people's lives in an earthquake, and helps the scientist to anticipate earthquakes. Based on the GPS technology, meteorologists can access water vapour content by transmissions of GPS data through the atmosphere, to track a storm and predict flooding (gps.gov, 2012).

- **Roads and highways**

The accuracy and availability of the GPS provide high efficiency and safety for the vehicles that use the roads, motorways and mass transit systems. Many of the issues related to the routing and dispatch of commercial vehicles is significantly reduced or eliminated when the GPS is used (gps.gov, 2012).

The GIS is integrated with GPS and provides monitoring of vehicle locations, making possible effective strategies that can keep transit vehicles on schedule and inform passengers of precise arrival time (gps.gov, 2012). The GPS can also help to survey the road and motorway networks, by identifying the location of features on, near or adjacent to the road networks. The vehicles drivers will learn the road or motorway situation and make a decision to avoid the high traffic and choose a better route to the destination. The Intelligent Transportation Systems (ITS) is a future development of the road/motorway monitoring system and GPS is playing an essential part in it. The system will be used to estimate the position of a vehicle relative to lane and road edge with an accuracy of 10cm (gps.gov, 2012).

- **Timing**

The GPS satellites contain multiple atomic clocks which contribute very precise time data to the GPS signals. The GPS receivers decode these signals and synchronize the receivers with the atomic clocks. This feature enables the users to determine the time within 100 billionths of a second, without owning or operating an atomic clock (gps.gov, 2012). Precise time is important to different activities around the world, such as communication systems, electrical power grids and the financial networks. The free available GPS time enables cost savings for the companies that depend on the precise time for their normal operation. As the GPS becomes updated, the additional second and third civilian GPS signals will increase the accuracy and reliability of GPS time, and remain free to the public, thus providing more benefits to the industries that rely on the precise time.

- **Marine**

The GPS has changed the way that marine operations function, including research and rescue, as the GPS provides fast and accurate method for the marine to track the location. It's important for marine officers to know the location of their vessel while in open sea or in a congested harbour. The accurate position, speed and direction are very important for the vessels to reach their destination safely. The marine critically requires accurate position information when a vessel departs or arrives in a port, as the hazards there may make the manoeuvring difficult and increase the probability of accidents (gps.gov, 2012). There is an enhancement of the current GPS used for the marine that is known as Differential GPS, which will provide higher precision on the location tracking and increase the safety in its coverage area.

GPS is also playing an important role in the marine port management. The GIS software integrated into the GPS is the key to efficient management and operation of automated container replacement in the world's largest port facilities (gps.gov, 2012). The Automatic Identification System (AIS) transmission is certified by the International Marine Organization to be used for vessel traffic control around busy seaways. The AIS is embedded with the GPS and the service is not only important for navigation, but is also used for the security of the ports and waterways, providing governments with greater situational awareness of commercial vessels and their cargo (gps.gov, 2012).

2.3 GPS MEASUREMENT SYSTEMS

The basic concept of GPS measurement is that the GPS satellites high above the earth send signals to the GPS receivers continually; the signal data includes the time of the message sent and the satellite position at the time of sending the message. In the meantime, the GPS receivers time the signals precisely and calculate the user's position (Global Positioning Systems, 2002). The knowledge of the precise position of the satellites allows them to be used as reference points, from which GPS receivers on the earth can determine their position. This technique of determining the position of an object is called ranging (physics.hmc.edu, 2012).

A satellite that is at a distance of 25,000 kilometres from a person holding a GPS receiver determines the person's position to be somewhere on a sphere with a radius of 25,000 kilometres, centred on the satellite. However, the exact location of the person on that sphere is yet unknown. If at the same time, the distance from the person to a second satellite can be determined to be 20,000 kilometres, then a second sphere with a radius of 20,000 kilometres can be determined on which the person is also positioned. Thus the person must be on the circle formed by the intersection of the two spheres of position. A third satellite provides yet a third sphere, which narrows down the location of the person to exactly two points. One of these points is often an impossible solution, frequently several thousand kilometres off in space, thus three satellites ranges can determine the precise position of the person. Three satellites provide enough information to find the x, y and z coordinates of an object. However, in practice, four satellites are required to pinpoint a position (physics.hmc.edu, 2012).

From the above example we understand how the ranging model assists the GPS to locate the receiver. However, we didn't mention how the distance was determined. The Global Positioning System works by having each of the 21 active satellites constantly radiate microwares. These microwares are received by the GPS receiver, which can use the method of ranging to locate its position. The distance from the receiver to one satellite is measured in the following way. The satellite and receiver are controlled by separate clocks, the satellites are set as accurately as possible with an atomic clock, and are assumed to be synchronized with one another; at some known time a satellite emits a signal in the form of microwares. This signal reaches the receiver after a certain interval of time has passed. Since microwares travel at the speed of light, a known velocity and a known time allows the receiver to determine the distance to the satellite. Thus it is important that the time be measured precisely in order to accurately measure distance, as an error of the synchronizations of the two clocks of one microsecond creates an error of 300 meters. This requires a fourth satellite, since a fourth variable – time, has been added to the unknowns that previously included only the x, y, z distances (physics.hmc.edu, 2012).

In order to maintain control over the navigation system, the military wanted to limit access to the most accurate GPS measurements. The method they chose for this operation was to transmit inaccurate information to civilians about when the signals had been sent from the satellites. By altering the satellites clocks slightly according to a specific code, those with access to the code are able to obtain accurate information while civilians are forced to deal with the inaccuracy in distance measurements resulting from the time error. The modified signals allowed non-military GPS users to obtain navigational readings that are accurate to approximately 100 meters. However, civilians have found ways around this dithering of the clocks. By comparing the GPS-measured position of a known location with its actual coordinates, it is possible to detect the amount of dithering. Once the amount of dithering is known, the corrections can be broadcast to the GPS receiver, and an accurate calculation of the receiver position can be achieved. Thus even without access to the dithering codes kept secret by the military, it is possible for a civilian to determine their position with an accuracy of millimetres (physics.hmc.edu, 2012).

2.4 GPS HEALTH AND ACCURACY

How do we know if a navigation system is actually achieving its advertised accuracy and not misleading the GPS users with the incorrect information? In order to get the accurate position from the GPS, it is essential to maintain the health and accuracy of the system.

2.4.1 GPS Accuracy and Precision

When the accuracy of GPS is to be defined, we compare the measured value with the reference value and find out how well they agree. Ideally, the reference value for the GPS would be the published coordinates of a geodetic reference mark (Langley, 1999). The deviation is simply the difference between the measured value and the reference value. If we make a series of repeats of the measurement, and work out the mean value of the series of measurements, the difference between the mean and the reference value is called the bias (also named systematic error). As a result, we usually take accuracy to mean the absence of bias, and we measure inaccuracy by the value of the bias (Langley, 1999).

However, accuracy is not necessarily the same thing as precision. Precision refers to the closeness to the mean of observations and accuracy refers to the closeness to the truth (earthmeasurement.com, 2005). There are different ways to identify the precision, such as standard deviation, confidence, variance, range and probability intervals. The accuracy can't be calculated solely from measurement values. If the system's bias can be calibrated, or if the bias is negligible, then we can interpret precision estimates as the accuracy estimates with caution.

The GPS accuracy will be affected by a number of factors, such as noise in the radio signal, atmospheric conditions, satellite positions and natural barriers to the signal. The signal noise results from signal disruption near the receiver or different signals in the same frequency, and creates errors from 1 meter to 10 meters. Some high objects such as mountains or buildings that are between the satellite and the receiver can also produce errors, and the bias could be up to 30 meters (maps-gps-info.com, 2012). To get around problems caused by factors that affect the GPS accuracy, some other technologies such as Differential GPS (DGPS), Assisted GPS (AGPS) and WAAS needed to be developed to aid in determining an accurate location.

DGPS can improve accuracy to three feet or better. DGPS employs both roving receivers that make satellite position measurements and stationary receivers that use their position to compute signal timing (Bajaj, Ranaweera and Agrawal, 2002). The signals that reach both receivers have virtually identical errors; the reference receiver can calculate the difference between proposed and actual signal travel time. The reference receiver doesn't know which satellite the roving receiver is using to calculate the position, so it calculates error corrections for all visible satellites. The receiver broadcast this information to the roving satellites, which then apply corrections for the particular signals they are using (Bajaj, Ranaweera and Agrawal, 2002).

The reference point of an assisted GPS provides navigation and signal timing data to a location server, which relays this information to a GPS-enabled cell phone or PDA, as the linking mobile receivers to a cellular, Bluetooth based, or wireless local-area network infrastructure that has a reference receiver with a clear view of the sky, that can help to improve the GPS performance and accuracy. The client device pre-processes and returns basic GPS measurements along with statistical measures that characterize the signal environment to the server, which in turn performs a sequence of complex calculations on the data received from the client to determine the user's position (Bajaj, Ranaweera and Agrawal, 2002).

2.4.1.1 Ideal Conditions for GPS Measurement

Ideal conditions for GPS Surveying or Navigation are clear view of the sky with no obstructions from about 15 degrees elevation and up (earthmeasurement.com, 2005).

In the actual world, any obstructions in the area of the GPS antenna can cause a very significant reduction of accuracy. The interfering obstructions include fences, buildings, trees, cables and so on. Obstructions might have the following affects hence reducing the accuracy (earthmeasurement.com, 2005):

- Satellite signal multipath (Figure 2.2);
- Reduced number of satellites seen by the receiver
- Reduced strength of satellite geometry
- Corrupt GPS measurements

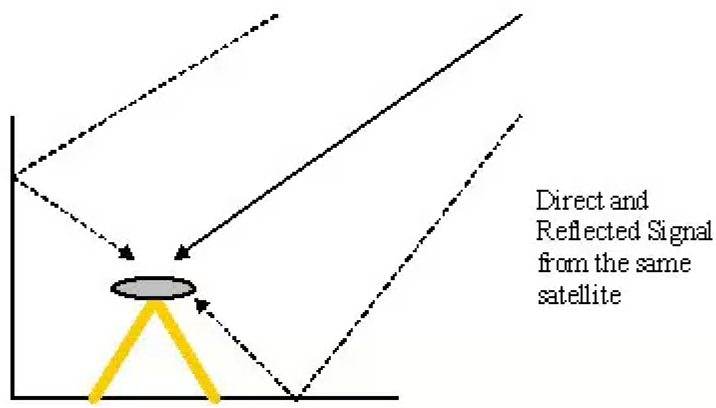

Figure 2.2: Satellite Signal Multipath (Earth Measurement Consulting, 2012)

The multipath is caused by GPS signals reflected from surface near the GPS antenna that can either interface with or be mistaken for the signal that follows the straight line path from a satellite. In order to get an accurate measurement from a GPS satellite, it is necessary that the signal from the GPS satellite travels directly from the satellite to the GPS antenna. If the signal has been reflected off another surface prior to being received by the antenna, its length will be greater than was anticipated and will result in positioning error. Multiple path is difficult to detect and sometimes hard to avoid (earthmeasurement.com, 2005).

2.4.2 Master Control Station

The GPS satellites are monitored by Master Control Station at Schriever Air Force Base. With the help from the five monitor stations distributed around the globe to collect the data, the MCS assesses the GPS performance every 15 minutes by conducting tolerance and validation checks of the measured pseudo-ranges using a Kalman-filter, an error-management process (Langley, 1999).

In certain circumstances, ranging errors could be undetected by the MCS performance assessment process for as long as 29 minutes. To mitigate any potential problems caused by such long delays, MCS installed new software in February 1995 to check incoming range measurements every six seconds (Langley, 1999). The system raises an alarm if it detects an anomaly, and the reaction will be taken in one minute. Since the anomaly has been confirmed, the MCS staffs render the offending satellite's L-band signals untraceable. This procedure also affects the control segment tracking (Langley, 1999).

In addition to changing the satellite navigation message to inform the users of the GPS health problems, MCS issues NANUs (Notice Advisories to Navstar Users) that report satellites outages as well as planned service outage caused by maintenance (Langley, 1999).

2.5 EVIDENCE COLLECTION FROM A GPS

There are two different types of evidence collection from GPS devices: one is the traditional historical collection from GPS receivers (or GPS-enabled phones, PDAs and so on); and the other type is using live tracking on GPS receivers to collect the evidence. In most cases, the traditional historical collection is used commonly to perform the evidence collection and it is done on standard consumer grade GPS receivers. However, mobile GPS are widespread and especially as GPS receivers are embedded into mobile phones/ PDAs or used as car navigations, the live tracking evidence collection plays an important role. In both instances the validity of the collected information is paramount but they are used in different situations. The traditional collection (post factum) is more suitable to situations like retrieving the record showing what location the GPS receiver has been at, its time at the location and so on. In some recent cases, when a car with embedded GPS or a mobile with GPS receiver were stolen, the GPS signal could be tracked down via the GPS receiver feature by the forensic investigators or even by amateur sleuthing, to locate the stolen car or the mobile phone, and then take the next step of action. From the above examples it is clear that it is very important to know the level of accuracy of the GPS data.

Civilian GPS receivers are mostly embedded into mobile phones, which are often equipped with Bluetooth connectivity, MP3 player, image viewer, video capabilities and some other applications (Strawn, 2009). This means there would be much more data for forensic investigators to examine as potential evidence, not just the data collected from the GPS readings. The forensic investigators need to be aware of the relevant data that might be potentially stored on the device in question. Combining multiple types of data would help investigators to work out a scenario that may have been unfeasible if using only one single type of data (Strawn, 2009).

Similar to evidence collection on other digital devices the GPS data integrity and availability must be assured. Hence any of the GPS receivers/ GPS tracking systems must be forensically sound on different levels if it is to be determined valid. All the steps taken for investigation on GPS devices must have controls to ensure the evidence gathered is valid for law enforcement.

2.6 SUMMARY OF ISSUES AND PROBLEMS

The literature review chapter identified two major problem areas when looking at the accuracy of GPS devices – the location measurement and the veracity of GPS information. The physical limitations of the GPS not only affect the forensic investigation viability, but also influence the GPS devices efficiency in their day to day use. From the issues raised we need to understand and evaluate the factors and conditions that contribute to the GPS data inaccuracy.

Understanding the reliability of GPS information and accuracy is extremely important for a forensic investigation. The GPS tracking system uses the positioning information for operation; however, the positioning information is not 100% accurate at present. Section 2.5.1 already outlined the factors that would affect the GPS accuracy, as well as suggested some methods for improving the accuracy and for ensuring a regular stream of accurate data. The lack of location data constancy will be causing problems when dealing with what could be the evidence in criminal proceedings.

When retrieving data from a GPS receiver investigators need to have certain understanding of the current issues that relate to the usage of a common GPS receiver. The measurement errors need to be identified, and the veracity of any information gained for being used in a court of law required to be verified. While there is no pre-defined acceptable margin of error for GPS location information, some further analysis is potentially required. Section 2.4 discusses GPS measurements, and that for different types of GPS receivers there would be different ways to measure the location.

2.7 CONCLUSION

The literature review chapter has provided definitions for and an overview of the GPS; it also gives a brief introduction to the GPS measurement and location tracking technology. The basic concepts of the GPS have been reviewed and some issues with data accuracy have been identified. Some ways to mitigate the issues have also been discussed. From a forensic investigator's point of view, the challenge of evidence collection from GPS is that the veracity and consistency of measurements depend on environmental conditions.

The review of previous research showed it is very likely to have errors when determining the precise location of a GPS receiver based on the GPS data. The forensic investigator should be aware of the challenges and take actions to mitigate the issues. For the GPS tracking systems, the whole process of the tracking system must be taken into consideration. Despite the current GPS potentially not being 100% accurate, understood the causes of the inaccuracy will be useful. Further research is required. In Chapter 3 a methodology will be derived to investigate the GPS accuracy problem.

Chapter 3 : RESEARCH METHODOLOGY

3.0 INTRODUCTION

The objective in Chapter 3 is to formulate a research question and to build up a feasible methodology for developing a framework for the GPS accuracy research. GPS data or the live tracking information could be a source of evidence as it provides information for the location of the suspected object at a given time. There are several issues that arise regarding the topic of GPS accuracy. These issues are not only related to locating the position, time and direction correctly, but also identifying the relevant evidence on the GPS-enabled devices that is relevant to a case. For example, date, time and location stamps may not only be incorrect or inaccurate but also unrelated to the investigation.

As a starting point in developing a research methodology some previously published research on how to measure GPS accuracy is to be reviewed. Chapter 2 has identified the problem area but the review of five studies looking at the problem area can help to better understand what to do and how to do research in this area. The previous research provides important information such as methodology, tools and steps taken to accomplish the examination, as well as the testing results that show the accuracy of the GPS. It is also helpful to understand the challenges and problems to be faced.

Five studies in the chosen research area will be presented and reviewed in Section 3.1, with the purpose of learning from the experience of other researchers who have worked in a similar domain of study. Based on the knowledge from Chapter 2, Section 3.1 discusses some facts from the studies which are important to form the research question and hypothesis for testing. Section 3.2 will formulate the main research question and sub-questions that are associated with the hypothesis based on the gathered information. Section 3.3 will focus on building up a practical research model of the projected architecture, and will outline the hardware and software that would be used for this research and their requirements. Subsequently, section 3.4 will specify the data collection requirements. Such as how the data will be collected, processed and analysed. Section 3.5 and Section 3.6 will discuss the expected outcome from this chapter the limitations of this research and any foreseeable constrains on the research outcomes.

3.1 REVIEW OF SIMILAR STUDIES

Five studies have been identified for scrutiny with the aim to find out how other researchers have researched the GPS accuracy problem. . Chapter 2 evaluated some general articles and the various issues related to GPS accuracy. The following five studies have been selected by theme to be similar to what I hope to do in terms of methodology for researching GPS accuracy. Each study is analysed and presented as a possible way of doing the research.

According to Diggelen (1998), there are seven common GPS accuracy measurements (See Table 3.1).

Table 3.1: Common GPS accuracy measures

Dimension	Accuracy Measure	Probability %	Typical Usage	Definition
1	rms	68	Vertical	Square root of the average of the square errors.
2	CEP	50	Horizontal	A circle's radius, centered at the true antenna position, containing 50% of the points in the horizontal scatter plot.
2	rms	63-68	Horizontal	Square root of the average of the square errors.
2	R95	95	Horizontal	A circle's radius, centered at the true antenna position, containing 50% of the points in the horizontal scatter plot.
2	2drms	95-98	Horizontal	Twice the rms of the horizontal errors.
3	rms	61-68	3-D	Square root of the average of the square errors.
3	SEP	50	3-D	A sphere's radius, centered at the true antenna position, containing 50% of the points in the 3-dimensional scatter plot

The first study was conducted by Taylor, Brunsdon, Li, Olden, Steup and Winter (2006) and developed a method called a Map Matching technique to determine the precise GPS position, in order to calibrate an odometer with the help of a GPS receiver. The technique can be further improved with a more superior low cost GPS receiver technology or more attention to its operational application. This is discussed in section 3.1.1. Akiyama, Tanaka and Yonekawa (2007) from Keio University in Japan discovered an important factor, namely ionosphere delay, which affects the measurement accuracy. Some experiments and simulations were setup by the researchers aiming to correct the ionosphere delay and improve the measurement accuracy. Section 3.1.3 discusses the signal interruption probability (SIP) estimation of GPS accuracy under different forest conditions. This research and experiments were conducted by Hasegawa and Yoshimura (2007) under forest conditions, while the data was captured via GPS stations. The research revealed that float solutions produced by dual-frequency or single-frequency GPS data were less stable and predictable than positions calculated using code-phase DGPS data. Section 3.1.4 explores the research that looks into the consumer-grade GPS accuracy and reliability and was conducted by Wing, Eklund and Kellogg (2005). The researchers set up three measurements testing experiments in open sky, young forest and closed canopy setting within a conifer-dominated forest to test the positional accuracy of six different GPS receivers. Section 3.1.5 reviews a study conducted by Chalko (2007) that investigates the factors that influencing high speed measurement accuracy. The researcher set up a series of experiments under different conditions in order to find out how to improve the measurement accuracy.

3.1.1 Map Matching Technique to Improve Accuracy

The study conducted by Taylor et al. (2006) develops a method that uses absolute GPS positioning, map matched, to locate the vehicle on a road centre-line, when GPS is known to be sufficiently accurate. The test-bed application is called Map Match GPS (MMGPS) and processes raw GPS output data from GPS derived coordinates or RINEX files. MMGPS software has now been adapted to incorporate positioning based on odometer derived distances (OMMGPS), when GPS positions are unavailable. This article describes an experiment that used GPS and odometer observations taken on a London bus on a predefined route in central London, used Map Matching technique to test the GPS's accuracy, and identified grossly inaccurate GPS positions (Taylor et al, 2006, 757).

Taylor et al. (2006) introduced five models for GPS accuracy measurement in this paper. Usually the normal method to determine the location of a vehicle is by using GPS and some form of inertial navigation system (INS) or dead reckoning (DR) system, including odometer, gyro and compass, to determine the vehicles' current position relative to an initial position.

The article also refers to a solution from other researchers. This method integrates GNSS and DR using a technique called Kalman filtering. A test route was established in Australia, and the result of the experiment shows that by the end of a 10 min period the DGPS/DR solution degrades from an error of 1m to errors as great as 35m. The performance of the filter depends on the model it uses. If too much weight has been put on the dynamic model, an overly smooth track is the result; While if too much weight has been put on the measurement model, the errors would be constructed as sharp changes in direction. The Kalman filter would deliver a wrong result if the model being used is not very good, but a correct model is hard to design. Fuzzy logic is an alternative method to Kalman filtering for GPS/ INS integration. Other than the Fuzzy logic, there is a GPS/ INS multi-sensor navigation system which utilises an artificial neural network and it is another alternative to Kalman filtering method.

In the past few years, a group of researchers developed and implemented a software application package utilising techniques and algorithms that improve GPS data accuracy based on navigation and tracking. This application is called Map Match GPS (MMGPS) and processes raw GPS output data. MMGPS can identify the correct road on which the vehicle is travelling. MMGPS also corrects the derived position using its own computed correction parameters. In addition, a new algorithm OMMGPS (Odometer Map Matching GPS) was developed to integrate the odometer observations with MMGPS. With the OMMGPS the height information is obtained from digital terrain models (DTM) and is used to work out 3D GPS point positions. Adding the height improves the accuracy of GPS positioning with poor satellite geometry when multipath occurs.

There is an experiment conducted with OMMGPS to test the accuracy and reliability of the GPS .A couple of separate trips along a bus route in central London were made to test this method. During the test, the GPS observations used a low cost L1 GPS receiver and OMMGPS used the existing mechanical odometers, and the measures were taken at each second on the bus. The test result shows that the average errors when using the low cost L1 GPS receiver are much higher than the errors when using

OMMGPS. There is an obvious improvement in accuracy when using OMMGPS instead of the low end GPS receivers.

3.1.2 GPS Accuracy by Ionosphere Delay Correction

Research conducted by Akiyama et al. (2007) carried out experiments on different models of GPS receivers to find out which model has the highest accuracy in terms of GPS positioning. The researchers identified the factors that affect the GPS accuracy and intended to reduce the delays of the signals to the receivers in order to improve the accuracy.

Akiyama et al. started the research by finding out how the GPS receiver works out its position by calculating the distance between the GPS satellite and the receiver that uses three-dimensional coordinates. The pseudo-range can be expressed as:

$$\boldsymbol{r_i = c \times \Delta t = \sqrt{(x - x_{si})^2 + (y - y_{si})^2 + (z - z_{si})^2} + s}$$

In the above equation, r_i is pseudorange, c is the velocity of light, Δt is the wave transmission time, (x , y , z) are coordinates of the receiver, and s is the clock error of the receiver (Akiyama et al, 2007). The pseudo-range r_i here includes satellite clock error d_c, troposphere delay error d_t and ionosphere delay error d_{ion}. They also assume that R_i means the pseudorange without any correction, and since the ionosphere delay has a great effect on the GPS accuracy, the delays should be taken off from the current pseudo-range; the new pseudo-range should be expressed as:

$$\boldsymbol{r_i = R_i + d_c - d_{ion} - d_t} \textbf{(Akiyama et al., 2007, p.1766).}$$

The researchers "consider the velocity of two electric waves that have different frequency, the two velocities are different because the change of electric density in ionosphere" (Akiyama et al, 2007, p.1767). As a result, the arrival time interval is caused between the two different frequency waves. Based on this feature, the researchers can measure the ionosphere delay by recording the arrival time interval, and correct the pseudorange with the high degree accuracy. Hence an equation was created to calculate the ionosphere delay:

$$\boldsymbol{I = \frac{f_{L2}^2}{f_{L1}^2 - f_{L2}^2}(\rho_{L2} - \rho_{L1})}$$

Regards the equation, f_{L1} and f_{L2} represent the frequency of electric waves L1 and L2, respectively, and ρ_{L1} and ρ_{L2} represent Pseudorange for L1 and L2 respectively.

However, Akiyama et al. (2007) found out that the noise included in the pseudorange increases with correction by double frequency and some researchers used a quadratic approximate expression for the double frequency and try to remove the noise. On the other hand, Akiyama et al. used least-squares method to decrease the noise by demanding the approximation and found an expression which would be satisfied to minimise the square residual error sum (Akiyama et al, 2007, p.1767):

$$\frac{\partial S}{\partial a_0} = -2\sum_{i=0}^{n}(y_i - (a_2\, x_i^2 + a_1 x_i + a_0) = 0$$

$$\frac{\partial S}{\partial a_1} = -2\sum_{i=0}^{n}x_i(y_i - (a_2\, x_i^2 + a_1 x_i + a_0) = 0$$

$$\frac{\partial S}{\partial a_2} = -2\sum_{i=0}^{n}x_i^2(y_i - (a_2\, x_i^2 + a_1 x_i + a_0) = 0$$

In the above equation, x_i means the local time, y_i is the ionosphere delay by double-frequency method; while a_0, a_1, $a_2$is the coefficient of 0, 1, 2 clause, S is the square residual error sum. (Akiyama et al, 2007, p.1767):

$$\begin{bmatrix} n & \sum_{i=1}^{n} x_i & \sum_{i=1}^{n} x_i^2 \\ \sum_{i=1}^{n} x_i & \sum_{i=1}^{n} x_i^2 & \sum_{i=1}^{n} x_i^3 \\ \sum_{i=1}^{n} x_i^2 & \sum_{i=1}^{n} x_i^3 & \sum_{i=1}^{n} x_i^4 \end{bmatrix} \begin{bmatrix} a_0 \\ a_1 \\ a_2 \end{bmatrix} = \begin{bmatrix} \sum_{i=1}^{n} y_i \\ \sum_{i=1}^{n} x_i y_i \\ \sum_{i=1}^{n} x_i^2 y_i \end{bmatrix}$$

In the measurement experiment, the researchers set the antenna on the rooftop of the Yagami campus of Keio University. The surroundings of the antenna presented no obstacle, so there was no need to consider the influence of multipath. Akiyama et al. simulated the autonomous GPS with the expression:

$$r_i = c \times \Delta t = \sqrt{(x - x_{si})^2 + (y - y_{si})^2 + (z - z_{si})^2} + s$$

The other errors such as satellite clock error, ionosphere delay error, and troposphere delay error are obtained from the experiment (Akiyama et al, 2007, p.1768). Then the researchers used the expression:

$$r_i = R_i + d_c - d_{ion} - d_t$$

to calculate the pseudorange. The normal and revised positioning results from the above experiment are shown in Table 3.2.

Table 3.2: Result of Positioning

	Normal	**Klobuchar model**	**IONEX**	**Double frequency**
East error average	-0.275	-0.098	0.009	0.262
North error average	1.015	0.994	0.815	0.694
Height error average	16.883	0.191	7.641	1.237
Horizontal error average	3.405	2.442	2.334	1.756
2drms	7.381	5.001	4.875	3.717
Height error deviation	5.299	2.693	3.568	2.688

According to the result table, double frequency is the best conventional method, but it causes unevenness. Therefore the approximation method is suggested, because the noise is included in the double frequency, and the approximation is a way to remove the noise. Table 3.3 compares the double frequency positioning results and the second approximation results.

Table 3.3: Result of Positioning (Double frequency and second approximation)

Date	**2drms**		**Horizontal error average**		**Height error deviation**		**Height error average**	
	dbl	app	dbl	app	dbl	app	dbl	app
7/3	3.51	2.81	1.62	1.30	2.43	2.05	0.94	0.89
7/10	3.72	3.14	1.76	1.54	2.69	2.26	1.24	1.24
10/15	4.59	3.91	1.82	1.57	3.30	3.05	1.12	1.01
12/21	3.99	3.21	2.04	1.69	2.39	2.24	0.92	0.79
12/27	4.50	4.26	1.91	1.87	3.07	2.72	0.71	0.62

3.1.3 GPS Accuracy under Forest Conditions

The research conducted by Hasegawa and Yoshimura (2005) proposed a SIP (signal interruption probability) index which indicates the frequency of GPS signal interruption. They estimated the success probability of ambiguity resolution in carrier-phase DGPS and the horizontal precision of code-phase DGPS under different forest conditions using the SIP index; they also identified the factors that affect the GPS accuracy (Hasegawa and Yoshimura, 2005).

The researchers chose four observation points for static surveying in Wakayama Forest Research Station. The four observation points had different forest canopy opening percentage: point 1 was located on a landing under open sky where the forest canopy opening was 99.2%; point 2 was located on a forest road which was 5.5 meter wide and 1.0 meter from the base of 5.2 meter high cut slope, and was susceptible to multipath interference in this observation point. The index of forest canopy opening at this point was 44.5%; Point 3 was selected in natural forest where the average tree height was 10 meter, with an index of canopy opening at 17.5%; Point 4 was chosen in a coniferous plantation of Japanese cedars, with an index of canopy opening at 19.6% (Hasegawa and Yoshimura, 2005).

The researchers did the data collection in two days, and no rain was experienced during the collection. For the data collection two dual-frequency receivers were used, one was for GPS rover and another one was for the base station. In order to evaluate the frequency of GPS signal interruption, they extracted portions of continuously received GPS signals and counted their frequency (Hasegawa and Yoshimura, 2005). SIP has been used in this research to indicate the frequency of GPS signals interruption or the fragmentation of GPS signals and SIP was defined as the percentage value for the increasing probability of GPS signal interruption at an elapsed time (in minutes). In summary, the experimental results allowed the researchers to come up with the SIP index and they defined as the probability that any signal randomly sampled from all received GPS signals would be included in a section of continuously received signals interrupted within k epochs. Table 3.4 represents the results obtained for the SIP index for the four observation points for a period of 10 minutes.

Table 3.4: SIP of the observation points

Observation point	Condition	Obstacle for GPS signal reception	Index of canopy opening (%)	SIP_{10}	Baseline distance (m)
P1	Landing	None	99.2	5.5	25.6
P2	Forest road	Cut slope	44.5	29.9	313.7
P3	Deciduous natural forest	Closed canopy	17.5	44.8	701.8
P4	Coniferous plantation	Closed canopy	19.6	64.9	92.3

According to the research, the dependent variable in this static surveying consisted of log-transformed horizontal errors, while the independent variables were the location, the observation period, the type of observation data (signal or dual frequency), and ambiguity resolution (fix or float) (Hasegawa and Yoshimura, 2005).

The mean horizontal errors and RMS of the static surveys are displayed in Table 3.5. This table contains two types of ambiguity resolution – fix and float. The longer observation period was necessary to obtain ambiguity-fixed solutions with obstacles rather than without them (Hasegawa and Yoshimura, 2005).

Table 3.5: Horizontal mean errors and RMS

Observation Point	Observation Period (m)	L2CR (fix)		L2CR (float)		L1CR (fix)		L1CR (float)		L1CD	
		Error	RMS	Error	RMS	Error	RMS	Error	RMS	Error	RMS
P1	1	0.006 (4)	0.008	-	-	0.003 (1)	N/A	0.211 (3)	0.274	0.120 (4)	0.154
	5	0.006 (4)	0.008	-	-	0.002 (3)	0.002	0.047 (1)	N/A	0.115 (4)	0.141
	15	0.006 (4)	0.009	-	-	0.006 (4)	0.010	-	-	0.143 (4)	0.154
	30	0.006 (4)	0.008	-	-	0.006 (4)	0.009	-	-	0.145 (4)	0.176
P2	1	0.008 (1)	N/A	0.525 (3)	0.636	-	-	0.228 (4)	0.199	0.452 (4)	0.546
	5	0.004 (2)	0.003	0.199 (2)	0.210	0.321 (1)	N/A	0.579 (3)	0.703	0.506 (4)	0.524
	15	0.006 (3)	0.008	0.210 (1)	N/A	0.303 (1)	N/A	0.412 (3)	0.401	0.294 (4)	0.289
	30	0.016 (4)	0.022	-	-	0.154 (4)	0.295	-	-	0.287 (4)	0.337
P3	1	-	-	0.661 (4)	0.747	-	-	1.219 (4)	1.782	1.163 (4)	1.596
	5	0.008 (2)	0.011	0.515 (2)	0.594	-	-	0.682 (4)	0.824	0.906 (4)	1.101
	15	0.012 (2)	0.013	2.538 (2)	3.251	-	-	0.496 (4)	0.731	0.669 (4)	0.687
	30	0.018 (2)	0.014	1.709 (2)	2.149	0.696 (3)	1.117	1.185 (4)	N/A	0.771 (4)	0.838
P4	1	-	-	2.301 (4)	2.718	-	-	1.203 (4)	0.954	2.683 (4)	1.722
	5	-	-	0.670 (4)	0.985	1.671 (1)	N/A	0.927 (3)	1.127	1.335 (4)	1.271
	15	-	-	2.097 (4)	2.813	-	-	1.426 (4)	1.870	1.299 (4)	1.188
	30	-	-	1.737 (4)	2.299	0.556 (1)	N/A	1.370 (3)	2.051	0.774 (4)	0.681

The outcomes of this study illustrate that ambiguity-fixed solutions produced by dual-frequency GPS data were most accurate, and that float solutions were more accurate than those produced by code-phase DGPS. However, this research also revealed that float solutions produced by dual-frequency or single-frequency GPS data were less stable and predictable than positions calculated using code-phase DGPS data. When carrier-phase DGPS was used, ambiguity resolution was the most important factor in determining positional accuracy, and the success probability of ambiguity resolution was mostly affected by forest conditions, which were well explained not by the index of canopy opening but by the SIP in a 10 minute period.

3.1.4 Consumer-Grade GPS Accuracy

The main purpose of the research presented in the paper by Wing et al (2005) is to test different consumer grade GPS receivers for accuracy and reliability in different landscape settings. The total of six GPS receivers from different manufacturers were tested (Table 3.6). Their performances were varied in different landscapes for different brands.

Table 3.6: Name and Manufacturer of the Tested Consumer-grade GPS

GPS name	Manufacturer	Price
Etrex Vista	Garmin	$245
Geko 301	Garmin	$220
GPS V	Garmin	$320
GPSmap 76S	Garmin	$310
Meridian Platinum	Magellan	$280
SportTrak Map	Magellan	$150

The main distinction between consumer-grade GPS and other GPS receivers is "in the ability to differently correct coordinate data that have been collected" (Wing et al, 2005). The survey-grade and the mapping GPS receivers always use embedded software to correct the coordinate data for the consumers. The quality control of satellite reception including the number of points necessary for coordinate determination and minimum reception quality standard is another distinction between the consumer-grade GPS receivers and other GPS receivers. In addition, the mapping GPS and survey-grade GPS receivers allow point averaging, which collects multiple coordinate readings and average them in order to get a more reliable location estimate; however, the consumer-grade GPS receivers only support a single read of the coordinate data.

Three measurement courses were set up by the researchers to test the six consumer-grade GPS receivers. The three measurement courses included three different landscapes – open sky, young forest and close canopy. Six GPS receivers were established in close proximity to each other at the three measurement courses. At all these testing courses, each GPS receiver was placed at one of the six measurement areas to begin recording coordinates. An audible count at about 4 second intervals was used to synchronize the collection of 25 measurements at each station at the same time by the six GPS operators. This synchronization was designed to minimize the effect of satellite geometry and time on measurements between the six GPS receivers. At the completion of 25 measurements, each GPS receiver was moved to the next measurement benchmark where another 25 measurements were collected. This process was carried out until each GPS receiver had collected 25 measurements from all six measurement benchmarks. All GPS receivers were set to collect data in a UTM coordinate system. An average UTM coordinate was calculated from each set of 25 coordinates that was collected at all measurement stations.

The average positional errors for the course of the open sky setting varied from 1.4m to 19.6m, only the Geko 301 and Meridian Platinum had average errors greater than 4.0m. Within the young forest setting, the course average error ranged from a low of 1.3m to high of 6.8m. With the exception of the SportTrak Map and Meridian Platinum, the course summary average error was greater than 3.5m for all other GPS receivers. The average errors for the closed canopy course summaries varied from 2.7m to a high of 11.4m. The Ertes Vista (4.9m), Geko 301 and GPS V (4.7m) had measurement error sums in excess of 4.6m, while all other units errors were 3.2m or less. The three receivers with the largest positional errors also had the largest Standard deviation (SD) varying between 2.8 and -5.0m, while the other units featured SD of 1.7m or less.

3.1.5 High Accuracy Speed Measurement Using GPS

The study conducted by Chalko (2007) demonstrated that speed measurement with accuracy approaching 0.01 knot was possible by using GPS Doppler data. Typical approach to use GPS for measurement was to consider a series of tracking positions which recorded position estimates determined by the GPS at regular time intervals. However, each GPS tacking position was determined with some errors which were variable and not easy to agree on. As a result, the accuracy of speed values calculated from a series of tracking positions was unknown and unreliable. It was unlikely to prove the speed accuracy which was calculated from a recorded series of tracking positions.

An alternative to measuring speed from series of tracking positions was using Doppler Effect (Chalko, 2007). However, the Doppler speed measurement accuracy was not constant as the method depends on the number of tracked satellites and their geometrical distribution above the horizon. The most convenient way of verifying the Doppler speed measurement accuracy was to record the speed data of a GPS receiver at regular time intervals which could account for all known GPS-Doppler speed measurement errors.

An experiment was designed by the researchers that used the Doppler speed measurement to compare its accuracy with the trackpoint-derived speed for the GPS stationary GT-11. The results showed that the measured average Doppler speed was 0.0554 knot, while the position-derived average speed was 0.479 knots. The GPS unit was stationary, however the accumulated distance calculated from the trackpoint was almost 1 km.

Based on a series of tests s conducted in the study, Chalko (2007) pointed out that the Doppler frequency was relatively insensitive to distances from satellites, phase delays and many other factors that were major sources of errors for tracking positions. Doppler method for speed measurement provided proof of speed, as it was traceable to units of measurement. Accuracy of Doppler speed measurements could be significantly improved by adopting the average speed as a measure of speed. For example, if a speed contest was made at the location and recorded the data present in the above test during the same time interval, an average of 10 consecutive 1-second Doppler readings could produce an average speed over 10 seconds with accuracy of 0.044 knot and 95% confidence – assuming the standard error is 0.0841 knot. The accuracy of the average speed of 5x10 second intervals would be 0.019 knots. If 4 GT-11 stationary GPS units were used simultaneously for a 20 second run, the speed measurement accuracy should be about 0.015 knot with 95% confidence and 0.019 knot with 98% confidence (Chalko, 2007).

Accuracy of the average speed measurement over a given time interval increased with the number of Doppler speed samples in this interval. Very high accuracy of the average speed measurement could be achieved, providing that sufficiently large number of suitable GPS instruments was used to measure the speed. Doppler speed measurements were repeatable and reproducible with experimentally verifiable accuracy and resolution. GPS Doppler tracking data from multiple satellites provides a very accurate and very easy way of measuring averages speeds. Factors that would improve accuracy are: longer measuring period, frequent Doppler speed samples, and a higher number of GPS receivers used for the measurement.

3.2 THE RESEARCH QUESTIONS AND HYPOTHESES

The five previous studies reviewed in section 3.1 discussed a number of potential factors which could degrade the level of accuracy of GPS measurement; they also suggested methods both for improvement and for further investigation. Chapter 2 literature review provides a solid foundation of knowledge related to GPS accuracy, and the results regarding the relevant research area. Accuracy in terms of time/ position identification is a major issue for tracking moving objects such as vehicles, people and locations on maps. Various studies have covered the issue of accuracy, ranging from Survey-grade GPS to Consumer-grade GPS receivers, and including satellite communications, architectures, limitations and their accuracy. The review of relevant research studies in Section 3.1 has provided a comprehensive knowledge of the GPS accuracy measurement that can be used to set up the GPS accuracy testing in the experimental phase of this project. The main element that needs to be established is how accurate the GPS receivers are and how to reduce the impact on the accuracy of time/ position assertions that are made for evidential purpose.

Most of the literature reviewed used experimental methods to gather the data from GPS receivers (Chalko, 2007; Akiyama et al, 2007; Langley, 1999; Chan, Xu, Ding, Xiong and Dai, 2006). This approach is taken by the researchers to assess the accuracy of the GPS receivers and provides significantly better results when compared to other methods reported in literature. Consequently, the experiment-based method is the best solution for testing GPS devices and to assess the accuracy of different brands of devices and in different conditions.

The research question was built up based on the literature review in Chapter 2; also, the review of previous studies related to GPS accuracy measurement presented in Section 3.1 identified the best methods/ experiments for testing the GPS accuracy and the possible issues with accuracy. Moreover, it has been discovered that the incorrect GPS positioning would cause survey-mapping deviation, so the engineer can't determine the exact location which might cause trouble; GPS accuracy also affects criminal prosecutions where the inaccurate position information given by the GPS could not be used as court evidence. There are a number of issues around this topic of GPS accuracy across different industries. The issues include some external factors that could influence the GPS accuracy, such as the surrounding situation of the GPS receivers, the reflection from the buildings and other large, solid objects; the design of the GPS and the GPS clock time are other important factors that affect the accuracy.

The main research question and the associated hypothesis that have been developed based on the literature reviews in Chapter 2 and Section 3.1 both are presented below:

Main Research Question: *How accurate is a GPS device over the test period?*

Asserted Main Hypothesis: *The system is designed to acquire precise location information from the GPS and is capable of providing viable evidential trails together with ample information to support the forensic investigation in which the GPS is involved.*

In addition, six related research sub-questions have also been developed and are presented further below. The aim of the sub-questions is to address and answer various aspects related to the main research question.

Sub-Question 1: *What are the hardware and software requirements for maximizing the accuracy of the GPS?*

Sub-Question 2: *What are the methodologies, tools and techniques used to conduct a test to locate an object's precise location from GPS?*

Sub-Question 3: *What is the deviation of the GPS accuracy when testing it in different land situations and weather?*

Sub-Question 4: *What is the effect on the GPS accuracy when the testing object is moving at a different speed?*

Sub-Question 5: *What actions can be taken to improve the GPS accuracy of the tested object?*

Sub-Question 6: *What are the capabilities of the system design to acquire the position information for prosecution purposes?*

Some hypotheses have also been formed for each of the above sub-questions and are presented below:

Hypothesis 1: *The hardware configuration employed will have capability to maximise the accuracy of the GPS, including Central Processor Unit (CPU) with a high processing speed, GPS antenna operating in a high accuracy mode when receiving the GPS signals, and high refresh rate on the screen.*

Hypothesis 2: *The software requirement will effectively position the testing object with minimum deviation. The most recently updated map and a high refresh rate GPS receiver will be needed to get the higher accuracy.*

Hypothesis 3: *A suitable speed for moving the tested GPS receiver with a high refresh rate to get most precise location information.*

Hypothesis 4: *The GPS accuracy would be tested under different weather conditions, to find out they affect the accuracy. The GPS accuracy would be higher if; the testing object is located in a wide open area and if the GPS receiver is tested in a sunny weather.*

Hypothesis 5*:* *The GPS accuracy would be tested for different speed of the moving objects, to find out how peed affects the accuracy. The GPS receivers would get higher accuracy when moving at a faster speed.*

Hypothesis 6: *The proposed system will be capable to improve the accuracy due to the method of improving the testing environment and the external factors (such as location, running speeds and so on).*

Hypothesis 7: *The proposed system will be capable of providing the positioning information in a forensic manner if the accuracy is high and accepted by the court.*

In order to answer the proposed research questions, to confirm the asserted hypotheses and to conduct research testing in a planned manner, a research data map has been developed and is presented in Figure 3.1. It outlines the main research question, the sub-questions and connects to the associated research phases. In addition, each research phase and finding from related experiments will be used to aid in determining the asserted hypothesis.

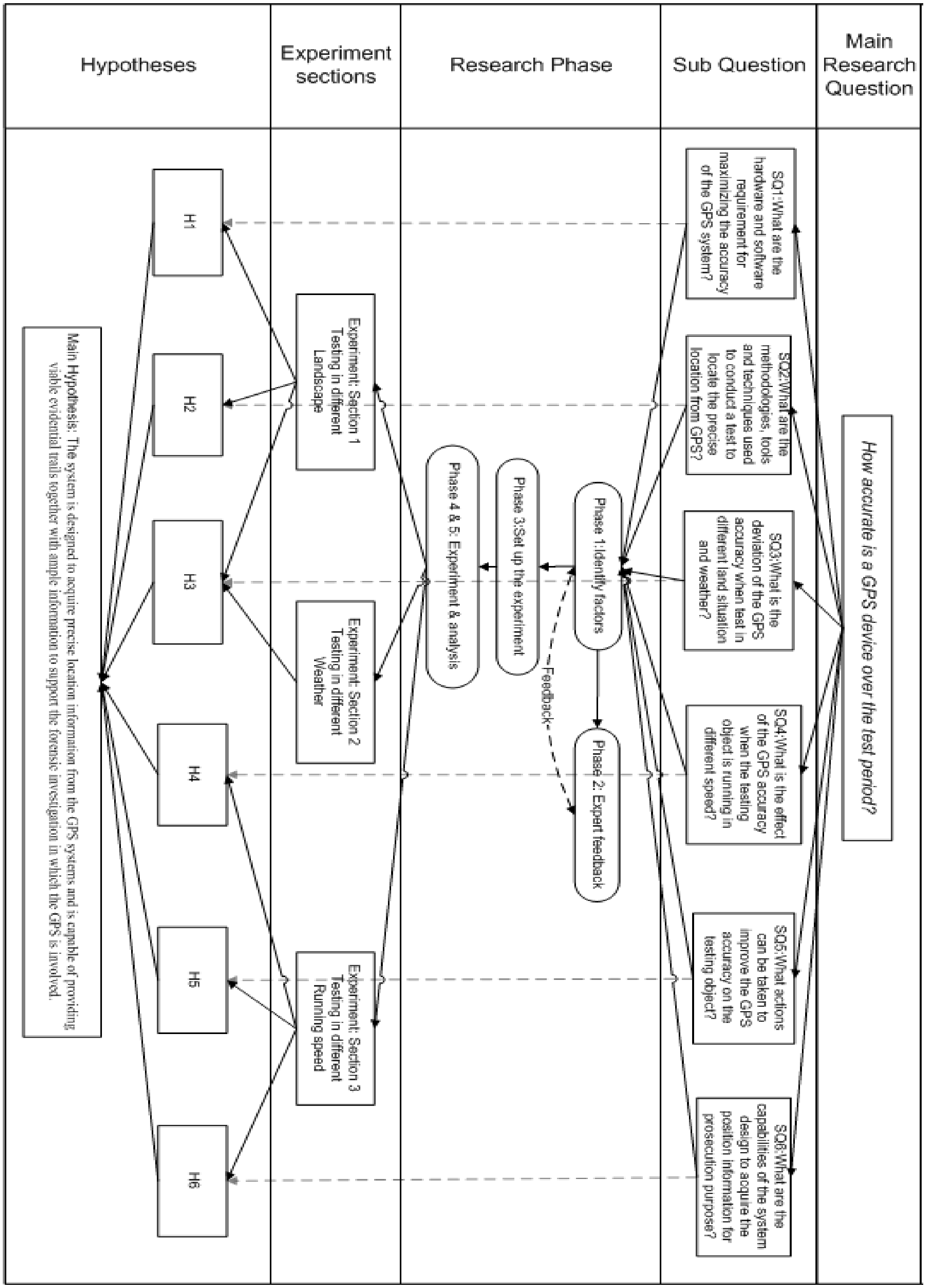

Figure 3.1: Research Data Map

3.3 TESTING DATA COLLECTION

The purpose of this research is to test the accuracy of civil GPS devices and whether it is high enough to allow the acquisition of evidence. It also aims at providing some suggestions and advice for the improvement of the design of current GPS devices in order to improve their accuracy. A theoretical research model is developed using a design science approach in order to set up a framework for the research to be conducted. Descriptive methodology will be used to perform the fact-finding exploration to establish the state of affairs in the proposed research area. The system design will be developed based on the proposed system architecture and the associated components that are required.

The design science approach will be taken to establish the system design. Peffers, Tuunanen, Rothenberger and Chatterjee (2007) indicated that several researchers brought the design research into the information service research area, making the case for the legitimacy and value of design science as an information service research theory and integrate the design as a major component of the research.

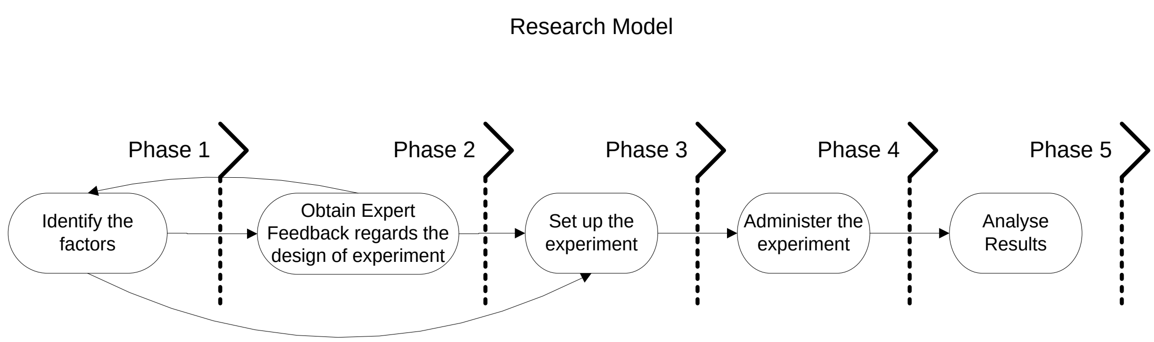

Figure 3.2: Research Model

The intention of this research is to test the GPS receivers and find out the factors that would affect their data accuracy. The goal is to seek ways to improve the GPS accuracy and meet the criminal court requirements for data accuracy. It is proposed that a series of testing under different conditions be implemented and reviewed to determine the accuracy of the selected GPS devices and the affecting factors. The testing will find out the difference between the real location and the position that is shown on the map. The proposed theoretical research model is illustrated in Figure 3.2 and consists of five steps: identifying the factors, obtaining expert feedback regarding the design of experiment, setting up the experiment, administering the experiment, and analysing the results.

Phase 1 entails identifying the factors under different circumstances which might affect the GPS accuracy and conditions needed to be considered while running the testing on the GPS receivers. The hardware and software of the GPS receivers and associated settings on the devices will also be described and discussed in order to identify the potential factors.

Phase 2 involves getting expert feedbacks from Dr. Brian Cusack who is the supervisor of this thesis regarding the testing system design. The testing setups and the testing conditions are informed by the literature review; there might be some steps that would be impractical in New Zealand's situation, such as weather and topography. Outcomes from Phase 2 will dictate which components in the proposed testing need to be modified in order to achieve the most accurate result in the testing phase.

The obtained expert feedback will be used for fine-tuning my original design and to draw out a more appropriate testing plan. Once the test plan is finalized, the next step is to set up the GPS devices and the testing scenarios in the real world. Several scenarios are set up for testing the GPS accuracy: tree canopies testing in One Tree Hill in Auckland; urban arterials testing in Highbrook industrial park; test the GPS device when running in inner city, test the GPS device while walking inside a building. For the testing that will be operated outdoor, the weather conditions need to be considered, as this is an important factor that affects the accuracy.

There are four stages involved in the experiment. The testing conditions and the surrounding environment in each testing stage are listed in Table 3.7 as below.

Table 3.7: Testing Conditions and the surrounding environment in each testing stage

Testing Stage	Surrounding Environment	Weather	Testing conditions
1	Tree canopies, One Tree Hill	Sunny	Walking/ Jogging/ Riding a bike

1	Tree canopies, One Tree Hill	Rainy	Walking/ Jogging/ Riding a bike
2	Urban arterials, Highbrook Industrial park	Sunny	Walking/ Jogging/ Riding a bike
2	Urban arterials, Highbrook Industrial park	Rainy	Walking/ Jogging/ Riding a bike
3	Queen Street, Auckland (canopy opening varied)	Sunny	Walking/ Jogging
3	Queen Street, Auckland (canopy opening varied)	Cloudy	Walking/ Jogging
4	Indoor environment (canopy opening 0%)	Sunny/ Rainy	Walking

The first testing stage is carried out in the tree canopies area in One Tree Hill (see Figure 3.3) and the same test cases are implemented in a sunny weather and in a rainy weather. The purpose for this is to find out how the weather conditions affect the GPS accuracy. The tree canopies provide a covered condition to the GPS signals, and the signals might be blocked by trees which would affect the accuracy. Before the testing, it's necessary to choose the starting point and the destination point and to measure the distance between the two points.

The testing scene for stage one is in One Tree Hill domain, Auckland, the total length of the testing route is 450m. The testing method for this stage is holding the GPS device and moving from point A to point B (as marked on the map in Figure 3.3), once Point B is reached, the travelled distance is recorded on the GPS device, that's the distance measured by the device. The same test will be implemented three times, which is represented as three rounds in the testing results presentation. The test results will be presented in Section 4.3.1.

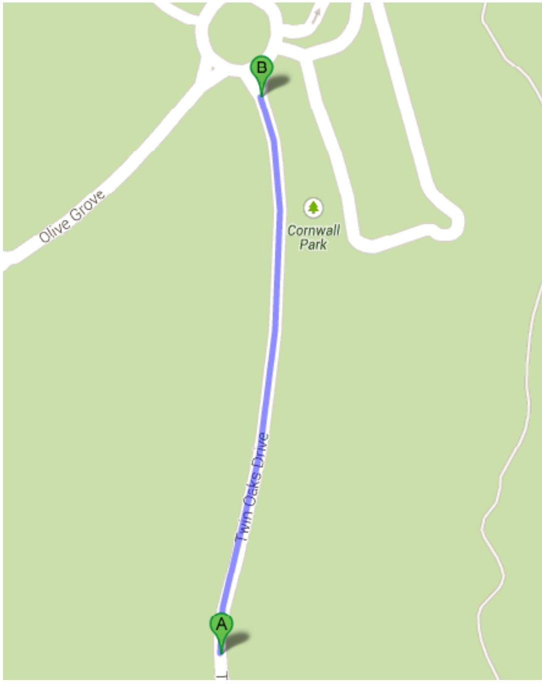

Figure 3.3: Testing Route for Stage 1 in Google Map

The second testing stage is performed on Highbrook Drive in Highbrook Industrial park (see Figure 3.4). The distance between points A and B is 200 m. The testing method in Stage 2 is fairly similar to Stage 1. That would be travelling from point A to point B, and record the travelled distance. The same test is repeated three times, and the distance for each test is recorded. The second stage testing includes two weather conditions – sunny and rainy, the same as the testing in Stage 1. The testing in two different weather conditions is necessary to find out how the weather affects the GPS accuracy.

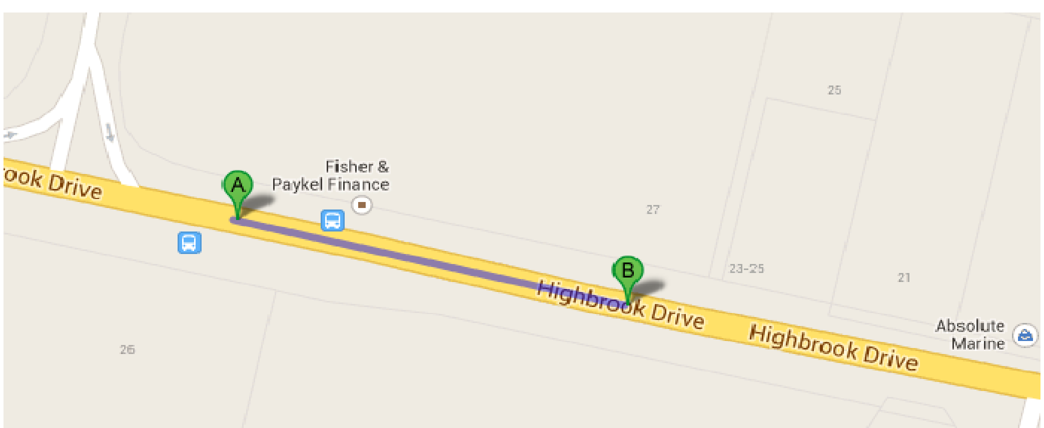

Figure 3.4: Testing Route for Stage 2 in Google Map

The third stage testing is held in Auckland city centre, the method of movement for GPS accuracy measurement is walking or using a bicycle to travel on Queen Street between point A (Queen Street and Karangahape Road intersection) and point B (Queen Street and Custom Street East intersection) (Figure 3.5). The distance between point A and point B is 1.5 kilometres.

The testing method in Stage 3 is holding a GPS device and walking from point A to point B in Queen Street. For the first time measurement, the travelled distance between A and B is be used as the reference value. The same test is repeated 5-6 times and the average distance for the series of testing is calculated. Next, the distance obtained from the first time measurement will be compared to find out the deviation between the first time measurement and the rest of the testing. The Stage 3 testing is carried out under two different weather conditions in order to find out how the weather affects the GPS accuracy in the low speed object.

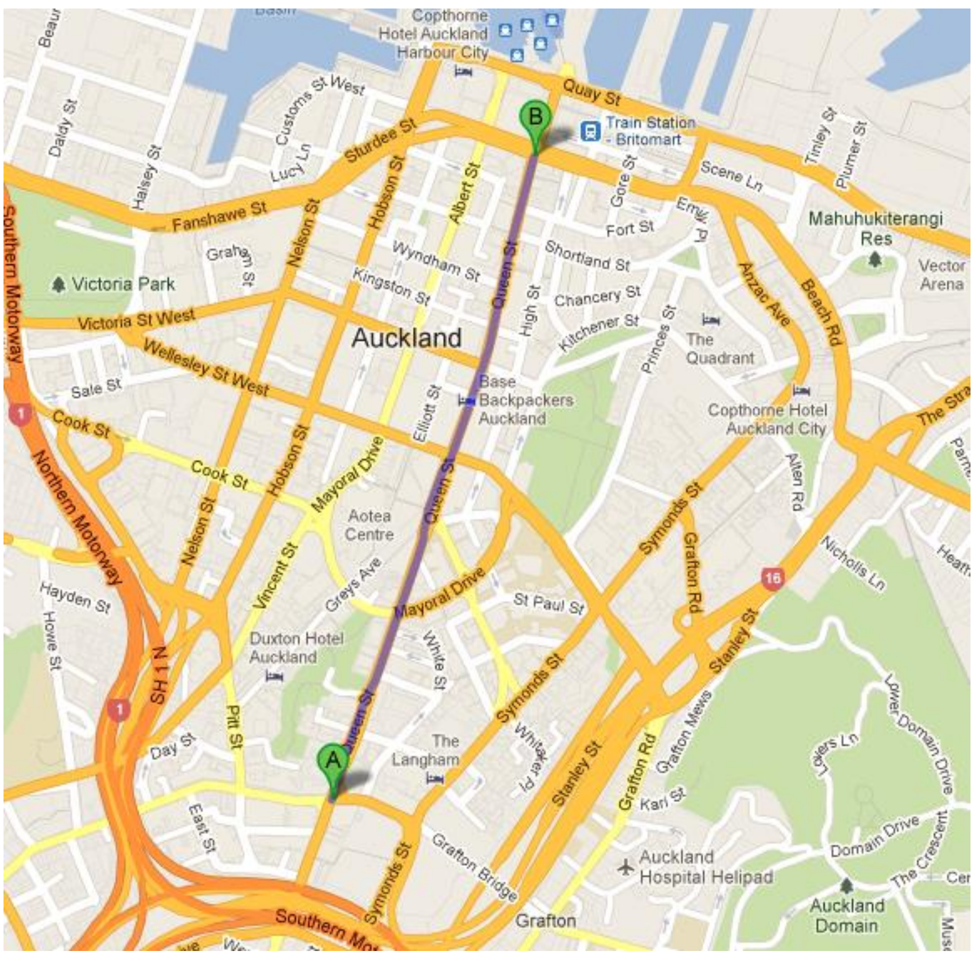

Figure 3.5: Testing Route for Stage 3 in Google Map

The fourth stage testing in an indoor environment, which means the testing environment is 100% closed canopy. The purpose is to simulate the scenario that a car is travelling in a tunnel and to find out how the 100% closed canopy affects the GSP accuracy. The testing location for this stage is inside my house, i.e. in an indoor environment, and the testing is carried out in sunny and rainy weather. Before beginning the test, it is essential to identify the two points A and B in the living area, and make sure there is no wall, table, or chair in between. Once the two points are identified, a tape measure is used to measure the distance between them, read the distance and use that as a reference value. The testing method in Stage 4 is holding a GPS device and walking from point A to point B, and to record down the distance shown on the GPS device. The same test is repeated 5-6 times, and the average distance from the series of testing is calculated. It is then compared to the distance obtained from the ruler measurement, to find out the deviation between the first time measurement and the rest of the testing.

In summary, the data is collected from testing the GPS in different canopy open size, different weather conditions as well as different testing speed such as walking, jogging and running.

3.4 DATA ANALYSIS AND PRESENTATION

Following the data collection in different testing phases, the obtained data will be identified, analysed and presented in order to gain some insights related to the research question. Data reporting is required to deliver the findings from each separate testing stage. The different testing methods outlined by the data collection requirements are examined and the data produced will be presented clearly in a table format. It is recommended that there will be a range of testing methods and testing conditions which need to be reported. In addition, the percentage results will be also calculated to provide an overview of the accuracies. Data analysis will be performed in order to compare results with the findings from previous researches. SPSS (Statistical Package for the Social Sciences) offers a full set of data analysis tools and is used for analysis of the collected data. A number of statistical tests will be performed using SPSS in this project:

- One sample t-test: used to compare a sample mean to a known population mean.

- Two independent samples t-test: used to compare means from independent groups.
- Paired sample t-test: used to compare two related means.

In addition, the above statistical tests will be interpreted using P value to determine the significance of the test results. The P value is the probability of obtaining a test statistic at least as extreme as the one that was actually observed, assuming that the null hypothesis is true (Wikipedia.com). The significance level for all the statistical tests in this research was specified to be 0.05. Thus P values less than 0.05 are reported as "statistically significant".

Table 3.8: Procedures of analysing the test outputs

Data Analysis Procedure	**Description of Data Analysis**
Data manipulation	Pre-process the data gathered from each GPS device and each testing stage then get the average results of the testing.
Accuracy analysis	Statistical analysis of the testing results and comparing to the reference value in order to determine the GPS accuracy.

Different brands of GPS devices are tested for this research under the same weather condition in each testing stage. In order to get the most accurate results, only one GPS device is tested at a time. First all selected GPS devices are tested in one type of weather conditions (e.g. sunny) and through all four testing stages. Then they are all tested again in a different weather condition, e.g. cloudy or rainy.

The GPS measured distance between the testing points is recorded for each device in every single testing. The collected data is typed into SPSS manually and analysed by following the steps of the proposed method to compare the testing results to the reference value. Therefore, we can find out how the accuracy of different brands of GPS devices is affected by different testing environments.

Finally, the findings based on the collected, processed and analysed testing data are clearly presented. Different graphs/ charts are used so that the research results are presented visually for best interpretation.

3.5 EXPECTED OUTCOMES

The expected outcomes from the proposed research methodology will be listed and discussed briefly regarding each of the testing stages proposed in the research model design (Figure 3.2).

The first stage testing involves running the GPS test in the tree canopies area – Twins Oaks Drive in One Tree Hill, and under two different weather conditions (sunny and rainy). After the testing distance is measured (and used as a reference value), each GPS device is tested in sunny weather, multiple times to reduce the effect of human error. Once all the GPS devices are tested under the sunny weather condition in the tree canopied area, the same test is conducted on the same devices rainy weather. It is expected that in sunny weather the testing results are not much different from the reference value. However, in rainy weather the testing results would have some differences with the reference value.

The second stage testing involves running the GPS test in Highbrook Drive in Highbrook Industrial Park, and also includes sunny and rainy weather conditions for the GPS devices. The testing method is very similar to the testing in the first stage. The expected outcome from this testing stage would be similar to the outcome from stage one, i.e. in sunny conditions the results would not be much different from the reference value, but would be different from the reference value when tested on rainy days.

The third stage of testing involves carrying the GPS devices and walking in Queen Street in Auckland CBD to test the accuracy in both sunny and cloudy/rainy conditions. Compared to the testing at stage 1 and stage 2, the testing method of this stage is walking instead of using a bicycle. Once the testing distance is measured, all GPS devices are tested in both sunny and rainy/cloudy conditions. The testing results are expected to be different from the reference value in sunny weather as Queen Street is not 100% open canopy due to some high buildings on both sides of the street. The testing results would have a greater deviation in a cloudy/ rainy weather.

The fourth stage testing involves carrying the GPS device and walking in an indoor environment, such as my home's living area. Although the testing location is an indoor environment, the weather conditions still need to be considered – both sunny and rainy weather are chosen for this stage. Each GSP device is tested multiple times to reduce the human error. It is expected that the testing results will be different from the reference value. Since the testing environment is 100% closed canopy and the GPS signal might not be able to reach the GPS device properly.

3.6 LIMITATIONS OF RESEARCH METHODOLOGY

The proposed research methodology has certain limitations that are identified and discussed further below in this section. It is important to identify these limitations in order to evaluate the obtained results correctly, and determine if, or where, further research is required in order to improve the GPS accuracy and meet the forensic prosecution requirements.

The first main limitation of the proposed research methodology is that the distance between the two testing points might not be measured 100% accurately. Although a mechanism explained in Section 3.3 would help to improve the precision, there might be some additional factors affecting precision. Such distance measurement between the two observation points includes using the distance measurement tool in Google Map or using a ruler to measure the distance between two points in an indoor environment. There would be human errors or errors in the technology itself (such as Google Map), which will cause the errors in the measurement.

Another limitation of the proposed research methodology is the hardware specification of the GPS devices that are tested. Previous research has tested different consumer grade GPS devices (see Section 3.1.4). Due to their hardware specification, different brands of GPS devices will provide different accuracy under the same testing conditions. Each GPS device might have different CPU speed, different size of memory, or different refresh rate on the device screen. These factors are related to the GPS hardware design, and the accuracy measured from these devices does not reflect the true accuracy of the GPS technology in the specific weather conditions and testing location.

A further limitation of the proposed research methodology is the type of testing conducted on the GPS devices. The GPS technology is widely used in agriculture, aviation, marine, rail, space and so on. The GPS accuracy testing can’t be carried out in these conditions due to the time and budget limitation of this research; only the conditions specified in Table 3.11 are suggested for testing.

3.7 CONCLUSION

Chapter 3 focuses on the development and specification of the research methodology to conduct the testing in the chosen study area of determining the GPS accuracy and analyse how the external factors affect the accuracy. Previous studies in a similar area were reviewed to learn from existing methodologies. The toolkits and recommendations offered by other researchers were identified to help in the development of testing methodologies for this project. The additional information gained from the review of similar studies, combined with the comprehensive literature review in Chapter 2, was used to develop the research questions and the hypotheses associated with each question. The proposed research model consists of several steps, and provides a logical progression of testing stages to be conducted. The derived methodology was employed to establish the proposed testing design, including the testing weather conditions and testing locations. Furthermore, the data requirements, expected outputs and the limitations of the proposed research methodology were outlined and discussed.

Chapter 3 has thus presented an overview of the chosen research methodology. The research data map (Figure 3.1) presents a diagram showing the main and sub-questions of the research, as well as how each question is linked to a specific phase of the research. The proposed research model (Figure 3.2) outlines the required phases of this research and the purpose of each phase of testing, including implementing the testing design and, testing location, and testing environment.

Chapter 4 : RESEARCH FINDINGS

4.0 INTRODUCTION

The previous chapter specified the research methodology in detail. Previous similar studies were analysed and the methodology presented there was used to collect data regarding the research questions. The main research question and the related sub-questions (Section 3.2) were derived from the literature review in Chapter 2. Chapter 3 formulated the research questions based on the issues and problems identified for the accuracy of the Global Positioning System (GPS) measurement and the research methodology was then established. Expected outcomes, and the limitations of the proposed research methodology were also discussed.

In order to investigate the accuracy of the GPS, the testing methods were used on different GPS devices to test them under different kinds of weather conditions as explained in Section 3.3. By design, the testing included four stages where tests were held in tree canopied area, urban arterials testing in Highbrook industrial park, Queen Street and indoor environment respectively. Each test was performed in a variety of weather conditions in order to get a more comprehensive data set for the analysis of accuracy. Chapter 4 will report the research findings from the GPS accuracy testing phases described in Chapter 3. Firstly, variations made to the proposed data requirements established in the research methodology will be addressed in Section 4.1. Then, in order to clearly articulate the research finding results, the results from each of the four independent phases of testing will be showed and analysed. They will be evaluated to determine the accuracy of the GPS. The summarised data from each phase will be presented in Section 4.2. Next, the analysis result of the summarised data would be presented in Section 4.3, followed by presentation of the findings about the GPS accuracy. The whole chapter will be concluded in Section 4.5.

4.1 VARIATIONS IN DATA COLLECTIONS IN EXPERIMENT

Most steps in the research experiments were done according to the adopted methodology explained in Section 3.3. A number of variations to the originally proposed research methodology and data requirements have been made. It is important to identify the variations prior to reporting the findings from the research testing phases. Any differences between the suggested methodology and the final implemented methodology during the testing phase of the research are therefore described in the following sub sections.

4.1.1 Design of the Testing Environment

During the experiment of the proposed GPS testing methodologies, A few problems with the proposed testing methodologies were encountered during the experiments and these are outlined in the following sections.

One such problem was that at the beginning of the testing phases the weather in Auckland was mostly sunny and dry, with very few rainy or cloudy periods. As a result, not enough GPS data could be collected in rainy or cloudy conditions for analysis purpose. Another issue occurred with the GPS signal coverage inside my house which was poor in some areas of the house. Therefore the indoor testing could only be performed for very short distances, i.e. between 1 and 5 meters, where the signal coverage was reasonably good.

I was inexperienced in the use of the selected GPS devices, especially the Garmin GPSmap62 which I had never used before. In order to understand the operations of the GPS devices, particularly how to measure the distance and how to collect data, I had to train myself with the devices and their operations.

4.1.2 Data Generation & Collection

During the course of performing the experiment phases of the research, a number of challenges were encountered which required some changes to be made in the proposed methods for data generation and collection.

The first change applied to the required weather conditions since throughout the whole period for the proposed testing phases, the high pneumatic pressure in of Auckland meant the weather was sunny and dry, and it rained very little. In order to overcome this problem, the tests in rainy/cloudy weather were conducted in mid to late March when the pneumatic pressure in Auckland was low and there were enough rainy days.

The second discovery was the GPS signals were not strong enough, and sometimes the signal was totally lost in the chosen testing locations, such as the hallway inside my house, which is a closed canopy area with only one open window. As a result, during the first set of testing, the tested GPS devices always lost connection with the satellite. In order to overcome the issue with the weak GPS signal, more windows had to be open in the indoor environment.

4.1.3 Data Reporting, Analysis and Presentation

Accuracy and precision are often used by the researchers to describe how well a GPS device acquires the position (NovAtel, 2003). The main distinction between the two terms is that accuracy refers to the degree of closeness of an estimate to the true value, while precision refers to the degree of closeness of observations to their mean values (NovAtel, 2003). In this research project, it is assumed that accuracy is the closest value to the actual distance, and the precision is the closest value to the mean of a series of actual distance measurements.

In order to get the precise distance between the two testing points, Google map and Survey Measuring Wheel were used to measure the distance in the following way: first the two testing points A and B are selected on the Google map, and the distance between them. As soon as the distance value is confirmed, the Survey Measuring Wheel is brought to the location associated with point A on the Google map, a starting point is selected that coincides with the real point A, and then SMW is driven from the marking point along the path to point B displayed on the Google map. Once the meter reading on the SMW is equal to the distance calculated by Google map, the measuring wheel is stopped and the destination point is marked as point B. To ensure the measured distance is correct, the measuring tool is then reset to "0" and driven back from point B to point A, on exactly the same path and the distance is written down. The same measurement is repeated a few times; if the value is very close to the distance calculated by Google map, then we can confirm the testing distance is correct and the two testing points are showing correctly on the map.

4.2 EVALUATION OF THE TEST FINDINGS

The purpose of evaluation testing was learn about the use and testing of GPS devices. I worked out how to use each GPS device to measure accuracy and to design experiments. This section is divided into five sub-sections. The first sub-section introduces the preliminary testing; each GPS device was then tested and is shown in the next three sub-sections; the last sub-section was to perform preliminary testing and data analysis on the collected data.

4.2.1 Preliminary testing

Preliminary testing of the project was proposed as it was anticipated that difficulties may occur in the implementation of the GPS device testing while configuring the software and hardware to be used during the research testing phase. The main goal of preliminary testing was for the researcher to become familiar with the selected GPS devices and to assess the implementation of the proposed system design for the GPS device testing, as well as the devices' ability to receive the data for evaluating the GPS accuracy.

In order to ultimately evaluate the capabilities of the GPS devices, it was essential first to perform preliminary testing in simple environment such as short distance in different weather conditions. Therefore, Phase One, Two and Three were performed in a preliminary testing of a variety of GPS devices that would later be used in the real testing phases. The aim of these preliminary tests was to ensure that the distance measurement and device positioning could be done properly and also to guarantee the GPS devices under investigation were able to provide high precision for the location tracking.

Once the preliminary testing of the GPS devices had shown the devices to be in working order and the level of precision of the GPS measurement was acceptable, a full research testing was conducted according to the plan explained and illustrated in Chapter 3.

4.2.2 Phase One: Preliminary testing of the Garmin GPSmap 62 Device

In Phase One, the first stage of preliminary testing involved configuring the Garmin GPSmap 62 GPS devices, as well as testing the device through with the waypoints to figure out the travelled distance.

The Garmin GPSmap 62 is a handheld GPS navigator (Figure 4.1), and this series of GPS device was "practically the standard by which all other handheld GPS devices are measured, at least at the enthusiast level" (Cangeloso, 2010). According to the user manual of this GPS device, Garmin GPSmap 62 is able to evaluate the distance between two testing points, even when the they are set close to each other at a distance less than 5 meters. For the preliminary testing the distance between the two testing points was set at 3 meters for both indoor and outdoor conditions.

Figure 4.1: Garmin GPSmap62

The next critical task was to configure the Garmin GPSmap 62 to receive satellite signals. The researcher needed to wait while the device was searching for satellites. Once the location was determined by the GPS device, a question mark flashed on the screen and the GPS bars displayed on the device indicate satellite the received signal strength. When the bars turned green, it meant the device had acquired satellite signals.

In order for the device to measure the distance between the proposed two testing points, the researcher needed to zoom in the map to a suitable scale and mark testing point A as waypoint 1, and then walk to testing point B which was marked as waypoint 2 and the cursor was then moved back to waypoint 1. Next step was to select “Measure Distance” from the device menu (Figure 4.2) and to move the cursor from waypoint 1 to waypoint 2. After that, the distance between the two waypoints (testing points) appeared on bottom right of the screen.

Figure 4.2: Measure distance option in GPSmap62

In order to determine the reliability and precision of GPSmap62 for short distance, three tests would be held and multiple distances were set for this testing: 5m, 15m and 30m. The distances were measured by a Survey Measuring Wheel (Figure 4.3), that is commonly used by the builders or engineers for surveying. The Survey Measuring Wheel could provide a good accuracy on a smooth surface, but is not suitable for rough surfaces as the bouncing and wheel slippage would reduce the accuracy.

Figure 4.3: Survey Measuring Wheel

All tests were completed on a sunny Saturday afternoon at about 3pm in outdoor area which is considered good GPS conditions. In order to minimise the human errors that might affect the testing results, I completed six linear runs for each of the three distances of 5 meters, 15 meters and 30 meters respectively (all together the number of runs n = 18). GPSmap62 was used to measure the distances. The testing results for Phase One are presented in Table 4.1 which clearly shows that precision improved with increasing the distance: while the Standard Error of Mean was 34.22% for the 5m distance, it decreased to 27.42% for the 30m distance. The tests for 15m distance generally maintained a middle position, with a Standard Error of Mean of 33.43%. Yet in term of GPSmap62 reliability, the data in table 4.1 indicates that stability also increased with increasing the distance, with the Coefficient of Variation of 21.68%, 6.04% and 2.39% for distances of 5m, 15m and 30m, respectively. Therefore, GPSmap62 didn't have good precision for short distances.

Table 4.1: Results recorded by GPSmap62 for the 18 rounds of tests at distances of 5m, 15m and 30m, and relevant statistical results

Test	Round number	Measured Distance (m)	Mean (m)	Standard Deviation	Std. Error of Mean	Coefficient of Variation
5 m	1	3.2	3.8667	83.83%	34.22%	21.68%
	2	2.6				
	3	4.3				

	4	4.5				
	5	3.8				
	6	4.8				
15 m	1	13.1	13.5667	81.89%	33.43%	6.04%
	2	12.9				
	3	14.6				
	4	13.6				
	5	14.5				
	6	12.7				
30 m	1	27.4	28.15	67.16%	27.42%	2.39%
	2	27.9				
	3	28.7				
	4	28.6				
	5	28.9				
	6	27.4				

4.2.3 Phase Two: Preliminary testing of the Navman EZY45 GPS

The second stage of the GPS preliminary testing was to test the Navman EZY45 (Figure 4.4) GPS device and determined how well it handled accuracy. Navman EZY45 is a GPS unit with a 4.3" touch screen and has a variety of features such as 3D junction views, safety alerts, speed limit alerts, optional live traffic updates and so on.

Figure 4.4: Navman EZY45 GPS

The Navman EZY45 GPS device is normally mounted on the car front screen inside the car, thus the driver could have full visibility of the GPS device screen. The power source for the GPS is provided by the car's AC power via an in-vehicle charger. In this research, driving a car will not be adopted as test method and this test would be performed by the researcher carrying the device while running between the two test points set at a distance of 200 meters.

The Navman EZY45 GPS device is an entry level GPS with user friendly interface that makes it easy for the user to configure the route navigation and the speed monitoring. First the navigation was set on the device, and then the user started running along the navigation path while carrying the device. In the meantime, the user was able to check on the GPS screen whether the navigation was working as expected and whether the refresh rate on the screen was normal or not; a slow refresh rate this would have a great impact on the accuracy.

Before starting the preliminary testing in Phase Two, the path which would be used during the testing should be entered to the testing GPS device. To make the testing process easier, I chose the street where my house is located and the starting point of the test was the location of my house. The next step was to start the navigation to start jogging from the starting point along the testing path. When travelled to the destination, I stopped the navigation and checked the position whether it was the precise position that set on the GPS device.

The test for Phase Two was commenced from the entrance gate of my house and ran in a straight line to the end of the street; the total distance for this testing was 167m when measure by survey measuring wheels. Three rounds of testing were conducted for this phase. The testing results were recorded for each round and are presented in Table 4.2. I also took these testing results and run a one sample t-test to test whether the mean of measured distance differs significantly from the reference distance (167 meter). Table 4.3 shows the summary statistics of the one sample t-test, which includes:

- The test value of -3.601
- The degrees of Freedom of 2
- The corresponding (two-tailed) P value of 0.069
- The difference sample mean of -1.1
- The 95% Confidence Interval (CI) for this difference from -2.4145 to 0.2145

The calculated P-value in table 4.3 was 0.069 which was greater than 0.05, the conclusion is that, the average of measured distance isn’t significantly different from the reference distance. It also means the precision of Navman EZY45 is high.

Table 4.2: Preliminary Test Result of Phase Two used Navman EZY45

	Reference Distance (m)	Round 1 (m)	Round 2 (m)	Round 3 (m)	Mean (m)	Std. Deviation	S.E. Mean
Result	167	165.7	166.5	165.5	165.9	52.91%	30.55%

Table 4.3: One Sample t-test result for preliminary test (Phase Two)

	Test Value = 167					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
VAR00001	-3.601	2	.069	-1.1000	-2.4145	.2145

4.2.4 Phase Three: Preliminary testing of the Smartphone embedded GPS

Phase Three tested a GPS application installed on an Apple iPhone 5.The Google Map app was a free application and it was available to download from Apple AppStore. There was a navigation function embedded into this app and consequently this preliminary testing could use this functionality to find out how GPS navigation worked on a smart phone.

This testing was very similar to the Phase Two test, as the Google Map application navigation performed similarly to normal GPS devices. Before the testing was carried out on the device, we should ensure the Location Service (Figure 4.5) for Google Maps was turned on. In this case, the current location would be identified by following a procedure operated by Apple: "when a customer requests current location information, the device encrypts and transmits Cell Tower and Wi-Fi Access Point Information and the device's GPS coordinates (if available) over a secure Wi-Fi Internet connection to Apple" (Chen, 2011).

Figure 4.5: Location Service for Google Maps

Since the Location Service for Google Maps was enabled on the iPhone, the current location would be displayed on the Google Map. The following step was to enter the destination address into the address search bar and search for that address until it was found. The next step was to choose the route on the screen and to start (Figure 4.6). Once I reached the destination point, I checked if it was at the precise position that had been set on the Google Maps in the iPhone.

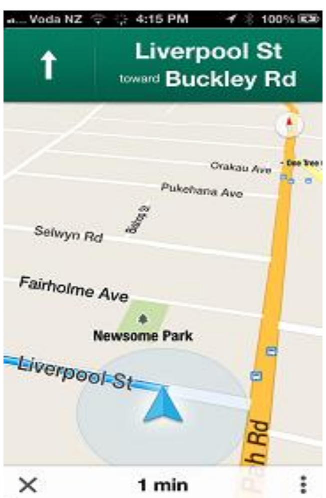

Figure 4.6: Navigation Screen of Google Maps in iPhone

The Phase Three tested the same route as Phase Two, and also used three rounds of testing. The testing results were recorded for each round, and are presented in Table 4.4.

Also, in order to find out if the iPhone Google Map can provide high precision location tracking or not, One sample t-test of the testing results and reference distance was run and the output is presented in Table 4.5. According to the P value of this test, the precision of iPhone Google Map was high.

Table 4.4: Preliminary Test Results of Phase Three with iPhone Google Map

	Reference Distance (m)	Round 1 (m)	Round 2 (m)	Round 3 (m)	Mean (m)	Std. Deviation	S.E. Mean
Result	167	166.7	165.9	166.2	166.27	40.42%	23.33%

Table 4.5: One sample t-test result for preliminary test (Phase Three)

	Test Value = 167					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
VAR00001	-3.143	2	.088	-.7333	-1.7373	.2706

4.2.5 Preliminary Testing Data Analysis

The purpose of the preliminary testing was for the researcher to get familiar with the operation of the selected GPS devices, as well as to get a general idea about how the environment factors impacted the GPS accuracy.

The results of performing GPS accuracy testing using different GPS devices through all three testing phases determined that these devices were operating normally. The testing in the phases was performed in the same conditions where the weather was sunny and the testing environment was in a 100% open canopy area. This test could not determine the factors that affect the accuracy of the collected data, so a further test would be implemented to address the issue.

The testing results of Phase One showed a great deviation between the real distance and the measured distance. For example, in the test performed for a distance of 5m, the mean error of the measured distance was 3.87 meter. Moreover, the test results showed that the accuracy of the GPS device improved when the distance increased. Another interesting point that was noticed was that the GPS device will have better stability when the distance increased.

On the other hand, the testing results of Phase Two presented a small difference between the measured values and the real distance. The Phase two testing was conducted along a straight line path that between the front gate of my house and the end of the street and the total length was 167 m. The testing was carried out in three rounds and the measured distance was 165.7 m, 166.5 m and 165.5 m respectively, with a mean value of 165.9 m and a standard mean error of measurement of 30.55%.

The testing in Phase Three found that the distance was measured very precisely as the results showed even smaller differences between the measured data and the real distance. The testing results of three rounds were 166.7 m, 165.9 m and 166.2 m respectively and the mean value was 166.27 m. In comparison, the mean values are similar between the tests of Phase Two and Phase Three, with errors (S. E. Mean) getting smaller when the iPhone Google Map was used. It means the precision of the iPhone Google Map was better than that of Navman EZY45 in the preliminary testing.

4.3 INVESTIGATION TESTING FINDINGS

The preliminary testing described and discussed in Section 4.2 offered a better understanding of the testing procedures and I became familiar with the selected GPS devices. The more intensive and comprehensive testing proposed in Chapter 3 was carried out later on and the results and findings are presented in this section. The testing was performed in different test scenarios, including different weather conditions, different speeds of movement of the tested devices, different time, different canopy opening percentage and so on.

In order to collect GPS accuracy data, four stages of testing were proposed in Chapter 3. These testing stages could be described as: tree canopied area test, urban arterial test, and 0% canopy opened indoor test. Each stage includes four rounds that were carried out as follows: test in sunny weather in the morning, test in sunny weather in the afternoon, test in cloudy/rainy weather in the morning and test in cloudy/rainy weather in the afternoon. For comparison of the device accuracy at different speeds of movement, each test was carried out while walking, jogging and/ or riding a bicycle with the tested device. The tests were also repeated on different days in the same weather condition. For example, a test was carried out on a sunny Saturday, and then the test would be repeated again in a few days (e.g. the following Saturday) when the weather conditions were the same. The following subsections discuss the research findings for the investigation testing of different GPS devices.

4.3.1 Stage One – Tree Canopies Area

The first stage testing was carried out on Twins Oak Drive in One Tree Hill domain that is a tree canopies area; Figure 4.7 shows the test path in Google Map. This area was covered by the trees, with 0% canopy opened, only one curve existed in the path, and the terrain was flat with no uphill or downhill sections. Distance between point A and point B was measured using the Survey Measuring Wheel and was recorded as 450m. Please note that the distance has been measured three times, and the mean distance has been used as the reference distance between point A and point B.

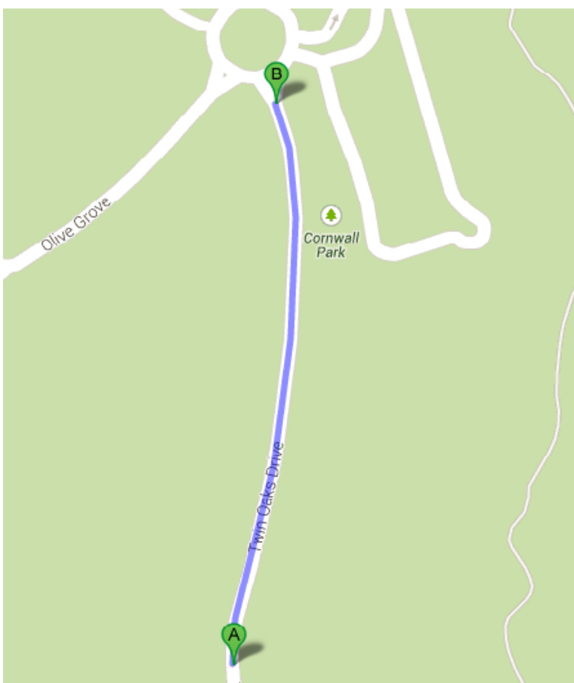

Figure 4.7: Tree Canopies area test path

4.3.1.1 Test One: Test on a sunny morning

Test One was performed on 5th January, when it was a sunny morning and the surface was really dry. The test involved the Garmin GPSmap62 and Google Map navigation on iPhone5. Three speeds were chosen for the testing – walking, jogging and riding a bike.

The first part of the testing was using the Garmin GPSmap62 to measure the distance between point A and point B. Before starting the test, location of point A should be setup in the GPSmap62 as a waypoint, and then the GPS device was carried by the researcher while he walked to point B where the travelled distance calculated by the "Measure Distance" in the GPS was recorded. The test was repeated three times with the same GPS device.

The second part of the test was using the same GPS device, but the researcher was jogging between points A and B. Three rounds of testing were conducted for this part. A similar testing method was applied for the third part of the test that the researcher was riding a bike rather than walking or jogging. The same GPS device Garmin GPSmap62 was used in all three parts of the test between point A and point B and the relevant distances was recorded for analysis.

The forth part of the test was using the GPS device on iPhone5 to measure the distance. First of all, the researcher had to enter the address of point B into the address bar and search for the destination. As soon as the destination was found, the navigation on the Google Map app in iPhone5 was turned on the phone was carried at walking speed to point B. At point B, the travelled distance was recorded. Three rounds of the test were performed on the GPS device on the iPhone 5 at walking speed.

The fifth part of the test was performed at jogging speed and used the same device as in the previous part; three rounds of this part were performed. The sixth part of the test was performed by the researcher riding a bike with the tested device and three rounds were performed for this test.

Table 4.6 shows the measured distances between point A and point B using Garmin GPSmap62 and iPhone5 at different speeds during the test.

Table 4.6: Measured Distances for each of the GPS devices in Test One (Stage 1)

Device	**Speed**	**Round 1 (m)**	**Round 2 (m)**	**Round 3 (m)**
Garmin GPSmap62	Walking	449.6	449.5	449.3
	Jogging	449.7	449.5	449.6
	Bike	449.8	449.7	450.3
GPS device on iPhone5	Walking	450.5	450.4	450.4
	Jogging	450.3	450.4	449.8
	Bike	449.7	450.3	450.1

Meanwhile, in order to find out if the selected GPS devices were able to provide high precision for the measurement for each of the tests, a One sample t-test was also run for each test in Test stage one. The output of test one is showed in Table 4.7 and since the P value was greater than 0.05, there was no significant difference between each of the measured distances and the reference distance.

Table 4.7: Result of One sample t-test between measured distances and reference distances for Test One (Stage 1)

	Test Value = 450					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
measured distances	-.663	17	.516	-.0611	-.2557	.1335

4.3.1.2 Test Two: Test on a sunny afternoon

Test Two was performed on the same day as Test One and used the same testing path, but took place in the afternoon rather than in the morning. The weather was sunny and the surface was dry. This test also used the Garmin GPSmap62 and Google Map on iPhone5 for testing. The same running speeds were applied in the test: walking, jogging and riding a bike.

The first part of the test was using the Garmin GPSmap62 between point A and point B at walking speed. Three rounds of testing were implemented under the same conditions. The second part of the test was using the same GPS device for three rounds at jogging speed. While the third part of the test was of the same device but the researcher rode a bike and the test was also repeated three times.

The forth part of the test was using the iPhone5 Google Map app to test the GPS accuracy on the test path at walking speed; the test was repeated three times. The fifth part of the test was performed at jogging speed and also had three rounds. Lastly, the sixth part of the test was performed at while carrying the iPhone 5 and riding a bike.

Table 4.8 presents the results of Test Two for both Garmin GPSmap62 and the GPS device on iPhone 5 while Table 4.9 shows the result of the t-test.

Table 4.8: Measured Distances for each of the GPS devices in Test Two (Stage 1)

Device	Speed	Round 1 (m)	Round 2 (m)	Round 3 (m)
Garmin	Walking	449.4	450.4	449.6

GPSmap62	Jogging	450.2	449.3	450.3
	Bike	450.2	449.7	449.8
GPS device on iPhone5	Walking	450.3	450.5	450.3
	Jogging	450.1	450.3	449.7
	Bike	450.1	449.9	450.2

Table 4.9: Result of One sample t-test between measured distances and reference distances for Test Two (Stage 1)

	Test Value = 450					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
measured distances	.199	17	.845	.0167	-.1600	.1933

4.3.1.3 Test Three: Test on a rainy morning

Test Three was first conducted on 17th March, when it was a rainy morning and the surface was wet. The same test path as in Test One and Test Two was used for this testing, as well as the same GPS devices. Also, the same running speeds were used, namely walking, jogging and riding a bike.

The three rounds of the first part of the test tested Garmin GPSmap62 and at walking speed. The second part tested the same GPS device in three rounds at jogging speed, while the third part did the same but the three rounds were conducted by riding a bike.

The next three parts of the test was performed on the GPS device on iPhone5 by using the Google Map. Each part was carried out with different running speed (walking, jogging and riding a bike). Each part had three rounds.

Table 4.10 presents the results from Test Three and Table 4.11 outlines the t-test result for Test Three.

Table 4.10: Measured Distances for each of the GPS devices in Test Three (Stage 1)

Device	Speed	Round 1 (m)	Round 2 (m)	Round 3 (m)
Garmin GPSmap62	Walking	449.1	448.9	449.3
	Jogging	449.2	448.8	450.5
	Bike	450.8	449.6	449.5
GPS device on	Walking	451.4	450.7	450.8

iPhone5	Jogging	449.2	450.9	450.7
	Bike	450.9	449.6	450.4

Table 4.11: Result of One sample t-test between measured distances and reference distances for Test Three (Stage 1)

	Test Value = 450					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
measured distances	.084	17	.934	.0167	-.4019	.4353

4.3.1.4 Test Four: Test on a rainy afternoon

Test Four was first conducted in the afternoon on 31st March, when it was raining and the surface was wet. The same test path as in the previous three tests was used for the testing, as well as the same GPS devices. Although the rain was very heavy that afternoon, the same speed was used for testing, namely walking, jogging and riding a bike.

The first three parts of the test were performed on Garmin GPSmap62 and three rounds of tests were done for each part.

The fourth, fifth and sixth part of the test were performed on the GPS device in iPhone5 using the Google Map app to travel between point A and point B; again three different speeds were used (walking, jogging and riding a bike).

Table 4.12 shows the results from Test Four and Table 4.13 provides the t-test result for Test Four.

Table 4.12: Measured Distances for each of the GPS devices in Test Four (Stage 1)

Device	Speed	Round 1 (m)	Round 2 (m)	Round 3 (m)
Garmin GPSmap62	Walking	448.7	450.6	449.4
	Jogging	449.4	449.3	449.3
	Bike	450.4	450.5	449.5
GPS device on iPhone5	Walking	450.8	450.8	449.3
	Jogging	450.9	449.5	449.6
	Bike	450.6	450.4	450.4

Table 4.13: Result of One sample t-test between measured distances and reference distances for Test Four (Stage 1)

	Test Value = 450					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
measured distances	-.205	17	.840	-.0333	-.3757	.3091

4.3.1.5 Repeating the tests for Stage One

All four tests included in Stage One were repeated on a different day but in the same weather and other conditions, in order to find out if the GPS accuracy would be different at different testing time. Test One was repeated on 12th January in the morning; Test Two was repeated on 12th January in the afternoon; Test Three was repeated on 4th May in the morning, and Test Four was repeated on 4th May in the afternoon. Tables 4.14 to 4.17 present the results of the repeated tests.

Table 4.14: Measured Distances for each of the GPS devices in Repeated Test One (Stage 1)

Device	Speed	Round 1 (m)	Round 2 (m)	Round 3 (m)
Garmin GPSmap62	Walking	449.4	449.3	450.4
	Jogging	449.5	449.7	449.5
	Bike	449.7	449.5	450.3
GPS device on iPhone5	Walking	450.7	450.5	450.3
	Jogging	450.3	450.4	450.3
	Bike	450.1	449.8	450.2

Table 4.15: Measured Distances for each of the GPS devices in Repeated Test Two (Stage 1)

Device	Speed	Round 1 (m)	Round 2 (m)	Round 3 (m)
Garmin GPSmap62	Walking	449.4	449.6	450.4
	Jogging	449.5	449.7	450.2
	Bike	450.3	450.1	449.8
GPS device on iPhone5	Walking	450.3	450.4	450.5
	Jogging	449.7	450.3	450.1
	Bike	449.8	450.1	450.2

Table 4.16: Measured Distances for each of the GPS devices in Repeated Test Three (Stage 1)

Device	Speed	Round 1 (m)	Round 2 (m)	Round 3 (m)
Garmin GPSmap62	Walking	448.9	449.4	449.2
	Jogging	450.5	449.0	449.3
	Bike	449.4	450.5	449.3
GPS device on iPhone5	Walking	450.9	450.9	450.5
	Jogging	450.6	450.4	450.7
	Bike	450.3	450.7	450.5

Table 4.17: Measured Distances for each of the GPS devices in Repeated Test Four (Stage 1)

Device	Speed	Round 1 (m)	Round 2 (m)	Round 3 (m)
Garmin GPSmap62	Walking	449.4	448.7	449.2
	Jogging	448.9	449.3	450.5
	Bike	449.5	448.9	449.7
GPS device on iPhone5	Walking	450.8	451.1	450.5
	Jogging	450.7	450.4	450.7
	Bike	450.5	450.4	450.7

4.3.2 Stage Two: Urban Arterials

The second stage of testing was conducted on Highbrook Drive in Highbrook Industrial Park (Figure 4.8). It is a wide open area for most of the testing path, but there are some street signs, electrical lines and telephone poles in the area that could possibly impact the GPS signal reception. The test path was chosen on the walking path, which was a straight line on a flat terrain with no uphill or downhill parts. The path length for this test was 200m. The measurement method for this testing stage was the same as in stage one, to ensure the precision of the measured distance.

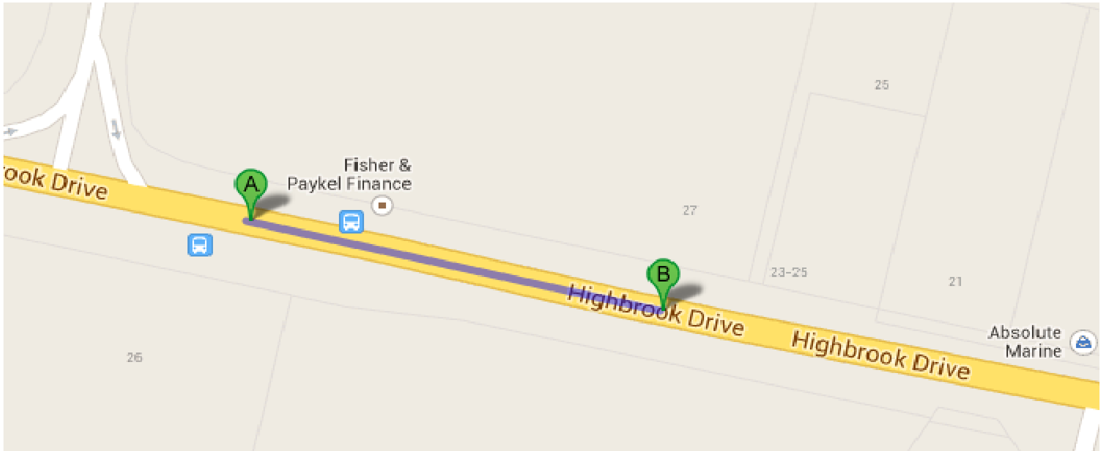

Figure 4.8: Urban Arterials Test Path in Google Map

4.3.2.1 Test One: Test on a sunny morning

Test One was first conducted on 22nd December, when it was a sunny morning and the surface was dry. The test involved the testing of Garmin GPSmap62 and the GPS device on iPhone5 using Google Map navigation. Three speeds were chosen for the testing – walking, jogging and riding a bike.

The first part of the test involved using the Garmin GPSmap62 to measure the distance between point A and point B. The testing procedure was as follows: firstly, setup the GPSmap62 device to set point A as a waypoint. Next, carry the GPS device to point B at walking speed. Secondly, record the travelled distance by using the "Measure Distance" function in the GPS device at point B. The test had three rounds with the same device and at the same speed.

A similar testing method was applied for the second part of the test with the same GPS device, but at jogging speed. Three rounds of the test were conducted between point A and point B for this part. The third part of the test used the same GPS device to travel from point A to point B three times but by riding a bike.

The forth part of the test was using the iPhone5 to measure the distance between point A and point B. At the beginning of the testing, the destination point had to be located manually on Google Map in iPhone 5. As soon as the destination was found, the navigation was started on the Google Map app and the phone was taken to point B by walking. The travelled distance was recorded at point B. Three rounds were performed for this part of the test.

The fifth part of the test was conducted on the same GPS device but at jogging speed; again three rounds of testing were carried out. The sixth part of the test was conducted on the same GPS device by a bike riding from point A to point B. Three rounds of testing also commenced for this part.

Table 4.18 presents the measured distances between point A and point B when using Garmin GPSmap62 and iPhone5at different speeds.

Table 4.18: Measured Distances for each of the GPS devices in Test One (Stage 2)

Device	Speed	Round 1 (m)	Round 2 (m)	Round 3 (m)
Garmin GPSmap62	Walking	200.3	200.5	199.5
	Jogging	199.7	199.5	199.8
	Bike	200.1	199.6	199.8
GPS device on iPhone5	Walking	199.8	200.1	200.2
	Jogging	199.9	200.1	200.1
	Bike	200.0	200.0	200.1

Moreover, in order to find out if the tested GPS devices were able to provide high precision of the measurements for each of the tests, a One Sample t-test was run for each test in Test stage two. The output of test one is shown in Table 4.19 and since the P value (0.447) is greater than 0.05, there was no significant difference between each of the measured distances and the reference distance.

Table 4.19: Result of One sample t-test between measured distances and reference distances for Test One (Stage 2)

	Test Value = 200					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
measured distances	-.778	17	.447	-.0500	-.1857	.0857

4.3.2.2 Test Two: Test on a sunny afternoon

Test Two was conducted on the same day as Test One and used the same testing path, but took place in the afternoon. The weather was sunny and the surface was dry. Garmin GPSmap62 and the GPS device on iPhone5 were tested. The weather and the surface conditions were the same as they were in the morning, and the same testing speeds were used, namely includes walking, jogging and riding a bike.

The first part of the test used Garmin GPSmap62 at walking speed; three rounds of test were performed with this running speed. The second part of the test was using the same GPS device at jogging speed on most of the path and there were three rounds of the test, while the third part of the test was conducted on the same GPS device, but riding a bike; this test was also repeated three times.

The same set of testing conditions would be adopted in the fourth to the sixth part of test that were conducted on the GPS device in iPhone5 using Google Map app. Again, the tests were conducted by walking, jogging and riding a bike and were repeated three times for each part of the test.

Table 4.20 presents the results both devices tested in Test Two and the result of the t-test between measured distances and reference distance for Test two is shown in Table 4.21.

Table 4.20: Measured Distances for each of the GPS devices in Test Two (Stage 2)

Device	Speed	Round 1 (m)	Round 2 (m)	Round 3 (m)
Garmin GPSmap62	Walking	200.5	200.6	200.3
	Jogging	199.6	199.5	200.3
	Bike	199.8	199.6	199.8
GPS device on iPhone5	Walking	199.9	200.1	200.2
	Jogging	200.1	200.1	200.1
	Bike	200.1	200.0	200.1

Table 4.21: Result of One sample t-test between measured distances and reference distances for Test Two (Stage 2)

	Test Value = 200					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
measured distances	.551	17	.589	.0389	-.1099	.1877

4.3.2.3 Test Three: Test on a rainy morning

Test Three was first conducted in the morning on 4th February, when it was raining heavily and the surface was wet. The test path and the GPS devices were the same as the ones used in Test One and Test Two. Although it was raining in the whole morning and the surface was covered by water, the same speeds were used in the test, namely walking, jogging and riding a bike.

The first part of the test used Garmin GPSmap62 at walking speed for most of the trip. Three rounds were carried out for this test. The second part of the test used the same GPS at jogging speed and again three rounds of testing were implemented. The third part of the test was the same but the test was performed by riding a bike.

The fourth to sixth part of the test were carried out on the GPS device in iPhone5 using the Google Map app to travel between the two test points; each part was performed at different speeds as before and had three rounds.

Table 4.22 presents the results of Test Three and Table 4.23 shows the t-test result for Test Three.

Table 4.22: Measured Distances for each of the GPS devices in Test Three (Stage 2)

Device	Speed	Round 1 (m)	Round 2 (m)	Round 3 (m)
Garmin GPSmap62	Walking	199.0	199.2	199.1
	Jogging	199.2	199.1	199.2
	Bike	199.5	199.3	200.5
GPS device on iPhone5	Walking	200.4	200.5	200.5
	Jogging	200.2	200.3	200.5
	Bike	200.2	200.2	200.3

Table 4.23: Result of One sample t-test between measured distances and reference distances for Test Three (Stage 2)

	Test Value = 200					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
measured distances	-1.084	17	.294	-.1556	-.4584	.1473

4.3.2.4 Test Four: Test on a rainy afternoon

Test Four was first conducted in the afternoon on 10th April, when it was cloudy with a few showers and the surface was wet. The same test path as in previous three tests was used for the testing and the same GPS devices were tested. The rain was very heavy in that afternoon and the surface was covered by water. Although the weather and surface conditions were different to those in the previous tests, the same set of running speeds were used, namely walking, jogging and riding a bike.

The first three parts of the test were conducted on Garmin GPSmap62; the researcher travelled between the two test points at mostly walking speed for part one, jogging speed for part two and riding a bike for part three. Three rounds were conducted for each part of the test.

The fourth to sixth part of the test were conducted on the GPS device on iPhone5 and the Google Map app. Part four was conducted at walking speed, part five - at jogging speed and part six was performed by riding a bike.

Table 4.24 shows the testing results from Test Four and Table 4.25 provides the t-test results for Test Four.

Table 4.24: Measured Distances for each of the GPS devices in Test Four (Stage 2)

Device	Speed	Round 1 (m)	Round 2 (m)	Round 3 (m)
Garmin GPSmap62	Walking	199.2	199.1	198.9
	Jogging	199.4	199.1	199.2
	Bike	200.4	199.3	199.5
GPS device on iPhone5	Walking	200.4	200.5	200.5
	Jogging	200.4	200.5	200.2
	Bike	200.3	200.3	200.2

Table 4.25: Result of One sample t-test between measured distances and reference distances for Test Four (Stage 2)

	Test Value = 200					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
measured distances	-1.005	17	.329	-.1444	-.4478	.1589

4.3.2.5 Repeating the tests for Stage Two

In order to find out if the GPS accuracy would be different when the test was conducted at different time all four tests included in Stage Two were repeated on a different day but in the same weather and other conditions. Test One was repeated on 31st December in the morning; Test Two was repeated on 31st December in the afternoon; Test Three was repeated on 28th April in the morning, and Test Four was repeated on 28th April in the afternoon. Tables 4.26 to 4.29 present the results of the repeated tests.

Table 4.26: Measured Distances for each of the GPS devices in Repeated Test One (Stage 2)

Device	Speed	Round 1 (m)	Round 2 (m)	Round 3 (m)
Garmin GPSmap62	Walking	200.3	199.5	199.4
	Jogging	199.7	199.5	199.8
	Bike	200.1	199.6	199.7
GPS device on iPhone5	Walking	200.2	199.8	200.1
	Jogging	200.1	200.2	199.9
	Bike	199.9	200	200.1

Table 4.27: Measured Distances for each of the GPS devices in Repeated Test Two (Stage 2)

Device	Speed	Round 1 (m)	Round 2 (m)	Round 3 (m)
Garmin GPSmap62	Walking	199.7	199.4	200.4
	Jogging	200.4	199.6	199.6
	Bike	200.1	199.7	199.7
GPS device on iPhone5	Walking	200.1	200.2	200.0
	Jogging	200.0	200.1	199.9
	Bike	200.0	200	200.1

Table 4.28: Measured Distances for each of the GPS devices in Repeated Test Three (Stage 2)

Device	Speed	Round 1 (m)	Round 2 (m)	Round 3 (m)
Garmin GPSmap62	Walking	199.3	198.9	199.2
	Jogging	199.2	199.3	199.1
	Bike	200.3	200.4	199.2
GPS device on iPhone5	Walking	200.3	200.6	200.4
	Jogging	200.4	200.5	200.2
	Bike	200.1	200.1	200.4

Table 4.29: Measured Distances for each of the GPS devices in Repeated Test Four (Stage 2)

Device	Speed	Round 1 (m)	Round 2 (m)	Round 3 (m)
Garmin GPSmap62	Walking	199.3	199	199.1
	Jogging	199.3	199.3	199.2
	Bike	200.5	200.4	200.4
GPS device on iPhone5	Walking	200.5	200.6	200.5
	Jogging	200.5	200.5	200.1
	Bike	200.1	200.2	200.2

4.3.3 Stage Three: Walking in Queen Street

The third stage testing was carried out on Queen Street (Figure 4.9) in Auckland CBD and the test method was walking down Queen Street. The aim of this test was to find out the accuracy when the moving speed of the test object was slow. Queen Street has no bends and the pedestrian pathway had a different percentage of canopy open. The reason for choosing Queen Street as the test path for this testing was that there is an uphill to Karangahapa Rd on the upper Queen Street side, therefore I could find out whether the terrain (i.e. uphill or downhill) would affect the accuracy.

Figure 4.9: Queen Street on the map

The distance between point A and point B was measured by the Survey Measuring Wheel, and the result was 1505m. Since the pedestrian pathway on each side of Queen Street had different percentage of canopy open, the test had to include both sides.

4.3.3.1 Test One: Test on a sunny morning

Test one was first conducted on 1st December and it was a sunny morning with no clouds in the sky. This test involved the testing of Garmin GPSmap62, Navman EZY45 and the GPS on iPhone5. Two testing methods were used for the testing – walking and jogging.

The first part of the test used Garmin GPSmap62 to measure the distance between point A and point B. First the GPSmap62 device had to be set up to mark point A and set it as a waypoint. Next, the GPS device was carried while walking to point B on the pedestrian pathway that was on the right hand side of Queen Street. The following step was to mark point B as another waypoint when I reached point B and to use the function "Measure Distance" to measure the distance that the GPS device had travelled. Then I used point B as the start point and walked back to point A following the same pathway; when I reached point A I marked it as a waypoint in the GPS and measured the distance just travelled. After that I carried out the test on the pathway on the left hand side of Queen Street. Again, I started from point A and walked to point B carrying the same GPS device. I measured the distance travelled when I reached point B and then returned to point A on the same pathway and measured the distance again. As a result, the test was carried out on both sides of Queen Street and in both directions. However, the second part of the test was using the same GSP device as in the first part, but at jogging speed rather than walking.

The third part of the test tested Navman EZY45 GPS. At the beginning of the testing, I entered the address of point B as destination and walked to point B on the right hand side of Queen Street. When the destination specified on the GPS (point B) was reached, and if that did not match the real point B marked before the testing, then the Survey Measuring Wheel was used to measure the distance difference. The next step was to use point B as a starting point and to walk back to point A; the same method to measure the distance difference was adopted when needed. The same test was conducted on the left hand side of Queen Street. I walked with the same GPS device from point A to point B and used the same measurement method to get the distance, and then returned to point A on the same pathway, and again measured the distance. The fourth part of the test was to use the same GPS device as in the third part, but at jogging speed rather than walking.

The fifth part of the test used iPhone5 GPS and the Google Map app to measure the distance. The same testing and measurement method as in the third part of the test was applied. The sixth part of the test was using jogging instead of walking to measure the distance. Table 4.30 displays the results from Test One.

Table 4.30: Measured Distances for each of the GPS devices in Test One (Stage 3)

Device	Speed	A to B (m)	B to A (m)	A to B (m)	B to A (m)
Garmin GPSmap62	Walking	1504.7	1504.6	1504.7	1504.6
	Jogging	1505.7	1505.6	1505.5	1505.6
Navman EZY45	Walking	1504.7	1504.7	1504.7	1504.6
	Jogging	1505.4	1505.5	1505.3	1505.4
GPS device on iPhone5	Walking	1504.7	1504.9	1504.8	1504.8
	Jogging	1504.7	1505.3	1505.1	1505.2

Meanwhile, in order to find out if the selected GPS devices for Test stage three were able to provide high precision for the measurement in each test, a One Sample t-test was run for each test at this test stage. The output of Test One is shown in Table 4.31; since the P value (0.676) is greater than 0.05, there is no significant difference between each of the measured distances and the reference distance.

Table 4.31: Results of One sample t-test between measured distances and reference distances for Test One (Stage 3)

	Test Value = 1505					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
measured distances	.423	23	.676	.0333	-.1298	.1965

4.3.3.2 Test Two: Test on a sunny afternoon

Test Two was conducted on the same day as Test One, the same testing path and testing speed were used, but it took place in the afternoon. The test was also carried out on Garmin GPSmap62, Navman EZY45 and on GPS device on iPhone5 as the selected GPS devices to test the accuracy.

The first and second part of the test used Garmin GPSmap62 to measure the distance between point A and point B, while the third and the forth part used the Navman EZY45 device; the fifth and the sixth part of the test used the GPS device on iPhone5 and the Google Map app. Table 4.32 presents the results from Test Two and the results from the t-test between measured distance and reference distance for Test Two are shown in Table 4.33.

Table 4.32: Measured Distances for each of the GPS devices in Test Two (Stage 3)

Device	Speed	A to B (m)	B to A (m)	A to B (m)	B to A (m)
Garmin GPSmap62	Walking	1504.7	1504.7	1504.8	1504.6
	Jogging	1505.2	1505.2	1505.2	1505.3
Navman EZY45	Walking	1504.9	1504.8	1504.9	1504.7
	Jogging	1505.1	1504.9	1505.2	1505.2
GPS device on iPhone5	Walking	1504.9	1504.8	1504.9	1505.0
	Jogging	1505.1	1504.9	1505.1	1505.2

Table 4.33: Results of One sample t-test between measured distances and reference distances for Test Two (Stage 3)

	Test Value = 1505					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
measured distances	-.703	23	.489	-.0292	-.1150	.0566

4.3.3.3 Test Three: Test on a cloudy morning

Test Three was first conducted on 16th December and it was a cloudy morning but there was no rain. The test also used Garmin GPSmap62, Navman EZY45 and the GPS device on iPhone5 to test the GPS accuracy.

The first two parts of the test used Garmin GPSmap62 to measure the distance between point A and point B, while the third and the forth part used Navman EZY45, while the last two parts of the test used the GPS device on iPhone5 and the Google Map app. Table 4.34 presents the results from Test Three and Table 4.35 outlines the t-test result for Test Three.

Table 4.34: Measured Distances for each of the GPS devices in Test Three (Stage 3)

Device	Speed	A to B (m)	B to A (m)	A to B (m)	B to A (m)
Garmin GPSmap62	Walking	1504.4	1504.2	1504.5	1504.4
	Jogging	1505.8	1505.9	1505.8	1505.8
Navman EZY45	Walking	1504.5	1504.5	1504.6	1504.6
	Jogging	1505.8	1505.6	1505.8	1505.6
GPS device on iPhone5	Walking	1504.6	1504.7	1504.5	1504.6
	Jogging	1505.3	1505.6	1505.2	1505.5

Table 4.35: Results of One-sample t-test between measured distances and reference distances for Test Three (Stage 3)

	Test Value = 1505					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
measured distances	.607	23	.550	.0750	-.1806	.3306

4.3.3.4 Test Four: Test on a cloudy afternoon

Test Four was conducted on the same day as Test Three and in the same testing conditions including speed of movement, path and GPS devices used. However, the tests were conducted in the afternoon rather than in the morning.

The first and second part of the test used Garmin GPSmap62 to measure the distance between point A and point B, while the third and the forth part used Navman EZY45; the fifth and the sixth part of the test used the GPS device on iPhone5 and the Google Map app. Table 4.36 presents the results of Test Four and Table 4.37 provides the t-test results for Test Four.

Table 4.36: Measured Distances for each of the GPS devices in Test Four (Stage 3)

Device	Speed	A to B (m)	B to A (m)	A to B (m)	B to A (m)
Garmin GPSmap62	Walking	1504.5	1504.4	1504.5	1504.7
	Jogging	1505.8	1505.5	1505.8	1505.9
Navman EZY45	Walking	1504.6	1504.6	1504.6	1504.7
	Jogging	1505.8	1505.5	1505.6	1505.6
GPS device on iPhone5	Walking	1504.8	1504.7	1504.8	1504.7
	Jogging	1504.8	1504.7	1505.3	1505.4

Table 4.37: Result of One sample t-test between measured distances and reference distances for Test Four (Stage 3)

	Test Value = 1505					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
measured distances	.518	23	.610	.0542	-.1622	.2705

4.3.3.5 Repeating the tests for Stage Three

In order to find out if the GPS accuracy would differ all-four tests included in Stage Two were repeated on a different day but in the same weather and street conditions. Test One was repeated on 1st January in the morning; Test Two was repeated on 1st January in the afternoon; Test Three was repeated on 24th January in the morning, and Test Four was repeated on 24th January in the afternoon. Tables 4.38 to 4.41 display the results from the repeated tests.

Table 4.38: Measured Distances for each of the GPS devices in Repeated Test One (Stage 3)

Device	Speed	A to B (m)	B to A (m)	A to B (m)	B to A (m)
Garmin GPSmap62	Walking	1504.6	1504.6	1504.7	1504.6
	Jogging	1505.9	1505.5	1505.5	1505.7
Navman EZY45	Walking	1504.6	1504.7	1504.6	1504.6
	Jogging	1505.3	1505.1	1505.2	1505.3
GPS device on iPhone5	Walking	1504.8	1504.7	1504.7	1504.7
	Jogging	1505.3	1505.2	1505.2	1505.3

Table 4.39: Measured Distances for each of the GPS devices in Repeated Test Two (Stage 3)

Device	Speed	A to B (m)	B to A (m)	A to B (m)	B to A (m)
Garmin GPSmap62	Walking	1504.6	1505.4	1504.6	1504.7
	Jogging	1505.2	1505.4	1504.7	1504.8
Navman EZY45	Walking	1504.7	1505.3	1504.8	1504.8
	Jogging	1505.1	1505	1505.2	1505.2
GPS device on iPhone5	Walking	1504.9	1504.7	1504.9	1505.3
	Jogging	1505.1	1505	1504.8	1505

Table 4.40: Measured Distances for each of the GPS devices in Repeated Test Three (Stage 3)

Device	Speed	A to B (m)	B to A (m)	A to B (m)	B to A (m)
Garmin GPSmap62	Walking	1504.3	1504.2	1504.3	1504.2
	Jogging	1505.8	1505.9	1505.9	1505.8
Navman EZY45	Walking	1504.4	1504.3	1504.7	1504.5
	Jogging	1505.7	1505.6	1505.5	1505.6
GPS device on iPhone5	Walking	1504.4	1504.6	1504.5	1504.5
	Jogging	1505.2	1505.5	1505.2	1505.4

Table 4.41: Measured Distances for each of the GPS devices in Repeated Test Four (Stage 3)

Device	Speed	A to B (m)	B to A (m)	A to B (m)	B to A (m)
Garmin GPSmap62	Walking	1504.3	1504.3	1504.7	1504.6
	Jogging	1505.5	1505.6	1505.7	1505.6
Navman EZY45	Walking	1504.6	1504.4	1504.6	1504.7
	Jogging	1505.3	1505.4	1505.3	1505.6
GPS device on iPhone5	Walking	1504.4	1504.7	1504.6	1504.8
	Jogging	1504.7	1504.8	1505.4	1505.2

4.3.4 Stage Four: Indoor Environment

The fourth stage testing was conducted in the hallway within my house, which is an indoor environment and 0% canopy opened, but the received GPS signal is of medium strength compared to the other testing environments.

Garmin GPSmap62 was the only GPS device that could be used in this stage of the test, as only this GPS would be able to measure small distances. The test path was from the front door of my house (point A) to the end of the hallway (point B). The Survey Measuring Wheel was used to measure the distance between the selected two testing points, and the distance was 6m.

4.3.4.1 Test One: Test on a sunny morning

Test one was first conducted on 8th December which was a sunny Saturday morning with no clouds in the sky. Considering the short distance of the test path, only walking was used as a testing method.

The test was using the Garmin GPSmap62 to measure the distance between point A and point B. Before starting the test, I waited for a few seconds so the GPS device could receive GPS signal and determine the current location; point A was marked as a waypoint on the device. I walked to point B while holding the GPS device, and marked point B as a waypoint; I also used the "Measure Distance" function of the device to find out the distance between the two points.

The next step was to reverse the test direction; I started from point B and walked to point A, and then measured the distance. I repeated the test from point A to point B and back, each time measuring the distance. Table 4.42 shows the results of Test One.

Table 4.42: Measured Distances for the GPS device in Test One (Stage 4)

Device	Speed	A to B (m)	B to A (m)	A to B (m)	B to A (m)
Garmin GPSmap62	Walking	5.8	5.2	4.5	5.4

4.3.4.2 Test Two: Test on a sunny afternoon

Test Two was conducted on the same day as Test One, used the same testing path and the same testing speed, but it took place in the afternoon. Table 4.43 displays the results from Test Two.

Table 4.43: Measured Distances for the GPS device in Test Two (Stage 4)

Device	Speed	A to B (m)	B to A (m)	A to B (m)	B to A (m)
Garmin GPSmap62	Walking	5.2	4.6	5.1	5.9

4.3.4.3 Test Three: Test on a rainy morning

Test Three was first conducted on 25th December, when it was a rainy morning. The same testing path and testing speed and testing method as in the previous two tests were used. Table 4.44 presents the results from Test Three.

Table 4.44: Measured Distances for the GPS device in Test Three (Stage 4)

Device	Speed	A to B (m)	B to A (m)	A to B (m)	B to A (m)
Garmin GPSmap62	Walking	4.9	3.6	5.1	5.3

4.3.4.4 Test Four: Test on a rainy afternoon

Test Four was first conducted on 26th December on a rainy afternoon. Table 4.45 shows the results from Test Four.

Table 4.45: Measured Distances for the GPS device in Test Four (Stage 4)

Device	Speed	A to B (m)	B to A (m)	A to B (m)	B to A (m)
Garmin GPSmap62	Walking	3.8	5.2	4.7	4.5

4.3.4.5 Repeating the tests for Stage Four

In order to find out if the GPS accuracy would be different all four tests included in Stage Four were repeated on a different day but in the same weather condition. Test One was repeated on 28th January in the morning; Test Two was repeated on 28th January in the afternoon; Test Three was repeated on 20th April in the morning, and Test Four was repeated on 20th April in the afternoon. Tables 4.46 to 4.49 present the results from the repeated tests.

Table 4.46: Measured Distances for the GPS device in Repeated Test One (Stage 4)

Device	Speed	A to B (m)	B to A (m)	A to B (m)	B to A (m)
Garmin GPSmap62	Walking	4.9	5.7	5.8	5.5

Table 4.47: Measured Distances for the GPS device in Repeated Test Two (Stage 4)

Device	Speed	A to B (m)	B to A (m)	A to B (m)	B to A (m)
Garmin GPSmap62	Walking	5.2	5.6	5.9	5.8

Table 4.48: Measured Distances for the GPS device in Repeated Test Three (Stage 4)

Device	Speed	A to B (m)	B to A (m)	A to B (m)	B to A (m)
Garmin GPSmap62	Walking	5.3	4.2	4.1	4.5

Table 4.49: Measured Distances for the GPS device in Repeated Test Four (Stage 4)

Device	Speed	A to B (m)	B to A (m)	A to B (m)	B to A (m)
Garmin GPSmap62	Walking	4.2	4.1	4.6	4.6

4.4 GRAPGICAL PRESENTATION AND ANALYSIS OF RESULTS

Section 4.3 discussed the test results regarding the four testing stages of the conducted research. The results reported in Section 4.3 are presented in this section graphically. The purpose is to visualise the results which will help with their interpretation and analysis.

Stage one involved testing the GPS devices in tree canopied area. The results from the first stage testing represent the distances measured by multiple GPS devices under different weather conditions and running speeds and are displayed in Figure 4.10, Figure 4.11, Figure 4.12 and Figure 4.13. These graphs are based on Table 4.6, Table 4.8, Table 4.10 and Table 4.12 respectively.

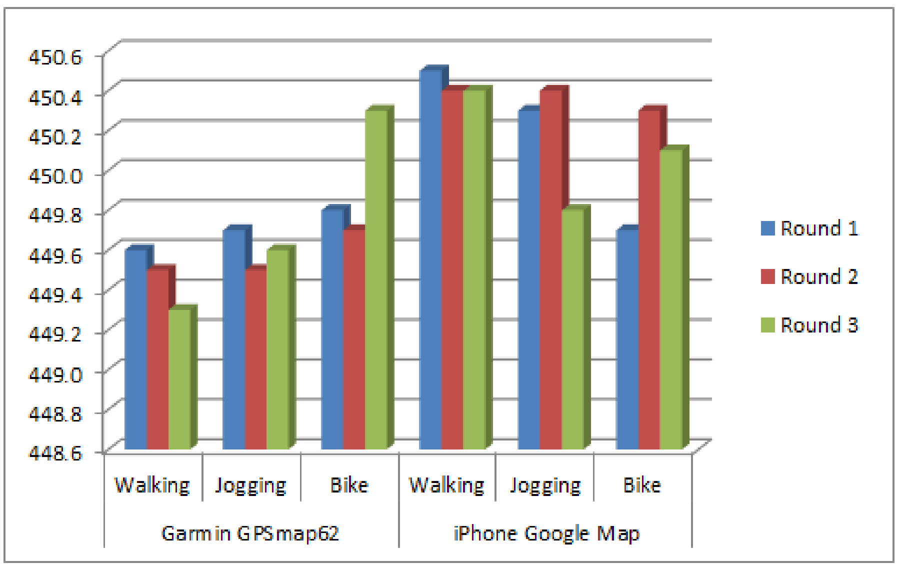

Figure 4.10: Measured Distances in tests performed on sunny morning (Tree canopied area)

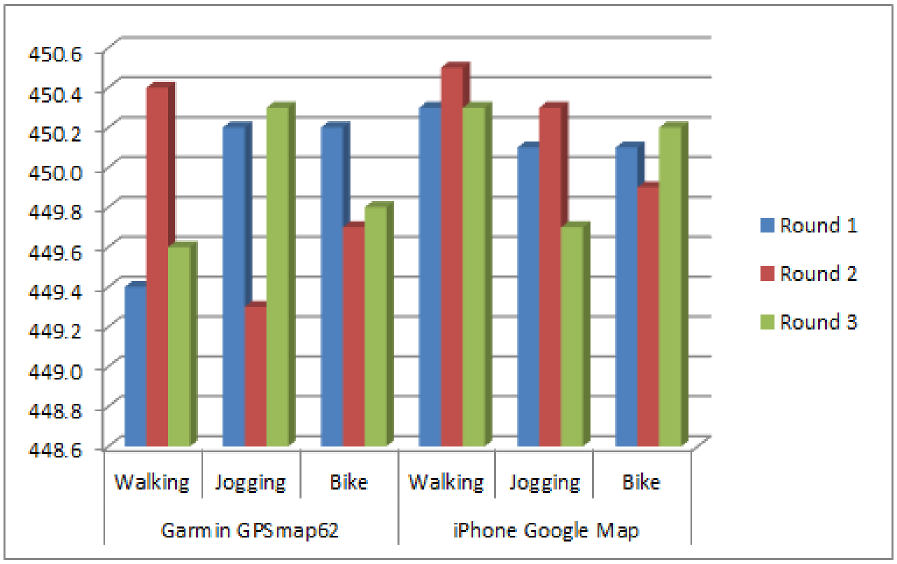

Figure 4.11: Measured Distances in tests performed on sunny afternoon (Tree canopied area)

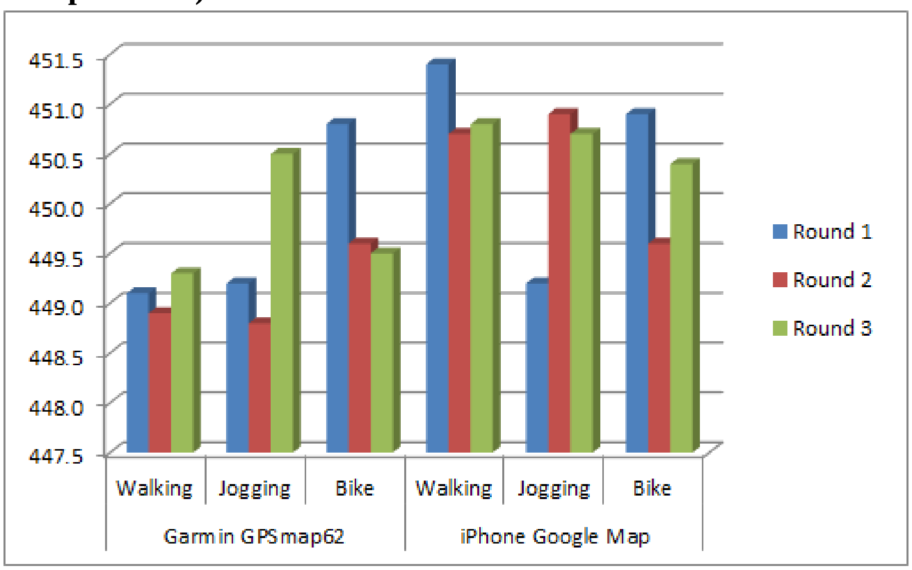

Figure 4.12: Measured Distances in tests performed on rainy morning (Tree canopied area)

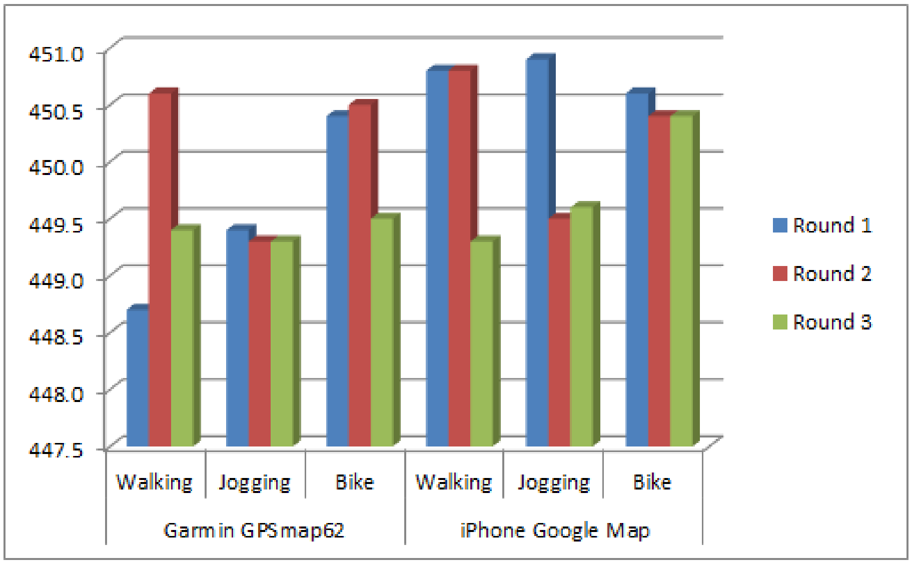

Figure 4.13: Measured Distances in tests performed on rainy afternoon (Tree canopied area)

Stage Two involved testing the GPS devices on urban arterials. The results from Test stage two present the measured distances by selected GPS devices under different weather conditions and running speeds and the graphs are displayed in Figure 4.14, 4.15, 4.16 and 4.17 and are based on Table 4.18, Table 4.20, Table 4.22 and Table 4.24 respectively.

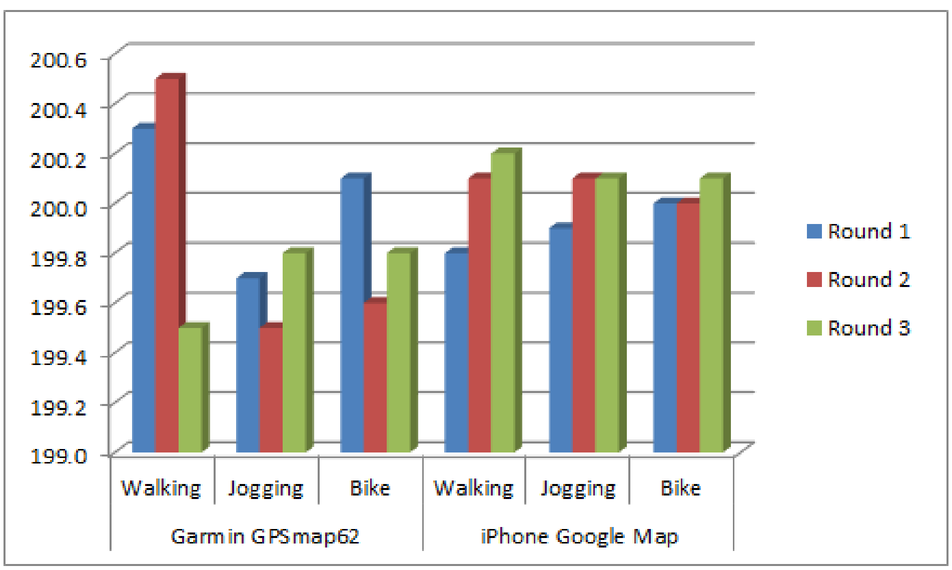

Figure 4.14: Measured Distances in tests performed on sunny morning (Urban arterials)

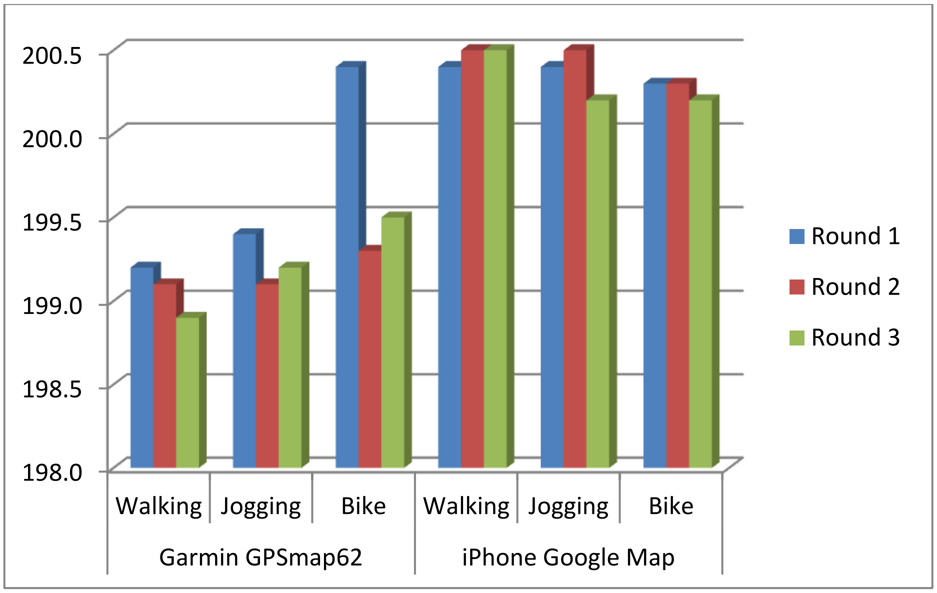

Figure 4.15: Measured Distances in tests performed on sunny afternoon (Urban arterials)

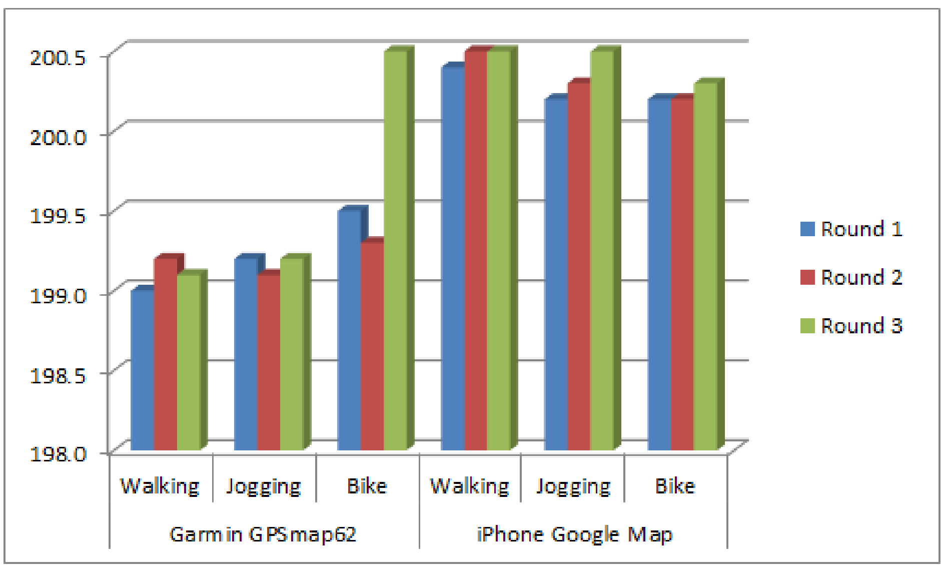

Figure 4.16: Measured Distances in tests performed on rainy morning (Urban arterials)

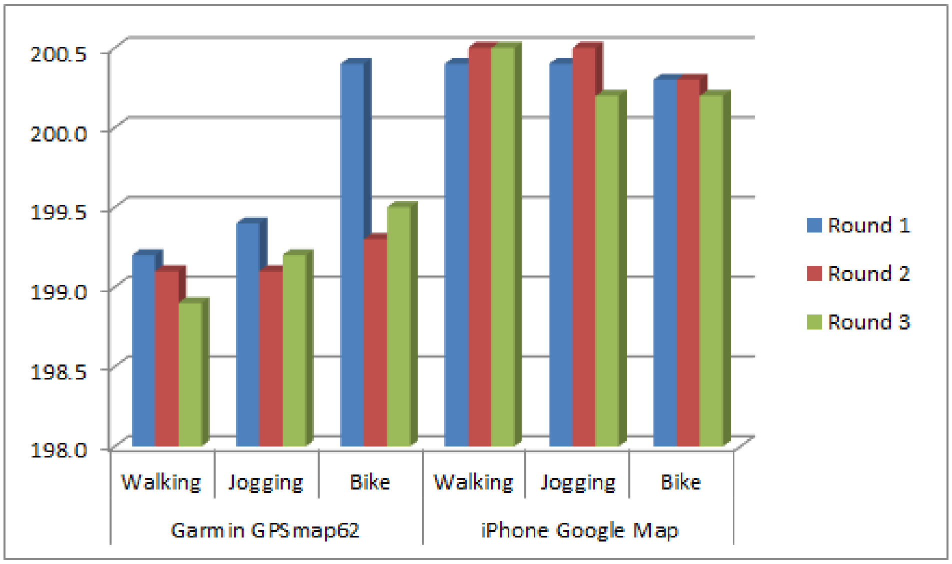

Figure 4.17: Measured Distances in tests performed on rainy afternoon (Urban arterials)

Stage Three involved the testing of the GPS devices on Queen Street by walking and jogging. The results from this stage are plotted and shown in Figure 4.18, Figure 4.19, Figure 4.20 and Figure 4.21 that are based on Table 4.30, Table 4.32, Table 4.34 and Table 4.36 respectively.

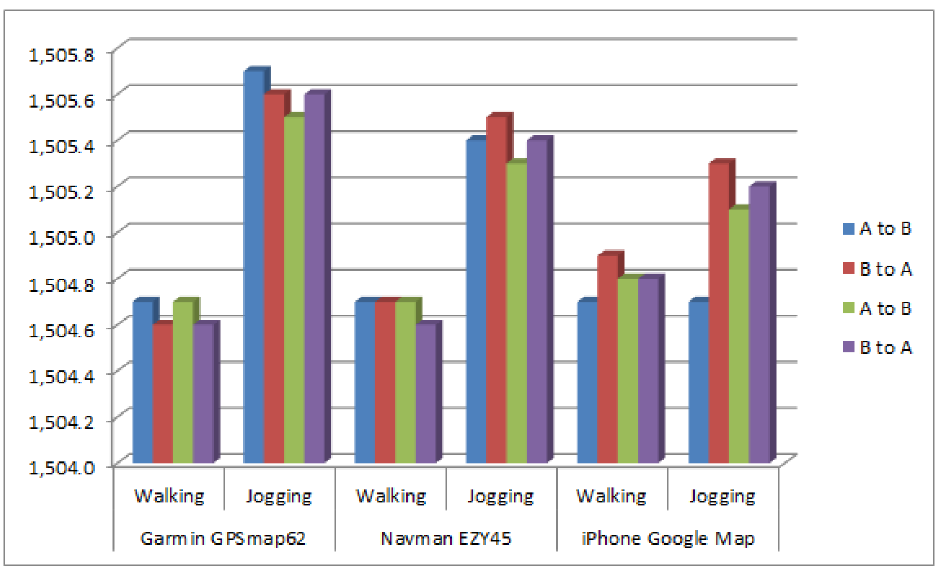

Figure 4.18: Measured Distances in tests performed on sunny morning (City area)

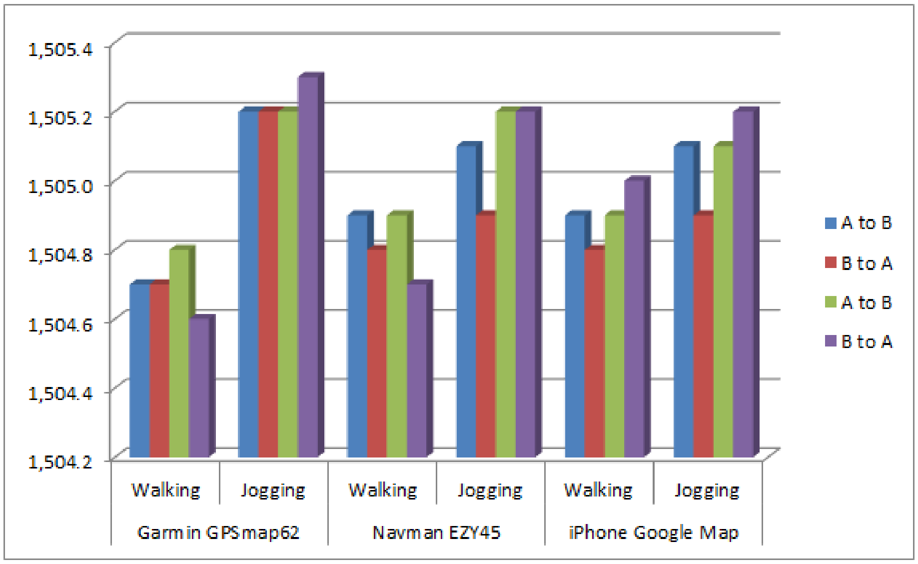

Figure 4.19: Measured Distances in tests performed on sunny afternoon (City area)

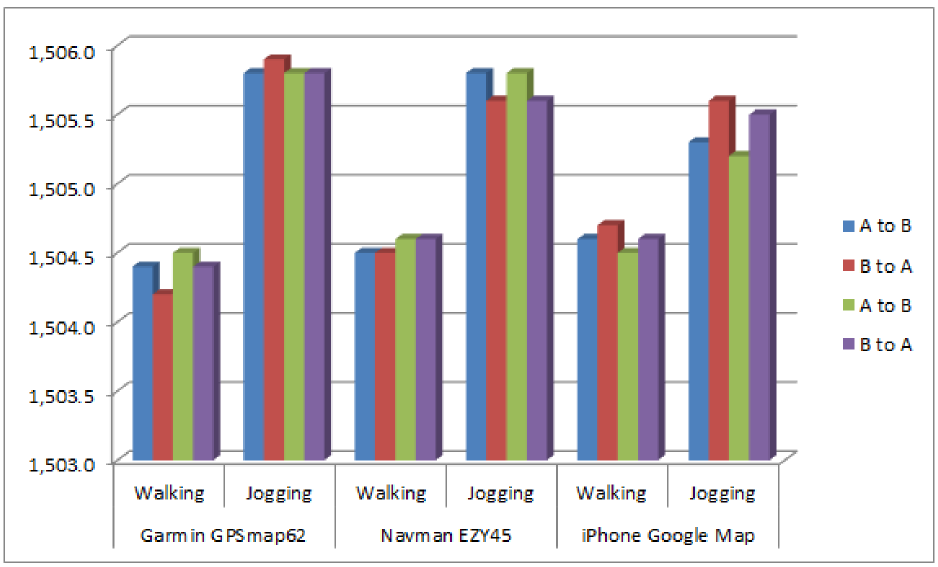

Figure 4.20: Measured Distances in tests performed on rainy morning (City area)

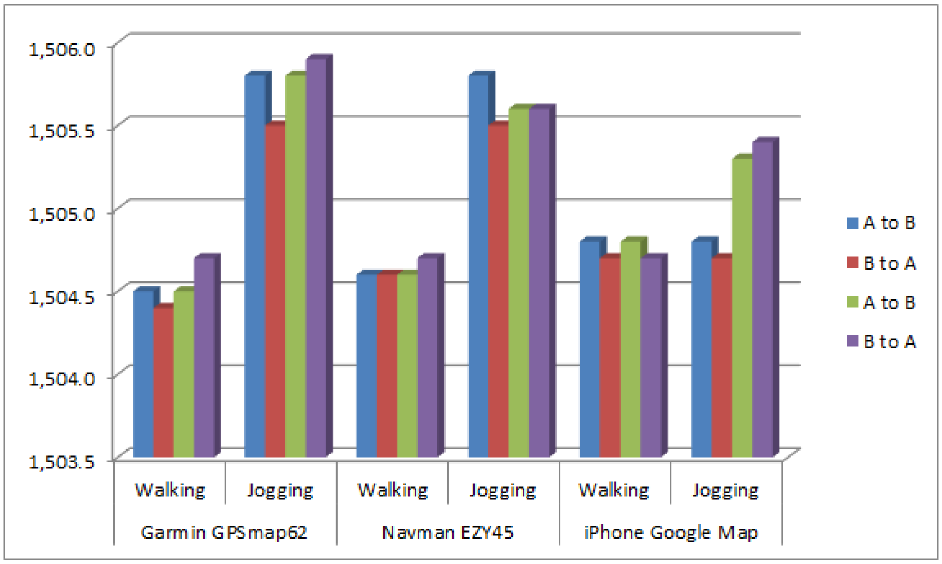

Figure 4.21: Measured Distances in tests performed on rainy afternoon (City area)

The last stage testing was testing the Garmin GPSmap62 GPS device in an indoor environment. The results from this stage are plotted and displayed in Figure 4.22, which is based on the testing results from Table 4.42, Table 4.43, Table 4.44 and Table 4.45.

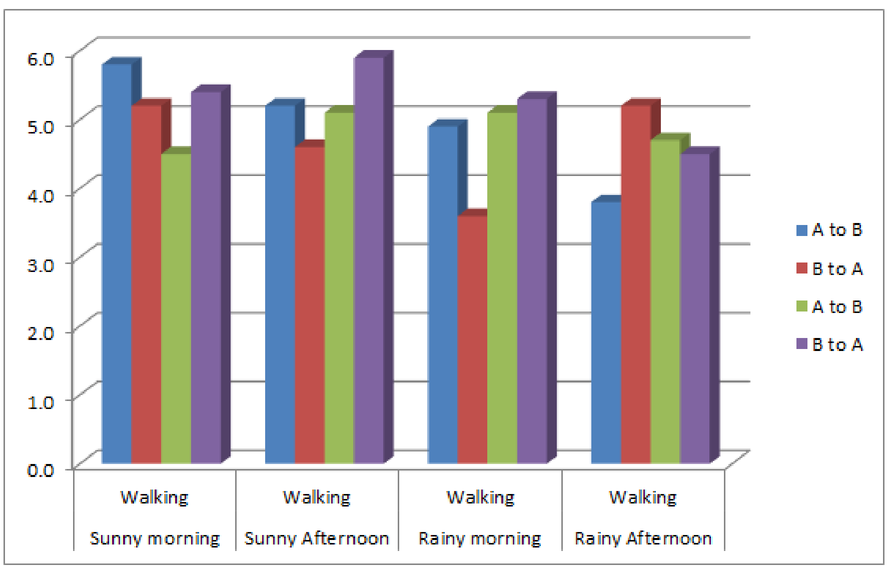

Figure 4.22: Measured Distances in all tests in Test stage 4 (Indoor)

To aid the data analysis, results from Stage One, conducted on a sunny morning, are compared with the testing results from the tests conducted on a sunny afternoon. As can be seen from Table 4.50, the testing results were quite close to the real distance (450 m). Test One of this testing Stage had the lowest value (449.3 m) that was measured by the Garmin GPSmap62 at walking speed, and the highest value (450.5 m) was measured by the iPhone 5 Google Map app at walking speed. Most of the values obtained in Test One are close to the real distance of 450 m, where the difference is within 0.5m, and the closest value 450.1 m was measured by the iPhone 5 Google Map app when I was riding a bike. On the other hand, the results of Test Two were slightly different from those from Test One but showed a similar trend across the test. For example, there were a number of test values in Test two where the difference was within 0.5m of the real distance. The closest value was also 450.1 m and was measured by iPhone 5 Google Map app when I was riding a bike. The next step was to compare the results of Test Three (on a rainy morning) and Test Four (on a rainy afternoon) in Stage one. Test Three recorded the lowest value for the distance of 448.8 m recorded by Garmin GPSmap62 at jogging speed and the highest value of 451.4 m recorded by the iPhone Google Map app at walking speed. The results from Test Four are similar to the results obtained in Test Three as the lowest recorded value was 448.7 m measured by Garmin GPSmap62 at walking speed and the highest value was 450.9 m measured by the iPhone Google Map app at jogging speed.

Table 4.50: Descriptive statistics for the difference between distances as measured in different tests in Test Stage 1 and the actual distance

Test	Mean (m)	S.E. Mean	Std. Deviation	Minimum (m)	Maximum (m)
1	449.94	9.22%	39.13%	449.3	450.5
2	450.02	8.37%	35.52%	449.3	450.5
3	450.02	19.84%	84.17%	448.8	451.4
4	449.97	16.23%	68.86%	448.7	450.9

In Stage Two, the real distance was 200 m. Descriptive statistics for the differences between distances measured in different tests in Test stage two are presented in Table 4.51. Test One was conducted on a sunny morning, and recorded the lowest value of 199.5 m measured by Garmin GPSmap62 at walking speed. Interestingly, the highest value of 200.5m was also measured by Garmin GPSmap62 at walking speed in this test.

Additionally, the most accurate value of exactly 200 m was measured by the iPhone Google Map app when I was riding a bike. This was followed by the result obtained in test two which was performed on a sunny afternoon and the lowest recorded value in the test was also 199.5 m as measured by Garmin GPSmap62 at jogging speed. The highest value was 200.6 m and was measured by Garmin GPSmap62 at walking speed. Not surprisingly, the most accurate value of 200 m was measured by the iPhone Google map app when I was riding a bike. Next, Test Three was conducted on a rainy morning and the lowest value of 199.0 m was measured by Garmin GPSmap62 at walking speed, while the highest value was measured several times when the tests used the iPhone Google Map app. Furthermore, Test Four was conducted in the afternoon with a few showers, when the lowest value of 198.9 m was measured by Garmin GPSmap62 at walking speed, while the highest value was 200.5 m measured by the iPhone Google map app at walking speed. In summary, one of the most interesting conclusions that can be made based on the provided data was that the lowest values in all tests were measured by GPSmap62 at walking speed.

Table 4.51: Descriptive statistics for the difference between distances as measured in different tests in Test Stage 2 and the actual distance.

Test	Mean (m)	S.E. Mean	Std. Deviation	Minimum (m)	Maximum (m)
1	199.95	6.43%	0.27%	199.5	200.5
2	200.04	0.07%	0.30%	199.5	200.6
3	199.84	0.14%	0.61%	199.0	200.5
4	199.86	0.14%	0.61%	198.9	200.5

The real distance in Stage Three was 1505m. Table 4.52 contains the descriptive statistics for the difference between each of test in Test stage three. The test in a sunny morning recorded the highest value of 1505.7 m by Garmin GPSmap62 while jogging; the lowest value 1504.6 m was measured by Navman EZY45 while walking. The next test was in a sunny afternoon, and recorded the highest value of 1505.3 m that also measured by Garmin GPSmap62 while jogging, while the lowest value 1504.6 m was measured by Garmin GPSmap62 when I was walking. Followed by test three which was tested in a cloudy morning and the lowest value of 1504.2m has been occurred when I was using Garmin GPSmap62 with walking speed. Then the highest value (1505.9 m) was again measure by Garmin GPSmap62 but with jogging speed. Moreover, test Four was implemented in a cloudy afternoon, measured the lowest value of 1504.4m by Garmin GPSmap62 on walking speed, the highest value of 1505.9 m was measured by Garmin GPSmap62 on jogging.

Table 4.52: Descriptive statistics for the difference between distances as measured in different tests in Test Stage 3 and the actual distance.

Test	Mean (m)	S.E. Mean	Std. Deviation	Minimum (m)	Maximum (m)
1	1505.03	0.79%	0.39%	1504.6	1505.7
2	1504.97	0.04%	0.20%	1504.6	1505.3
3	1505.08	0.12%	0.61%	1504.2	1505.9
4	1505.05	0.10%	0.51%	1504.4	1505.9

Stage Four was conducted in an indoor environment and used Garmin GPSmap62, and the tested distance was 6m. Test One was conducted on a sunny morning and recorded a highest value of 5.8 m; Test Two was conducted on a sunny afternoon and measured the best value of 5.9 m; Test Three recorded the best value of 5.3 m and Test Four recorded the highest value of 5.2 m.

From these results, it appears that the most obvious factor which affected the GPS accuracy was the weather conditions. When comparing the results from tests done on sunny and rainy/cloudy days, it can be seen that the accuracy on sunny days was higher than that on rainy/cloudy days. Furthermore, the GPS hardware specification and the travelling speed was also a factor influencing the accuracy. For these tests, the screen refresh rate on Navman EZY45 and Garmin GPSmap62 was not as high as that of iPhone5; also, iPhone5 had a high speed CPU and greater memory to process the images, so generally the iPhone5 could have better accuracy if the same conditions applied to all three tested GPS devices. Also, the iPhone5 Google Map app had the best performance during all testing stages, as it had the highest accuracy while the test method was riding a bike. It did especially well in the low speed measurement, had the highest accuracy in Stage Three, with a very little difference when compared with the real distance.

4.5 CONCLUSION

Chapter 4 has covered the reporting, presentation and analysis of the test data and discussed the research findings based on the data analysis. Differences from the original proposed data collection requirements were outlined and discussed in order to clarify those changes made to the proposed testing methodology. The preliminary testing of the GPS devices was conducted with the aim for the researcher to get familiar with the GPS devices and understand their operations, such as locating the position and collecting distance data. Then four stages of tests were conducted in different weather and locations to find out how the environment factors affected the GPS accuracy. The four stages of tests included tests in tree canopied area, urban arterials testing in Highbrook industrial park, tests on Queen Street in Auckland CBD and indoor testing. Each stage of the testing was conducted in different weather conditions, different speed and re-tested on a different day.

Key findings from the test data were that the weather conditions, the refresh rate of the GPS screen, and the running speed were the strongest factors that affected the GPS accuracy with the weather being the main factor. Furthermore, , when the same test was performed on two different days, as long as the weather conditions were the same, the accuracy was not affected. The findings showed that the proposed test design was capable of researching the factors that would affect the GPS accuracy.

Chapter 5 : RESEARCH DISCUSSION

5.0 INTRODUCTION

Chapter 4 reported the significant findings based on the data collected from the research experiments. The purpose of proposing a research methodology and then performing the various stages of testing was to investigate the level of accuracy of distance measurement recorded by a few different GPS devices in a certain time period and the factors that affect the accuracy. Chapter 5 will present a discussion of the research findings for each of the test stages so that the significance of the results can be evaluated within the context of the discipline area. Furthermore, the findings will prove the hypothesis that stated in the research methodology, also conclude this chapter.

This chapter aims to test the seven hypotheses by using the research findings presented in Chapter 4. Although the testing results have been briefly analysed in Chapter 4, a more detailed analysis is needed in order to answer the research questions formulated in Chapter 3. The selected GPS devices for the tests are Garmin GPSmap 62, Navman EZY45 and GPS device on iPhone5. The four stages of testing include tests in the following locations: Tree canopies area in One Tree Hill, Urban arterials in Highbrook Industrial park, Queen Street and indoor environment; all tests were also conducted at different testing times and different running speed. Essentially, each test was conducted in various weather conditions, with different percentage of canopy open area, and various running speeds, which simulated most of the civilian GPS operation environment. Those factors will be discussed in details in order to answer the main research question, as well as the research sub-questions associated with the main question.

The structure of this chapter is the following: section 5.1 explains the variations encountered in testing and discusses their impact on the results; section 5.2 mainly answers the research questions; section 5.3 discusses the research results and the factors that impact the accuracy, and also presents some suggestions for how to potentially improve the GPS accuracy based on the research findings. Section 5.4 concludes the chapter.

5.1 VARIATIONS ENCOUNTERED

Chapter 3 proposed the testing conditions, testing steps and the expected outcomes for the various testing phases. However, during the actual testing period, some changes of the plan had to be made to match the change in conditions, such as the weather and the surface used for testing. As expected, these variations did affect the expected outcome results. It is essential to describe these variations and discuss their impact on the final results. Chapter 4 has already indicated some of the variations to the proposed testing plan and this section will discuss how these variations impact the results.

5.1.1 Testing Environment Variation

The testing environment includes the testing locations and the weather conditions and they were specified in section 3.3. Accordingly, the tests for this study were divided into four stages – Tree canopies area, Urban arterials, Queen Street testing and indoor environment, and the same test should be ran in sunny and in a cloudy/rainy weather conditions.

However, the weather in Auckland was mostly sunny and dry for most of the testing period and these weather conditions lasted for about three months. Even though occasionally the sky was covered by clouds, it didn't last long enough for the testing to continue under the same weather conditions. As a result, the testing date of the test that had been scheduled on a rainy date would have to be postponed for at least a month. The original plan was to complete all testing stages for the first time by middle of January; due to the weather conditions, the tests in rainy weather had to be re-scheduled to the earliest possible date which was the 4th of February, when Test Three took place to test Stage Two on a rainy morning. The first test for Test Three which was planned to take place on a rainy morning in Stage One was postponed to the 17th of March; the first test for Test Four which was planned to take place on a rainy afternoon in Stage One was postponed to the 31st of March; and the Test Four which was planned to take place on a rainy afternoon for Stage Two was postponed to the 10th of April. Test Three and Test Four for Stage Three on Queen Street only took place in cloudy weather. Section 3.3 specified that Stage Four should not consider the weather conditions as the testing was planned to take place in indoor environment. However, according to the testing results of

Stage One, Two, Three, weather conditions were a significant factor that affected the accuracy. Hence the weather was considered in the real testing in Stage Four. Test Three and Test Four for Stage Four were conducted at the end of December, on the 25th and 26th of that month.

Based on the proposed test plan, Stage Three (test in Queen Street) should be implemented by walking and riding on a bicycle. However, for safety reasons, considering the traffic volume on Queen Street, the testing method of riding a bicycle was not implemented; instead, the alternative method of jogging was used.

For the proposed testing in Stage Four, the two testing points chosen for the test could be anywhere inside my house, as long as there was nothing in between them. It turned out that the only area in the house that had GPS signal was in the hallway and the test path for Stage Four was selected from the front door of the house (point A) to the end of the hallway (point B).

5.1.2 Data Analysis and Reporting

There are no variations regarding data analysis and reporting. It means the method adopted in the real testing was exactly the same as the method proposed in Chapter 3.

5.1.3 Discussion

The changes made to the original plan aimed to improve the collection of valid experimental data, and provide more information about the factors that affect the GPS accuracy. This sub-section will discuss how these variations help the research.

The first variation was the weather factor. According to the literature reviews of previous studies about GPS accuracy presented in Chapter 2, the weather factor impacts the GPS accuracy significantly. Unfortunately, within the proposed testing period for Stages One and Two, the weather in Auckland did not meet the requirements of the testing, thus the experiment had to be postponed to a suitable time when the weather met the criteria. The modification of the testing date made the period for experiments longer, which in turn shortened the time available for data analysis. Since the weather conditions eventually met the testing requirements, the testing results on rainy days were quite helpful to the analysis of factors that affected the GPS accuracy.

The second variation was related to the testing speed in Stage Three. A change was made to the running speed for Test Three and Test Four, where jogging was adopted as the test method to replace bicycle riding for those tests. Normally, when people are walking on Queen Street, they would walk on the sides of the street while a bicycle rider would share the street with the other vehicles. This means that the testing path when walking would be different from the testing path if using a bicycle. This means that the results obtained from Test Three and Test Four might not be a good sample to compare with the testing results in the first two tests. The modification of the running speed would definitely correct the testing path and therefore the testing results from Test One and Test Two were comparable.

The last variation was regarding the comparison of the measured data to the real distance. The change made was to compare each measured distance to the real distance rather than to the average value for the distance obtained from multiple measurements as specified in section 3.3. The advantage of this variation was the comparison between the measured data and the real data would be more intuitive, while the modified data could have eliminated some of the potential factors that affect the accuracy such as small speed change during the testing.

5.2 EVIDENCE FOR RESEARCH QUESTION ANSWERS

The main research question and the associated sub-questions were developed from the literature review presented in Chapter 2 and from the study of similar research articles in Section 3.1.

The research questions will be answered by using the information reported in Chapter 4 and table format will be used for evaluation.

The asserted hypotheses are based on the knowledge acquired from the literature review at the outset of the research project. In order to prove or refute the hypotheses, both arguments for and arguments against the hypotheses will be presented, based on the findings of the research testing phases and the technical knowledge acquired during the process of research. To validate the arguments references to specific findings will be used.

5.2.1 Main Research Question and Associated Hypothesis

The main research question was developed to provide a specific goal for the research testing phases and to focus the testing process on a particular area. The afore-mentioned main research question is:

How accurate is a GPS device over the test period?

In order to answer the main research question proposed in Section 3.2, various phases of research experiments were proposed and conducted. The intent of the testing was to collect test data in different canopy configurations, running speeds and weather conditions. Therefore, the tests were conducted under diverse weather conditions and running speeds in each testing stage. Table 5.1 presents the main research question, the associated hypothesis, arguments for and against are provided and a summary of the tested hypothesis is also given.

5.2.2 Sub-questions and Associated Hypothesis

A total of six sub-questions were also developed to assist the answering of the main research question.

Table 5.1, Table 5.2, Table 5.3, Table 5.4, Table 5.5, Table 5.6 and Table 5.7 present the sub-questions, from question one to six respectively. Each table also presents the associated hypothesis, the arguments for and against the hypothesis, a summary of points discussed and the significance of the research findings for each question. A statement of accepting, refuting or considering the hypothesis indeterminate is also included for each question based on a summary of research results and the primary research outcomes for each question.

Table 5.1: Main Research Question and Test Hypothesis

Main Question: *How accurate is a GPS device over the test period?*	
Main Hypothesis: The GPS device is able to acquire precise location information from the GPS and is capable of providing visible evidential trails together with ample information to support the forensic investigation in which the GPS is involved.	
ARGUMENT FOR: The location acquisition of GPS devices	**ARGUMENT AGAINST:** It is not possible to conduct full testing of

and evidence preservation can be accomplished by the GPS. The testing proved that the GPS devices are able to locate the test locations following the guidelines and operation process for navigation of each GPS device. Four stages of testing were done and GPS measurement statistics were gathered for each test within every testing stage (see Section 4.3). Also testing was held in rainy weather, which was included in each testing stage. The tests in such weather proved that the GPS could perform well in location acquisition.	the GPS devices location acquisition and preservation due to the limitation of the testing (Section 3.6); therefore, the testing results cannot represent all GPS devices. Further research and testing are still required. For example, the signals transmitted between satellites and GPS devices can be analysed in order to improve the signal strength in certain areas and weather conditions. In additional, poor signals received from satellites can potentially decrease the GPS devices performance.
SUMMARY: The location acquisition and preservation by GPS devices can be accomplished by the GPS. Furthermore, the GPS could perform well in location acquisition regardless of the weather conditions and the testing time. Although the tested GPS devices are capable to maintain the accurate position, the testing was limited as it did not include all hardware and software of the GPS devices or all weather and surface conditions.	

Table 5.2: Sub-question 1 and Tested Hypothesis

Sub-question 1: *What are the hardware and software requirements for maximizing the accuracy of the GPS?*
Hypothesis 1: The hardware configuration employed will have capability to maximise the accuracy of the GPS, including Central Processor Unit (CPU) with a high processing speed, GPS antenna operating in a high accuracy mode when receiving the GPS signals, and

high refresh rate on the screen. **Hypothesis 2:** The software requirement will effectively position the testing object with minimum deviation. The most recently updated map and a high refresh rate GPS receiver will be needed to get the higher accuracy.	
ARGUMENT FOR: The hardware performance shows that the high refresh rate of the GPS receiver was very important for GPS measurement as it increases the accuracy (see Section 4.3). The GPS antenna installed in the GPS device is also important and could affect the strength of GPS signals received by the device. Therefore, it is necessary to ensure the GPS antenna is not covered by material through which the GPS signal can't pass. The CPU speed is also important for the GPS accuracy, as the CPU handles the signal received from satellites and enables the location service to display on the screen.	**ARGUMENT AGAINST:** The hardware performance test determined that the GPS device screen size is not as important as anticipated. In terms of the software version, it was proven that the map version loaded on the GPS receiver was not as important as proposed in Chapter 3. The latest version of GPS map would reflect changes in the area, but it cannot improve the accuracy.
SUMMARY: Hardware is especially important for the GPS receiver. In particular, high refresh rate on the screen and the CPU speed are crucial. However, the screen size is not essential for the improvement of the GPS accuracy. Regarding the software requirements, the	

map version used in the GPS device has proved not that important to the GPS accuracy as the latest version of the map would only reflect the changes in the area, but it won't improve the accuracy.

Table 5.3: Sub-question 2 and Tested Hypothesis

<table>
<tr><td colspan="2">Sub-question 2: What are the methodologies, tools and techniques used to conduct a test to locate an object's precise location from GPS?</td></tr>
<tr><td colspan="2">Hypothesis 3:
A suitable speed for moving the tested GPS receiver with a high refresh rate to get most precise location information.</td></tr>
<tr><td>ARGUMENT FOR:
The tests in the four testing stages revealed that suitable running speed and a GPS with high refresh rate screen get the most accurate position (see Section 4.3).

According to the test results, the GPS devices would have a higher accuracy when carried at jogging speed on a sunny day.</td><td>ARGUMENT AGAINST:
The GPS accuracy would not be the same in different weather conditions, even the same GPS device was used and in the same running speed. Generally, in order to get higher accuracy, different factors need to be considered and some adjustments need to be made to address the issues.</td></tr>
<tr><td colspan="2">SUMMARY:
In order to improve the GPS accuracy. A GPS device with high refresh rate should be used and the running speed needs to be stable. However, on a rainy day, the GPS accuracy would be affected by the weather and generally the accuracy would decrease compared to the accuracy on a sunny day, even if the remaining conditions are the same (such as the same GPS device and running speed). Future research is required to find out more about why the accuracy is lower on a rainy day.</td></tr>
</table>

Table 5.4: Sub-question 3 and Tested Hypothesis

<table>
<tr><td colspan="2">Sub-question 3: What is the deviation of the GPS accuracy when testing it in different land situations and weather?</td></tr>
<tr><td colspan="2">Hypothesis 4:
The GPS accuracy would be tested under different weather conditions, to find out they affect the accuracy. The GPS accuracy would be higher if the testing object is located in a wide open area and if the GPS receiver is tested in a sunny weather.</td></tr>
<tr><td>ARGUMENT FOR:
The tests in the four testing stages were held in different weather conditions and different land conditions, which included sunny, rainy/cloudy weather, Tree canopies area in One Tree Hill Park, Urban arterials in Highbrook Industrial Park, Queen street which got varied canopy, and 0% canopy opened indoor area.

The GPS device received better signal when the tests were performed in the higher percentage of canopy opened area and subsequently the accuracy was higher. The more canopies covered the test environment, the weaker the received GPS signal would become, and the accuracy was lower.

The better the weather conditions, the higher accuracy level would be received from the GPS device. In sunny</td><td>ARGUMENT AGAINST:
The tests held in 100% canopy open area and on a sunny day showed that the GPS devices achieved different accuracy.

The GPS device itself could be a vital factor that affects the accuracy; if the antenna could receive a good signal, or the refresh rate of the GPS screen refreshes the location service fast enough to reflect the updated location the accuracy is higher. Even under the same weather and land conditions, different GPS devices achieve different accuracy depending on their antennae and refresh rate.</td></tr>
</table>

weather, especially if there was no cloud in the sky, the GPS device could receive a clear signal from the satellite, and the accuracy would be increased. On the contrary, in rainy/cloudy weather, the GPS signal reception would worsen, and the GPS accuracy decreases.	
SUMMARY: The GPS devices would receive stronger signals in areas with higher percentage of open canopy and in sunny weather. The GPS devices would work better the stronger signal and no doubt would have higher accuracy. However, even in the same weather and land conditions, different GPS devices would have different accuracy, as the GPS device itself could be a vital factor that affects the accuracy.	

Table 5.5: Sub-question 4 and Tested Hypothesis

Sub-question 4: *What is the effect on the GPS accuracy when the testing object is moving at a different speed?*	
Hypothesis 5: The GPS accuracy would be tested for different speed of the moving objects, to find out how peed affects the accuracy. The GPS receivers would get higher accuracy when moving at a faster speed.	
ARGUMENT FOR: The tests in the four testing stages used different speeds to test the GPS accuracy, which include walking and jogging on Queen Street, and also indoors; walking, jogging and riding a bike on One Tree Hill Park and Highbrook Industrial Park.	**ARGUMENT AGAINST:** The faster running speed could not guarantee higher accuracy of the GPS measurement. A number of tests conducted on One Tree Hill Park and Highbrook Industrial Park with three different running speeds (walking, jogging and riding a bike). In some of the tests, the GPS gained better

According to the test results from the four stages, the tests on Queen Street that used both walking and jogging as the testing methods, and the indoor tests that used walking method, showed that the accuracy was reasonably high.	accuracy when I was walking compared to when I was riding a bike. Other factors should be also considered such as the hardware specification of GPS devices, the GPS signals received by the device and so on.
SUMMARY: According to the test results, lower running speed would decrease the GPS accuracy. On the other hand, the experiments performed on Highbrook Industrial Park when the running speed was riding a bike show the highest GPS accuracy. The running speed is not the only factor that affects the GPS accuracy; some other factors might influence the accuracy, such as the GPS device hardware specification and the GPS signals received by the device.	

Table 5.6: Sub-question 5 and Tested Hypothesis

Sub-question 5: *What actions can be taken to improve the GPS accuracy of the tested object?*	
Hypothesis 6: The proposed system will be capable to improve the accuracy due to the method of improving the testing environment and the external factors (such as location, running speeds and so on).	
ARGUMENT FOR: The test results show that if the GPS devices could receive stronger signals from the satellite, as in tests held in the more canopy open area or in sunny weather, the GPS accuracy would be higher.	**ARGUMENT AGAINST:** Several tests were conducted in area with strong signal such as wide open area and in sunny weather, but the test results were not showing high accuracy. The GPS hardware impacts the accuracy significantly, especially when the tested object is moving.

If the running object (such as a bike or a human is holding the GPS) is moving, the running speed and GPS hardware are quite important as these two factors would make the GPS device to reflect the updating location on the map. According to the test results, in order to gain higher accuracy from the GPS device, it is important to have strong signal, GPS screen with high refresh rate and a proper speed.	
SUMMARY: In order to get higher accuracy for the GPS measurement, strong signal is quite important, as the device could communicate with the satellite clearly and obtain more accurate location information. The GPS hardware is also a vital factor, especially for a fast moving test object; if the object is moving fast and the refresh rate is slow, the displayed location is far behind the actual location, and the accuracy is low.	

Table 5.7: Sub-question 6 and Tested Hypothesis

Sub-question 6: *What are the capabilities of the system design to acquire the position information for prosecution purposes?*	
Hypothesis 7: The proposed system will be capable of providing the positioning information in a forensic manner if the accuracy is high and accepted by the court.	
ARGUMENT FOR: The location information can be stored in the GPS device. The Garmin GPSmap62 device has MicroSD slot and substantial internal memory that could store the location data. These GPS data can be exported via the USB	**ARGUMENT AGAINST:** The GPS data stored in the devices don't have MD5 hash functionality. Hence the data extracted directly from the GPS device might not be accepted by the court.

cable to the investigator's computer.	
SUMMARY: Some GPS devices such as Garmin GPS62 has the capability to provide the positioning information if the accuracy is high enough. However, these GPS devices do not use MD5 hash on the GPS location data. Thus some evidence preservation processes need to be carried out by the investigator for using the location data as evidence in court.	

5.3 DISCUSSION OF FINDINGS

The data collected in this research are reported and analysed and the findings are presented in Chapter 4. This section first compares the hardware and software of the tested GPS devices and then discusses and comments on each of the research testing stages and the significance of the obtained results. Each phase of testing will be discussed in relation to the main findings and in terms of answering the proposed research questions. Examination of the GPS accuracy will be carried out for each GPS device. To conclude the discussion, the potential issues of GPS device testing will be outlined and some suggestions will be presented.

5.3.1 Comparison of the tested GPS Devices

The following section will look at the tested GPS devices and compare their hardware and software specifications, as these factors will be discussed in the tested hypothesis of Sub-Question 1. The hardware and software specifications will be presented in two sub-sections and all tested GPS devices will be compared in each sub-section.

5.3.1.1 Comparison of the hardware of GPS devices

The hardware comparison will focus on a discussion of the hardware design and the output of the tested GPS devices. The gained knowledge from this section is used for considering the impact of the hardware specification on the GPS accuracy. Table 5.8 shows the comparison of the hardware of three GPS devices.

Table 5.8: Comparison of the hardware of three GPS devices

	Garmin GPSmap 62	**Navman EZY45**	**GPS device on iPhone5**
Product Description	It is the base model of the GPSmap 62 series	It is the mid-range of Navman EZY series product line up	-
Unit Dimensions (WxHxD)	6.1x16.0x3.6 cm	12.7x8.2x1.5 cm	5.9x12.4x0.76 cm
Display			
Display Size (WxH)	160x240 pixels	272x480 pixels (4.3 inches)	640x1136 pixels,4.0 inches (~326 ppi pixel density)
Touchscreen	No	Yes (4.3" LCD touchscreen)	Yes (capacitive touchscreen)
Display Type	65k Colours Display	-	LED-backlit IPS LCD, 16 M colours
Other Features			
PC interface	USB and NMEA 0183 compatible	USB	USB
Brand	Garmin GPSmap 62	Navman EZY45	Apple
Installed Memory	1.7 GB	2GB	16 GB
Expansion Slot Type	-	Micro-SD slot and SD (Secure Digital) Card Slot	No
Antenna	Built-in	-	Built-in

5.3.1.2 GPS device software comparison

The software comparison will focus on the GPS map and the software installed on the GPS devices. The information from this section is used for considering the software impact on the GPS accuracy. Table 5.9 shows the comparison of the software of the GPS devices.

Table 5.9: Comparison of the software of three GPS devices

	Garmin GPSmap 62	**Navman EZY45**	**GPS device on iPhone5**
Map Version	uses the map City Navigator downloaded from the Garmin official website, the part number is 010-D1257-00	uses latest map 2013 NZ Summer map which can be downloaded from the Navman official website	uses the Google Map which is downloaded from Apple AppStore, the latest update is already applied on this application
Basemap	Yes	Yes	Yes
Automatic routing (turn by turn routing on roads)	Yes(with optional mapping for detailed roads)	Yes	Yes
Photo navigation	Yes	Yes	Yes

5.3.2 Discussion of Testing Stages

Research testing was divided into four testing stages. Each stage used a specific testing location and the same weather conditions. This section discusses the research testing phases with the aim to identify and highlight the major findings. Reference will be made to specific findings from the testing and to the research questions which were addressed by each particular test.

5.3.2.1 Discussion of Test Stage One

Stage One was tested in a tree canopies area and two types of weather conditions were selected for this testing stage – sunny and rainy; also each weather type was tested in both morning and afternoon sessions. The main purpose of Stage One testing was to simulate different environments and determine the GPS accuracy under a tree canopy area.

5.3.2.1.1 Analysis of test results

There are four tests in Test Stage One and the results for each test are presented in Table 4.6, Table 4.8, Table 4.10 and Table 4.12 respectively. In order to analyse the results more effectively and compare the GPS accuracy in different weather and speed conditions, the results from all tests in this stage are presented in Table 5.10 along with relevant statistics. Please note that deviation represents the difference between the real distance and the distance measured by the tested GPS device.

Table 5.10: Deviation values recorded by each of the GPS devices in Test Stage 1, and the different statistics used to analyse the accuracy

Test	Weather Condition	Device	Speed	Round 1 (m)	Round 2 (m)	Round 3 (m)	Mean (m)	Standard Deviation	Std. Error of Mean
1	Sunny	Garmin GPSmap62	Walking	0.4	0.5	0.7	0.53	0.15%	0.88%
			Jogging	0.3	0.5	0.4	0.40	0.10%	0.06%
			Bike	0.2	0.3	0.3	0.27	0.06%	0.03%
		GPS device on iPhone5	Walking	0.5	0.4	0.4	0.43	0.06%	0.03%
			Jogging	0.3	0.4	0.2	0.30	0.10%	0.06%
			Bike	0.3	0.3	0.1	0.23	0.12%	0.07%
2	Sunny	Garmin GPSmap62	Walking	0.6	0.4	0.4	0.47	0.12%	0.07%
			Jogging	0.2	0.7	0.3	0.40	0.26%	0.15%
			Bike	0.2	0.3	0.2	0.23	0.06%	0.03%
		GPS device on iPhone5	Walking	0.3	0.5	0.3	0.37	0.12%	0.07%
			Jogging	0.1	0.3	0.3	0.23	0.12%	0.07%
			Bike	0.1	0.1	0.2	0.13	0.06%	0.03%
3	Rainy	Garmin GPSmap62	Walking	0.9	1.1	0.7	0.90	0.20%	0.12%
			Jogging	0.8	1.2	0.5	0.83	0.35%	0.20%
			Bike	0.8	0.4	0.5	0.57	0.21%	0.12%
		GPS device on iPhone5	Walking	1.4	0.7	0.8	0.97	0.38%	0.22%
			Jogging	0.8	0.9	0.7	0.80	0.10%	0.06%
			Bike	0.9	0.4	0.4	0.57	0.29%	0.17%
4	Rainy	Garmin GPSmap62	Walking	1.3	0.6	0.6	0.83	0.40%	0.23%
			Jogging	0.6	0.7	0.7	0.67	0.58%	0.03%
			Bike	0.4	0.5	0.5	0.47	0.06%	0.03%
		GPS device on iPhone5	Walking	0.8	0.8	0.7	0.77	0.06%	0.03%
			Jogging	0.9	0.5	0.4	0.60	0.26%	0.15%
			Bike	0.6	0.4	0.4	0.47	0.12%	0.07%
Mean							**0.52**	**28.15%**	**3.32%**

Table 5.10 shows the results of the GPS accuracy of three different running speeds for selected GPS devices. The GPS accuracy rate is measured by the deviation value. The table also contains some relevant statistics.

Test one of Stage One was implemented on a sunny morning. There were great differences in the deviation values when I used Garmin GPSmap62 during this testing. For example, the highest deviation value occurred when the adopted test method was walking with the mean value of 0.53 meter. This figure was overwhelmingly greater than the corresponding figure of 0.27 meter when the adopted test method was riding a bike. A similar pattern is also noted in the test results when I used iPhone Google Map app: the mean of deviation values increased when the running speed had been changed from riding a bike to walking. However, the difference was not significant (0.23 meter and 0.43 meter respectively). The performance of iPhone Google Map app was slightly better than Garmin GPSmap62 in all environments in this test. The mean SEM (Standard error of measurement) of 4% increased to 5% when I was using Garmin GPSmap62.

Test two was conducted in the afternoon on the same day as Test one. As might be expected, the results obtained from test one were slightly different from those obtained from test 1 but showed a similar trend across all tests. This test was conducted in two parts: the first part was using Garmin GPSmap62 as the selected GPS device and the second part was using iPhone Google Map. The results from Part one and Part two show that the GPS accuracy improved with increased running speed. In part one of this test, the mean deviation value was 0.47 meter when I was walking, which decreased by half when I was riding a bike, while the mean deviation value was 0.37 meter when I was walking and 0.13 meter when I was riding a bike in Part two of this test.

Next, test three in this stage was implemented on a rainy morning. Most of the deviation values in this test are greater than the corresponding values in test one and test two, but the trend is roughly the same. Regarding the running speed, the mean deviation values of the tests performed at walking speed were the highest with an average value of 0.94 meter across both GPS devices, closely followed by the mean deviation value of 0.82 meter for the test at Jogging speed. Surprisingly, the mean deviation value fell sharply to just 0.57 meters when I was riding a bike which means that the GPS had the highest accuracy when I was riding a bike in this test. Yet in terms of the test results of both selected GPS devices, on average, the deviation values of the Garmin GPSmap62 were relatively stable throughout this practice compared to iPhone Google Map. The mean deviation value increases gradually by around 70% when the running speed changed from riding a bike to walking when testing iPhone Google Map. Finally, test four was conducted with the same test path as test 3, but on a rainy afternoon. It is immediately obvious that there are many similarities between test three and test four. To be specific, the collected data appears to prove the following two points:

- The GPS has the highest accuracy when the running speed was riding a bike.
- The GPS accuracy of iPhone Google Map was better than that of Garmin GPSmap62.

5.3.2.1.2 Individual Analysis of each factor

Section 2.5.1 pointed out that the GPS accuracy would be affected by a few factors, namely the natural barriers to the signal, atmospheric conditions, satellite positions and noise in the radio signal. Therefore, the research testing design has already assumed that there are some associations between the GPS accuracy and four major factors. These factors include GPS device, running Speeds, weather conditions and testing time. This section discusses the impact of each of these factors on GPS accuracy.

- **GPS Device**

The GPS accuracy may be influenced by a number of factors and this analysis will focus on the impact of GPS devices. The GPS devices selected for test stage one are Garmin GPSmap62 and iPhone5. Table 5.11 contains the T-test results and the P value for the causal paths between the GPS accuracy and GPS devices at the significance level of 0.05. It is clear from the data that the relationship between accuracy and GPS devices is not significant with P value of 0.606 which is greater than 0.05. This is an interesting result obtained from this study since the GPS device has been always a strong factor in relation to GPS accuracy. It suggests the GPS device is not the only factor that affects the GPS accuracy and a further analysis will be applied at this section later.

Table 5.11: Statistics for the GPS devices in Test Stage 1

Group Statistics

	GPS DEVICES	N	Mean	Std. Deviation	Std. Error Mean
Deviation	Garmin GPSmap62	36	.5472	.27306	.04551
	iPhone Google Map	36	.4889	.29059	.04843

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Deviation	Equal variances assumed	.268	.606	.878	70	.383	.0583	.06646	-.07422	.19088
	Equal variances not assumed			.878	69.731	.383	.0583	.06646	-.07423	.19089

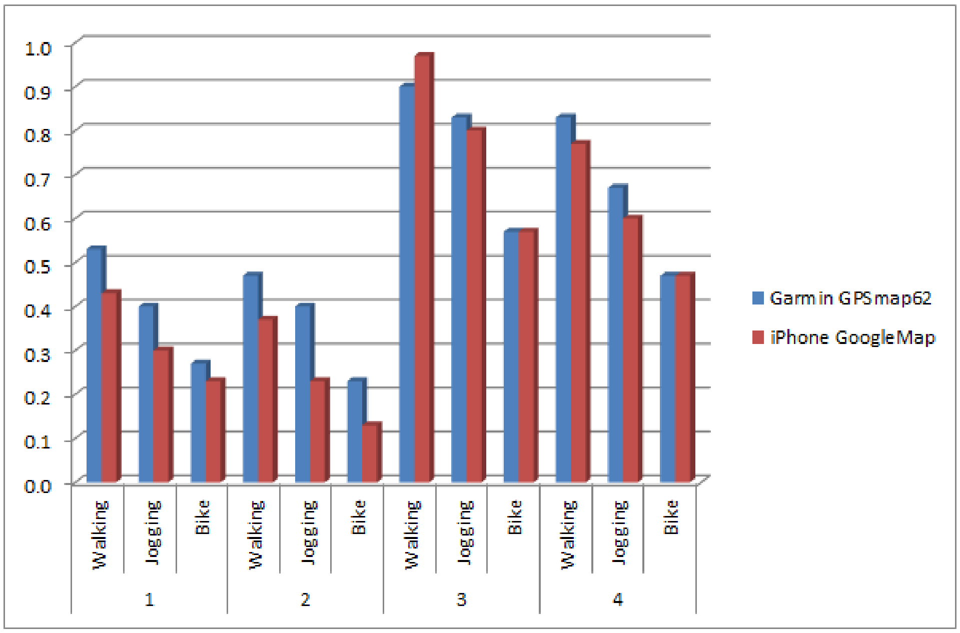

Figure 5.1: Mean deviation values for both GPS devices in Test Stage 1

The GPS accuracy rates for both GPS devices tested in Stage One are depicted in Figure 5.1. The graphs show that iPhone Google Map had higher accuracy than Garmin GPSmap62. Statistics presented in Table 5.11 show that the mean deviation value for iPhone Google Map is 0.4889 meter while Garmin GPSmap62 has a higher value of 0.5472 meter.

- **Running Speed**

It appears that the selected GPS devices are not the only factor that affects the GPS accuracy. For the analysis of the relationship between running speeds and GPS accuracy, the significance level was specified to be 0.05. T-test results and P-value at this significance level are presented in Table 5.12. It shows the significant relationship between running speed and GPS accuracy as the P value is 0.001 which is less than 0.05. According to the data shown in Table 5.10, the deviation value varies considerably across the different running speeds. Table 5.13 shows the relevant statistics for the difference between the three running speeds that include Walking, Jogging and riding a bicycle. It is obvious that the tests performed by bike have the lowest mean deviation value (0.37 meter). In contrast, the tests performed at walking speed have the highest mean deviation value (0.66 meter). Meanwhile, the tests conducted at Jogging speed generally maintain middle position, with mean deviation value approximately 0.53 meter. This suggests that the GPS has the highest accuracy when I was riding a bike. Moreover, the relationship between walking and riding a bike is significant at the significance level of 0.05 as the P value is 0.01 which is less than 0.05. (Table 5.13).

Table 5.12: Statistics for running speed in Test Stage 1 (t-test Result)

Dependent Variable: Deviation

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1.025[a]	2	.513	7.687	.001
Intercept	19.323	1	19.323	289.773	.000
SPEED	1.025	2	.513	7.687	.001
Error	4.601	69	.067		
Total	24.950	72			
Corrected Total	5.627	71			

a. R Squared = .182 (Adjusted R Squared = .159)

Table 5.13: Comparison of three running speeds in Test Stage 1

(I) Running Speed	(J) Running Speed	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
Walking	Jogging	.1292	.07455	.230	-.0573	.3157
	Bicycle	.2917*	.07455	.001	.1052	.4782
Jogging	Walking	-.1292	.07455	.230	-.3157	.0573
	Bicycle	.1625	.07455	.100	-.0240	.3490
Bicycle	Walking	-.2917*	.07455	.001	-.4782	-.1052
	Jogging	-.1625	.07455	.100	-.3490	.0240

Based on observed means.

*. The mean difference is significant at the .05 level.

Scheffe[a,b]

Running Speed	N	Subset	
		1	2
Bicycle	24	.3667	
Jogging	24	.5292	.5292
Walking	24		.6583
Sig.		.100	.230

Means for groups in homogeneous subsets are displayed.
Based on Type III Sum of Squares
The error term is Mean Square(Error) = .067.

a. Uses Harmonic Mean Sample Size = 24.000.

b. Alpha = .05.

- **Weather conditions**

The dependent variable 'GPS accuracy' can be tested against with the independent variable 'weather conditions' (such as Sunny and Rainy). The outputs from the t-test (First table within Table 5.14) show clearly the noticeable relationships between these two variables as the P value is 0.014 which is less than 0.05. Regarding the weather conditions, the data in Table 5.14 not only indicates that the GPS accuracy could be affected by the weather, but also shows that the testing performed on a sunny day has better accuracy, as the mean deviation value is only 0.33 meter. Conversely, the GPS accuracy decreased on the rainy day, as the mean deviation value increased to 0.7 meter.

As can be seen in Figure 5.2, the bar chart appears to confirm that the running speed would impact the GPS accuracy under the same weather conditions. When the running speed was Jogging and Walking, the mean deviation values for rainy days far exceeded that of the mean deviation values for rainy days. Especially when the running speed was walking on a rainy day, the mean deviation value is 0.87 meter compared to only 0.45 meter mean deviation value for the sunny day when the running speed was walking. However, when the running speed was riding a bike, the mean deviation value for the rainy day decreased slightly, compared to other running speeds. Moreover, another particularly interesting fact highlighted by the deviation values for each running speed group is that the testing with higher running speed had the higher GPS accuracy. This implies that the GPS accuracy increases when the running speed increases on a rainy day.

Table 5.14: Statistics for the weather conditions in Test Stage 1

Group Statistics

	Weather Condition	N	Mean	Std. Deviation	Std. Error Mean
Deviation	Sunny	36	.3333	.15306	.02551
	Rainy	36	.7028	.25910	.04318

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Deviation	Equal variances assumed	6.317	.014	-7.366	70	.000	-.3694	.05016	-.46948	-.26941
	Equal variances not assumed			-7.366	56.776	.000	-.3694	.05016	-.46989	-.26900

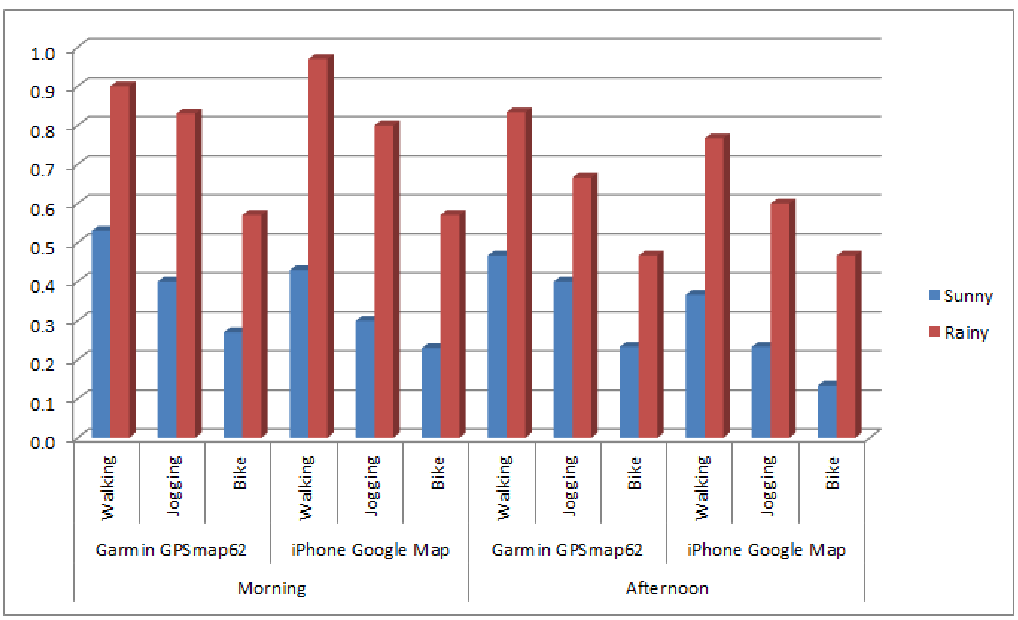

Figure 5.2: Mean deviation values for both weather conditions in Test Stage 1

- **Testing Time during the same day**

Regarding testing time during the same day (morning and afternoon), Table 5.15 shows that the relationship between testing on morning and afternoon on the same day and GPS accuracy is not significant because the P value (0.215) is greater than 0.05. Also noteworthy is the fact that the tested performed in the afternoon has the better accuracy, with mean deviation value 0.47 meter.

Table 5.15: Relevant Statistic for each testing time in Test Stage 1

Group Statistics

	Testing Time	N	Mean	Std. Deviation	Std. Error Mean
Deviation	Morning	36	.5667	.30048	.05008
	Afternoon	36	.4694	.25615	.04269

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Deviation	Equal variances assumed	1.565	.215	1.477	70	.144	.0972	.06581	-.03402	.22847
	Equal variances not assumed			1.477	68.289	.144	.0972	.06581	-.03408	.22853

To be specific, Figure 5.3 shows that the tests performed on sunny afternoons had the highest accuracy, with mean deviation value only 0.24 meter. This is followed by the results from testing performed on sunny mornings with mean deviation value 0.27 meter. Respectively, mean deviation values for both rainy morning and rainy afternoon were similar (0.56 meter and 0.55 meter respectively). The results also imply that the relationship between testing time (morning or afternoon on the same day) and GPS accuracy is not significant.

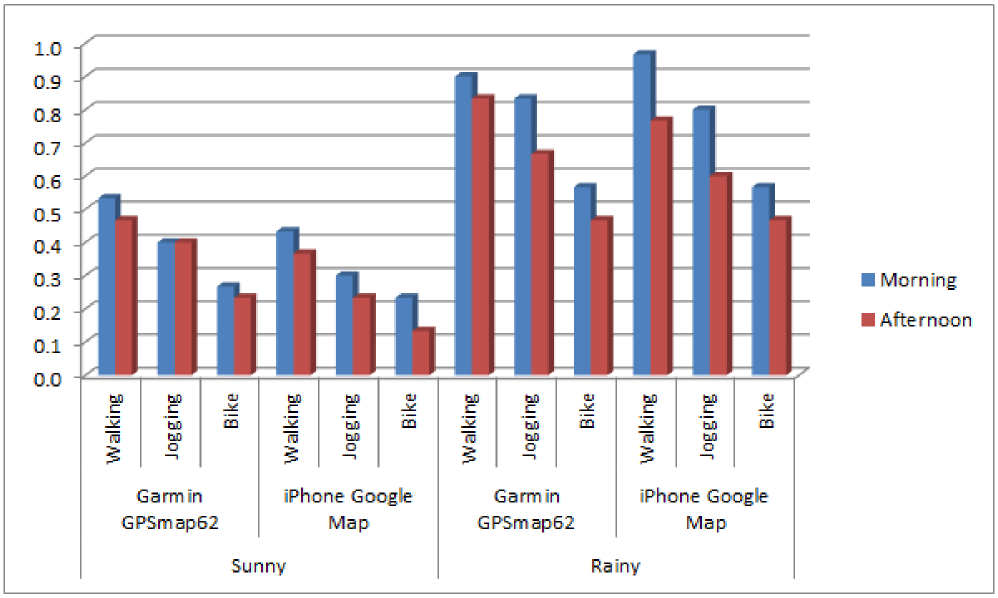

Figure 5.3: Mean deviation values for different testing time in Test Stage 1

- **Tests conducted on different days (Repeated Tests)**

In this research, I have assumed that the GPS accuracy could be impacted by the testing time on different days as well. With the aim to find out the relationship between these two variables, all the above four tests included in stage one were repeated on a different day. (For more details about these tests, please refer to Section 4.3.1.5) .Table 5.16 presents the deviation values for the results obtained from these tests for different running speed and weather conditions respectively.

The results from the analysis are consistent with the testing output from the original four tests. The data provided in Table 5.16 illustrates that the GPS accuracy was affected by the weather and there were higher accuracy rates on the sunny day compared with those on the rainy day. Interestingly, during the original tests (refer to Table 5.10), the mean deviation value for the tests on the rainy morning (0.77 meter) was slightly higher than that for the tests on the rainy afternoon (0.63 meter). On the other hand, the results from the repeated test are just the opposite. The mean deviation value for those tests on a rainy morning was 0.66 meter, which was lower than the mean deviation value for the tests on a rainy afternoon (0.71 meter). The data suggest that the testing time (morning or afternoon) will have greater influence on the GPS accuracy on a rainy day.

A further analysis of the relationship between the testing time and GPS accuracy was not possible since I had a limited time and budget for this research. This research does not provide enough test samples for further investigation of this relationship. A greater number of tests could provide additional data for further research.

Table 5.16: Deviation values for distances recorded by each of the GPS devices in the repeated tests in Test Stage 1, and the different statistics used to analyse the accuracy

Test	Weather	Device	Speed	Round 1 (m)	Round 2 (m)	Round 3 (m)	Mean (m)	Standard Deviation	Std. Error of Mean
1	Sunny	Garmin GPSmap62	Walking	0.6	0.7	0.4	0.57	0.15%	0.09%
			Jogging	0.5	0.3	0.5	0.43	0.12%	0.07%
			Bike	0.3	0.5	0.3	0.37	0.12%	0.07%
		GPS device on iPhone5	Walking	0.7	0.5	0.3	0.50	0.20%	0.12%
			Jogging	0.3	0.4	0.3	0.33	0.06%	0.03%
			Bike	0.1	0.2	0.2	0.17	0.06%	0.03%
2	Sunny	Garmin GPSmap62	Walking	0.6	0.4	0.4	0.47	0.12%	0.07%
			Jogging	0.5	0.3	0.2	0.33	0.15%	0.09%
			Bike	0.3	0.1	0.2	0.20	0.10%	0.06%
		GPS device on iPhone5	Walking	0.3	0.4	0.5	0.40	0.10%	0.06%
			Jogging	0.3	0.3	0.1	0.23	0.12%	0.07%
			Bike	0.2	0.1	0.2	0.17	0.06%	0.03%
3	Rainy	Garmin GPSmap62	Walking	1.1	0.6	0.8	0.83	0.25%	0.15%
			Jogging	0.5	1	0.7	0.73	0.25%	0.15%
			Bike	0.6	0.5	0.7	0.60	0.10%	0.06%
		GPS device on iPhone5	Walking	0.9	0.9	0.5	0.73	0.21%	0.12%
			Jogging	0.6	0.4	0.7	0.57	0.15%	0.09%
			Bike	0.3	0.7	0.5	0.50	0.20%	0.12%
4	Rainy	Garmin GPSmap62	Walking	0.6	1.3	0.8	0.90	0.36%	0.21%
			Jogging	1.1	0.7	0.5	0.77	0.31%	0.18%
			Bike	0.5	1.1	0.3	0.63	0.42%	0.24%
		GPS device on iPhone5	Walking	0.8	1.1	0.5	0.80	0.30%	0.17%
			Jogging	0.7	0.4	0.7	0.60	0.17%	0.10%
			Bike	0.5	0.4	0.7	0.53	0.15%	0.09%
Mean							**0.52**	**0.27%**	**0.10%**

Table 5.17 and Table 5.18 show that the results of repeated tests are not significantly different from the original tests as the P value 0.963 is greater than 0.05. Although the results of repeated tests were slightly different from those from the original tests, they showed a similar trend across all tests.

Table 5.17: Comparison of relevant statistics for original tests and repeated tests in Test stage 1

Test	Mean (m)	Std. Deviation	S.E. Mean	Correlation	Sig.
First Test	0.518	0.28%	0.33%	0.567	0.00
Repeated Test	0.517	0.27%	0.03%		

Table 5.18: Results of Paired simple t-test between original tests and repeated tests in Test Stage 1

		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
					Lower	Upper			
Pair 1	Deviation - Repeated Test _ Deviation	.0014	.25646	.03022	-.0589	.0617	.046	71	.963

Note: Original tests are Test 1, Test 2, Test 3 and Test 4 in Test Stage 1, please refers to Section 4.3.1 for more details.

5.3.2.2 Discussion of Test Stage Two

Stage Two of testing was conducted in the Highbrook Industrial Park in two types of weather conditions (sunny and rainy); each weather type was tested in both morning and afternoon. This section presents the test results and their analysis, in order to better understand the relationship between GPS devices accuracy and factors that might impact the accuracy.

5.3.2.2.1 Analysis of test results

Table 5.19 presents results for the accuracy of GPS measurement for three different running speeds with the tested GPS devices, for all tests in Stage Two. Overall, the GPS accuracy rates in this test stage across all tests followed a fairly constant pattern.

Table 5.19: Deviation values for distance recorded by each of the GPS devices in Test Stage 2, and the different statistics used to analyse the accuracy

Test	Weather Condition	Device	Speed	Round 1 (m)	Round 2 (m)	Round 3 (m)	Mean (m)	Standard Deviation	Std.Error of Mean
1	Sunny	Garmin GPSmap62	Walking	0.3	0.5	0.5	0.43	0.12%	0.07%
			Jogging	0.3	0.5	0.2	0.33	0.15%	0.09%
			Bike	0.1	0.4	0.2	0.23	0.15%	0.09%
		GPS device on iPhone5	Walking	0.2	0.1	0.2	0.17	0.06%	0.03%
			Jogging	0.1	0.1	0.1	0.10	0.00%	0.00%
			Bike	0	0	0.1	0.33	0.06%	0.03%
2	Sunny	Garmin GPSmap62	Walking	0.5	0.6	0.3	0.47	0.15%	0.09%
			Jogging	0.4	0.5	0.3	0.40	0.10%	0.06%
			Bike	0.2	0.4	0.2	0.27	0.12%	0.07%
		GPS device on iPhone5	Walking	0.1	0.1	0.2	0.13	0.06%	0.03%
			Jogging	0.1	0.1	0.1	0.10	0.00%	0.00%
			Bike	0.1	0	0.1	0.07	0.06%	0.03%
3	Rainy	Garmin GPSmap62	Walking	1	0.8	0.9	0.90	0.10%	0.06%
			Jogging	0.8	0.9	0.8	0.83	0.06%	0.03%
			Bike	0.5	0.7	0.5	0.57	0.12%	0.07%
		GPS device on iPhone5	Walking	0.4	0.5	0.5	0.47	0.06%	0.03%
			Jogging	0.2	0.3	0.5	0.33	0.15%	0.09%
			Bike	0.2	0.2	0.3	0.23	0.06%	0.03%
4	Rainy	Garmin GPSmap62	Walking	0.8	0.9	1.1	0.93	0.15%	0.09%
			Jogging	0.6	0.9	0.8	0.77	0.15%	0.09%
			Bike	0.4	0.7	0.5	0.53	0.15%	0.09%
		GPS device on iPhone5	Walking	0.4	0.5	0.5	0.47	0.06%	0.03%
			Jogging	0.4	0.5	0.2	0.37	0.15%	0.88%
			Bike	0.3	0.3	0.2	0.27	0.06%	0.03%
Mean							**0.39**	**0.27%**	**0.03%**

The most obvious trend in the statistics shown in table 5.19 is that there is a gradual decrease in the deviation value when the running speed increases. For example, in test one, the tests performed at speed of riding a bike have the lowest deviation values in most of the tests, whereas the tests performed at walking speed have the highest deviation values. To be specific, when I used iPhone Google Map, the mean deviation value at walking speed was 0.31 meter, but it was only 0.22 meter when riding a bike. The difference was even greater when I used Garmin GPSmap62 as the mean deviation value at walking speed (0.68 meter) was approximately twice greater than the mean deviation value when riding a bike (0.35 meter). A similar pattern can be also observed in the results from other tests. It is clear from the data that testing at higher running speed produced better GPS accuracy rate.

The second notable trend in the statistics shown in Table 5.19 is that there are clear differences between the accuracy rates of different GPS devices, with the iPhone Google Map having the highest GPS accuracy. In most of the tests, the deviation values for iPhone Google Map are considerably lower than those for Garmin GPSmap62; only in the case of test one with running speed was riding a bike, is the mean deviation value for Garmin GPSmap62 (0.23 meter) lower than that for iPhone Google Map (0.33 meter).

However, there are some differences between these four tests which are discussed further down in this section.

5.3.2.2.2 Individual Analysis of each factor

This subsection discusses the effect of each of the factors that are found to impact GPS accuracy and their relationships with each other:

- **GPS Devices**

Table 5.20 displays the T-test results and the P value between GPS device and accuracy at significance level of 0.05. Surprisingly, the provided data demonstrates that the relationship of accuracy and GPS device was significant, as the P value is equal to 0.002 which is less than 0.05. In comparison, there was contrasting result from test Stage One as Table 5.11 shows the relationship between accuracy and GPS devices was not significant. However, there are also some similarities between the results obtained from Stage One and Stage Two. For example, the results from both test stages indicate the accuracy of iPhone Map was greater than that of Garmin GPSmap62.

Another point worth mentioning is that in test Stage Two the iPhone Google Map accuracy was significantly higher than that of Garmin GPSmap62, as the mean deviation value for iPhone Google Map was 0.23 meter while that of Garmin GPSmap62 was much greater at 0.56 meter. On the other hand, in test Stage One, the mean deviation values for the two devices are similar, even though iPhone Google Map has lower mean deviation value.

Table 5.20: Statistics for the GPS device in Test Stage 2

Group Statistics

	GPS DEVICES	N	Mean	Std. Deviation	Std. Error Mean
Deviation	Garmin GPSmap62	36	.5556	.26235	.04372
	iPhone Google Map	36	.2278	.16144	.02691

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Deviation	Equal variances assumed	9.954	.002	6.384	70	.000	.3278	.05134	.22538	.43017
	Equal variances not assumed			6.384	58.184	.000	.3278	.05134	.22502	.43054

In Figure 5.4, the mean deviation values for iPhone Google Map across all running speeds in all cases are relatively stable. It produced better accuracy in most of the test cases except the test conducted on a sunny morning when I was riding a bike; the mean deviation value of 0.33 meter for iPhone Google Map dropped to 0.23 meter when I was using Garmin GPSmap62.

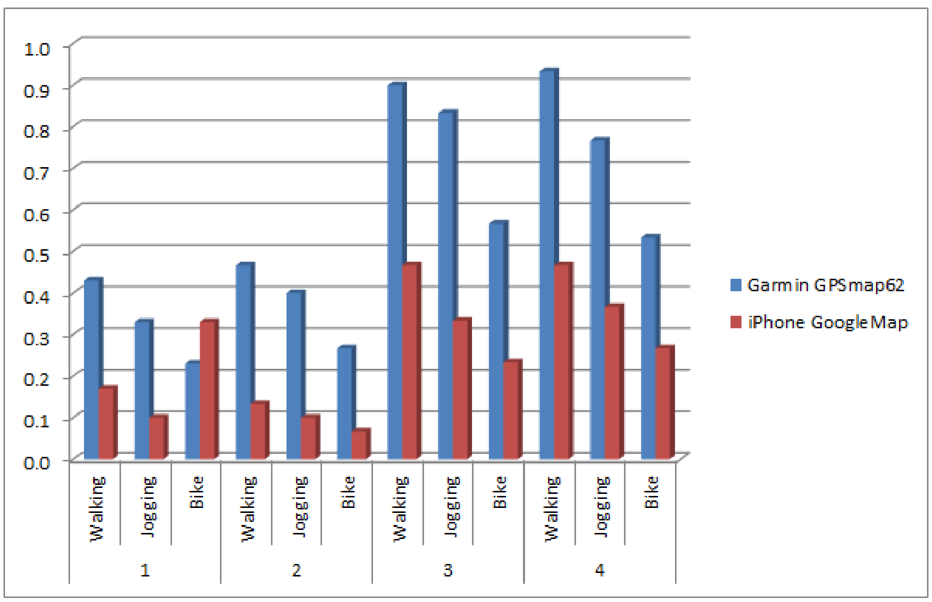

Figure 5.4: Mean deviation values for both GPS devices in Test Stage 2

- **Running speed**

In order to investigate the relationship between running speeds and accuracy, I took the mean of all tests and run a t-test with a significance level of 0.05. Table 5.21 shows the result which indicates a significant relationship between running speed and accuracy since the P value is 0.016 which is less than 0.05.

Table 5.21: Statistics for Running Speeds in Test Stage 2 (t-test Results)

Dependent Variable: Deviation

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	.591[a]	2	.295	4.370	.016
Intercept	11.045	1	11.045	163.396	.000
SPEED	.591	2	.295	4.370	.016
Error	4.664	69	.068		
Total	16.300	72			
Corrected Total	5.255	71			

a. R Squared = .112 (Adjusted R Squared = .087)

Table 5.22: Comparison of three Running Speeds in Test Stage 2

(I) Running Speed	(J) Running Speed	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
Walking	Jogging	.0917	.07505	.478	-.0961	.2794
	Bicycle	.2208*	.07505	.017	.0331	.4086
Jogging	Walking	-.0917	.07505	.478	-.2794	.0961
	Bicycle	.1292	.07505	.235	-.0586	.3169
Bicycle	Walking	-.2208*	.07505	.017	-.4086	-.0331
	Jogging	-.1292	.07505	.235	-.3169	.0586

Based on observed means.

*. The mean difference is significant at the .05 level.

Running Speed	N	Subset 1	Subset 2
Bicycle	24	.2750	
Jogging	24	.4042	.4042
Walking	24		.4958
Sig.		.235	.478

Means for groups in homogeneous subsets are displayed.
Based on Type III Sum of Squares
The error term is Mean Square(Error) = .068.

a. Uses Harmonic Mean Sample Size = 24.000.

b. Alpha = .05.

Moreover, the relationship between each running speed and accuracy was also investigated by running a frequency histogram. Table 5.22 demonstrates the comparison results for different running speeds (walking, jogging and riding a bike) and their relationship with accuracy. As can be seen in the table, accuracy improved with increased running speed: the mean deviation value of 0.28 meter when the tests were conducted by riding a bike increased by 80% when the running speed was walking.

- **Weather Conditions**

For the testing conducted in the Highbrook Industrial Park, it is apparent from the data provided in Table 5.23 that the relationship between weather conditions and GPS accuracy is significant with P value of 0.005 which is less than 0.05.

Table 5.23: Statistics for the Weather Conditions in Test Stage 2

Group Statistics

	Weather Condition	N	Mean	Std. Deviation	Std. Error Mean
Deviation	Sunny	36	.2278	.16837	.02806
	Rainy	36	.5556	.25795	.04299

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Deviation	Equal variances assumed	8.310	.005	-6.384	70	.000	-.3278	.05134	-.43017	-.22538
	Equal variances not assumed			-6.384	60.242	.000	-.3278	.05134	-.43046	-.22509

The mean deviation values for the different weather conditions at three running speeds are also depicted graphically in Figure 5.5. The figure illustrates that there is a significant difference between the GPS accuracy obtained when testing on a sunny day and the accuracy obtained on a rainy day. It can be clearly seen that the testing had low accuracy on the rainy morning with mean deviation value of 0.56 meter and also on a rainy afternoon with mean deviation value of 0.58 meter. On the other hand, greater GPS accuracy was obtained when the testing was performed a sunny day. It is evident that the testing performed on a sunny afternoon has the lowest mean deviation value (0.24 meters). This was followed by the testing performed on a sunny morning where the mean deviation value was 0.27 meter. The results from test Stage Two are similar to the testing results from test Stage One which again proved that on a rainy day the GPS accuracy would be affected by the weather and generally the accuracy would be decreased.

One of the most interesting results from Figure 5.5 is that the testing performed on a sunny day with riding a bike as running speed has the best GPS accuracy, with a mean deviation value of 0.22 meter. In comparison, the test Stage One showed a similar result of 0.21 meter in the same conditions. However, the mean deviation value for accuracy from the tests performed on a rainy day when I was riding a bike was 0.4 meter in test Stage Two, but the corresponding value in test Stage One was 0.52 meter which is significantly greater than 0.4 meter. This suggests that the GPS accuracy rates were relatively stable in test Stage Two.

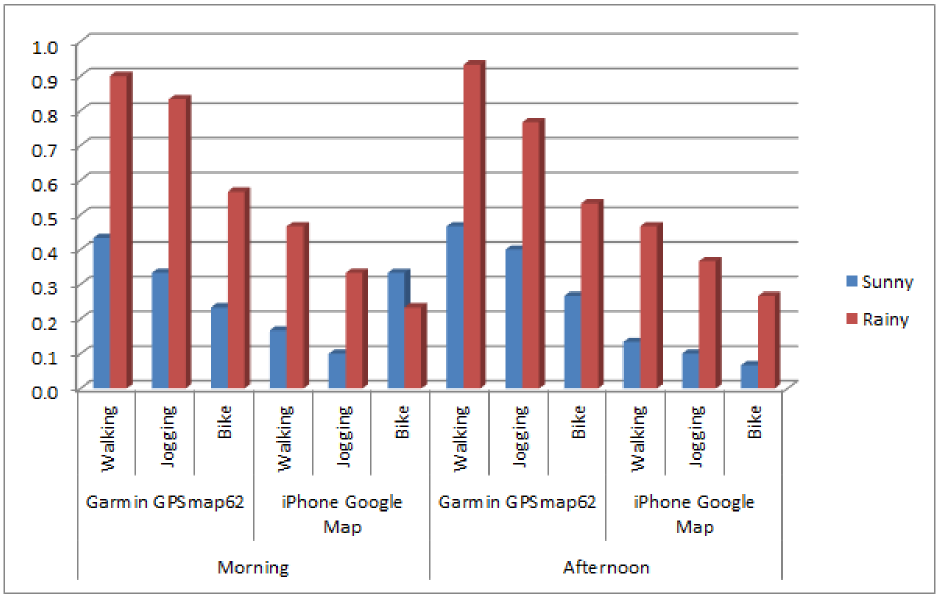

Figure 5.5: Mean deviation values in different weather conditions in Test Stage 2

- **Testing at different times on the same day**

As you can see in Table 5.24, the P value of the tests conducted at different time on the same day and GPS accuracy was 0.67 which is greater than 0.05. It means that the relationship of these two variables is not significant. Additionally, the data provided in Table 5.24 shows that the mean deviation values for the tests performed in morning and afternoon have no significant difference. However, accuracy of the tests conducted in the morning was slightly better. In comparison, the results of test Stage One (Table 5.14) shows the tests performed in the afternoon have better accuracy than the morning's tests. This implied that the relationship between the testing time (morning or afternoon on the same day) and GPS accuracy is not significant.

Table 5.24: Statistics for the testing time in Test Stage 2

Group Statistics

	Testing Time	N	Mean	Std. Deviation	Std. Error Mean
Deviation	Morning	36	.3861	.27687	.04615
	Afternoon	36	.3972	.27096	.04516

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Deviation	Equal variances assumed	.183	.670	-.172	70	.864	-.0111	.06457	-.13989	.11766
	Equal variances not assumed			-.172	69.967	.864	-.0111	.06457	-.13989	.11766

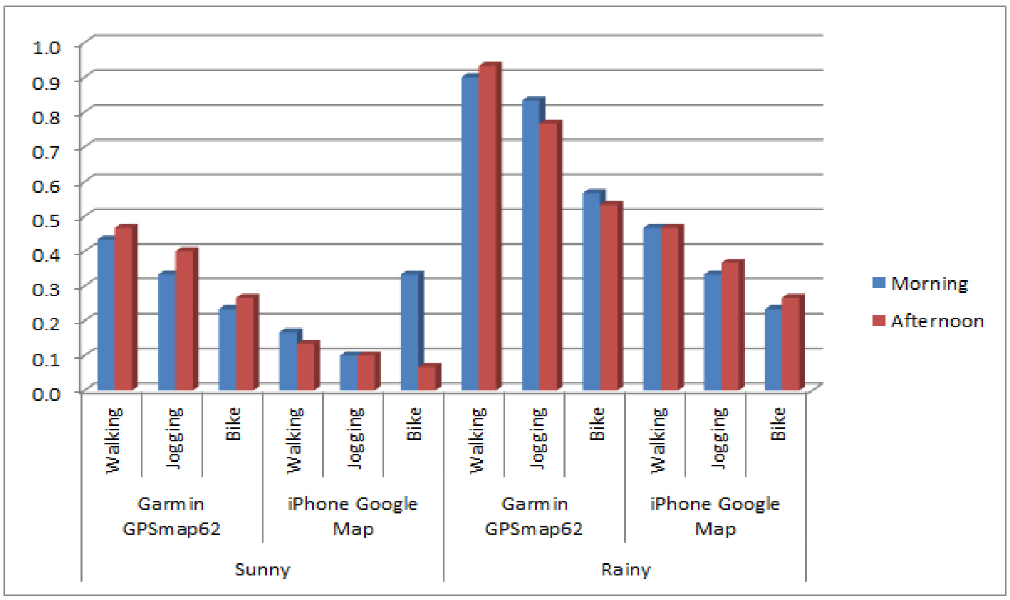

Figure 5.6: Mean deviation values at different testing times in Test stage 2

Figure 5.6 shows that the deviation values for morning and afternoon are quite similar. Apart from the testing performed with iPhone Google Map by bike, the mean deviation values for the tests performed in the morning are remarkably greater than those for the afternoon tests.

- **Tests conducted on different days (Repeated Tests)**

In order to identify the relationship between the testing time and GPS accuracy for Stage Two testing, all the above four tests were repeated on a different day. (Please refer to Section 4.3.2.5 for more details about the tests).

Not surprisingly, the results shown in Table 5.25 are consistent with those from the original four tests. The data appear to confirm the three findings made before:

- On a rainy day, the GPS accuracy is affected by the weather and overall the accuracy is lower.
- On a rainy day, testing at higher running speed produces better GPS accuracy rate.
- The time of testing has greater influence on the GPS accuracy on a rainy day.

Table 5.25: Deviation values recorded by each of the GPS devices for repeated tests in Test Stage 2, and the different statistics used to analyse the accuracy

Test	Weather	Device	Speed	Round 1 (m)	Round 2 (m)	Round 3 (m)	Mean (m)	Standard Deviation	Std.Error of Mean
1	Sunny	Garmin GPSmap62	Walking	0.3	0.5	0.6	0.47	0.15%	0.09%
			Jogging	0.3	0.5	0.2	0.33	0.15%	0.09%
			Bike	0.1	0.4	0.3	0.27	0.15%	0.09%
		GPS device on iPhone5	Walking	0.2	0.2	0.1	0.17	0.06%	0.03%
			Jogging	0.1	0.2	0.1	0.13	0.06%	0.03%
			Bike	0.1	0	0.1	0.07	0.06%	0.03%
2	Sunny	Garmin GPSmap62	Walking	0.3	0.6	0.4	0.43	0.15%	0.09%
			Jogging	0.4	0.4	0.4	0.40	0.00%	0.00%
			Bike	0.1	0.3	0.3	0.23	0.12%	0.07%
		GPS device on iPhone5	Walking	0.1	0.2	0	0.10	0.10%	0.06%
			Jogging	0	0.1	0.1	0.07	0.06%	0.03%
			Bike	0	0	0.1	0.03	0.06%	0.03%
3	Rainy	Garmin GPSmap62	Walking	0.7	1.1	0.8	0.87	0.21%	0.12%
			Jogging	0.8	0.7	0.9	0.80	0.10%	0.06%
			Bike	0.3	0.4	0.8	0.50	0.26%	0.15%
		GPS device on iPhone5	Walking	0.3	0.6	0.4	0.43	0.15%	0.43%
			Jogging	0.4	0.5	0.2	0.37	0.15%	0.09%
			Bike	0.1	0.1	0.4	0.20	0.17	0.10%
4	Rainy	Garmin GPSmap62	Walking	0.7	1	0.9	0.87	15.28%	0.09%
			Jogging	0.7	0.7	0.8	0.73	0.06%	0.03%
			Bike	0.5	0.4	0.4	0.43	0.06%	0.03%
		GPS device on iPhone5	Walking	0.5	0.6	0.5	0.53	0.06%	0.03%
			Jogging	0.5	0.5	0.1	0.37	0.23%	0.13%
			Bike	0.1	0.2	0.2	0.17	0.06%	0.03%
Mean							**0.37**	**0.27%**	**0.04%**

Table 5.26 and Table 5.27 show that the results from the repeated tests are not significantly different from results from the original test as the P value is 0.244 which is

greater than 0.05. In comparison, the results from test Stage One (Table 5.18) show greater P value of 0.963 which is considerably higher than 0.244. This is due to the fact that repeated test 3 and test 4 for test Stage Two were performed on a cloudy day with a few showers rather than rainy day with heavy rain, as this might impact the GPS accuracy.

Table 5.26: Descriptive statistics for original tests and repeated tests in Test stage 2

Test	Mean (m)	Std. Deviation	S.E. Mean	Correlation	Sig.
First Test	0.39	27.21%	3.21%	0.884	0.00
Repeated Test	0.37	27.01%	3.18%		

Table 5.27: Results of paired simple t-test between original tests and repeated tests in Test Stage 2

		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
					Lower	Upper			
Pair 1	Deviation - Repeated Test _ Deviation	.0181	.13036	.01536	-.0126	.0487	1.175	71	.244

Note: Original tests are Test 1, Test 2, Test 3 and Test 4 in Test Stage 2, please refers to Section 4.3.2 for more details.

5.3.2.3 Discussion of Test Stage Three

Test Stage Three was conducted on Queen Street in two types of weather conditions – sunny and cloudy. Furthermore, each weather type was tested in both morning and afternoon. This section presents the test results and their analysis with the aim to understand what factors affect GPS accuracy.

5.3.2.3.1 Analysis of test results

Table 5.28 shows the accuracy deviation values by GPS device and speed group for test Stag Three. This section will discuss these test results.

Table 5.28: Deviation values recorded by each of the GPS devices in Test Stage 3, and the different statistics used to analyse the accuracy

Test	Weather	Device	Speed	A to B (m)	B to A (m)	A to B (m)	B to A (m)	Mean (m)	Std. Deviation	S.E. Mean
1	Sunny	Garmin GPSmap62	Walking	0.3	0.4	0.3	0.4	0.35	5.77%	2.89%
			Jogging	0.7	0.6	0.5	0.6	0.60	8.17%	4.08%
		Navman EZY45	Walking	0.3	0.3	0.3	0.4	0.33	5.00%	2.50%
			Jogging	0.4	0.5	0.3	0.4	0.40	8.17%	4.08%
		GPS device on iPhone5	Walking	0.3	0.1	0.2	0.2	0.20	8.17%	4.08%
			Jogging	0.3	0.3	0.1	0.2	0.23	9.57%	4.79%
2	Sunny	Garmin GPSmap62	Walking	0.3	0.3	0.2	0.4	0.30	8.17%	4.08%
			Jogging	0.2	0.2	0.2	0.3	0.23	5.00%	2.50%
		Navman EZY45	Walking	0.1	0.2	0.1	0.3	0.18	0.10%	0.05%
			Jogging	0.1	0.1	0.2	0.2	0.15	0.06%	0.03%
		GPS device on iPhone5	Walking	0.1	0.2	0.1	0	0.10	0.08%	0.04%
			Jogging	0.1	0.1	0.1	0.2	0.13	0.05%	0.03%
3	Rainy	Garmin GPSmap62	Walking	0.6	0.8	0.5	0.6	0.63	0.13%	0.06%
			Jogging	0.8	0.9	0.8	0.8	0.83	0.05%	0.03%
		Navman EZY45	Walking	0.5	0.5	0.4	0.4	0.45	0.06	0.03%
			Jogging	0.8	0.6	0.8	0.6	0.70	0.12%	0.06%
		GPS device on iPhone5	Walking	0.4	0.3	0.5	0.4	0.40	0.08%	0.04%
			Jogging	0.3	0.6	0.2	0.5	0.40	0.18%	0.09%
4	Rainy	Garmin GPSmap62	Walking	0.5	0.6	0.5	0.3	0.48	0.13%	0.06%
			Jogging	0.8	0.5	0.8	0.9	0.75	0.17%	0.09%
		Navman EZY45	Walking	0.4	0.4	0.4	0.3	0.38	0.05%	0.03%
			Jogging	0.8	0.5	0.6	0.6	0.63	0.13%	0.06%
		GPS device on iPhone5	Walking	0.2	0.3	0.2	0.3	0.25	0.06%	0.03%
			Jogging	0.2	0.3	0.3	0.4	0.30	0.08%	0.04%
Mean								**0.39**	**0.27%**	**0.03%**

The most interesting observation is that the deviation values presented in Table 5.28 increase sharply when the speed is changed from walking to jogging in most of the cases. For instance, in test four the mean deviation value at walking speed was 0.37 meter, whereas in the test at jogging speed it was 0.56 meter. A similar situation can be seen in other tests. The data illustrates that tests with lower running speed produced better GPS accuracy. In comparison, there were contrasting results from test Stage One that the deviation values decreased gradually when the running speed increased and this suggested that the GPS will have higher accuracy when the running speed was higher.

Moreover, in most of the tests, the deviation values for the tests at walking speed remain stable between 0.1 - 0.48 meter. Conversely, results from test Stage Three shown in Table 5.28 show by far the greatest mean deviation value of 0.63 meter for tests at walking speed, which is approximately twice higher than the corresponding values from other three tests. A further analysis is carried out in this section later to explain more about this.

Furthermore, it is clear from the data given that there are some significant differences in the deviation values for different GPS devices. Predictably, iPhone Google Map appears to have the highest GPS accuracy.

5.3.2.3.2 Individual Analysis of each factor

The effect of each of factors influencing accuracy and their relationships are discussed below.

- **GPS Devices**

In order to discover the relationship between GPS devices and accuracy, the significance level has been set to 0.05, and the P value is 0.00 at this significance level (Table 5.29). The data shown in Table 5.29 clearly indicate the significant relationship between the type of GPS devices and accuracy since the P value is less than 0.05.

Table 5.29: Statistics for the GPS devices in Test Stage 3

Dependent Variable: Deviation

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1.161[a]	2	.580	16.023	.000
Intercept	14.570	1	14.570	402.241	.000
GPS	1.161	2	.580	16.023	.000
Error	3.369	93	.036		
Total	19.100	96			
Corrected Total	4.530	95			

a. R Squared = .256 (Adjusted R Squared = .240)

The accuracy of each device is further investigated in this study as I took the mean of the accuracies of the three tested devices and run a frequency histogram to understand the inter-relationship between the type of device and accuracy. Table 5.30 shows the results for the tested GPS devices Garmin GPSmap62, Navman EZY45 and iPhone Google Map. It can be seen that there were great differences in the deviation values. While the mean deviation value of the accuracy for Garmin GPSmap62 is 0.52 meter, the mean deviation value of the accuracy of iPhone Google Map is twice smaller (0.25 meter).

Meanwhile, the accuracy of Navman EZY45 generally maintains middle position with mean deviation value of 0.4 meter. The analysis of the data presented in Table 5.30 shows that the deviation values of iPhone Google Map across all tests are fairly constant and it also proves that the accuracy of iPhone Google Map is relatively stable in all environments.

Table 5.30: Comparison of three GPS devices in Test Stage 3

(I) GPS DEVICES	(J) GPS DEVICES	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
Garmin GPSmap62	Navman EZY45	.1187*	.04758	.049	.0004	.2371
	iPhone Google Map	.2688*	.04758	.000	.1504	.3871
Navman EZY45	Garmin GPSmap62	-.1187*	.04758	.049	-.2371	-.0004
	iPhone Google Map	.1500*	.04758	.009	.0316	.2684
iPhone Google Map	Garmin GPSmap62	-.2688*	.04758	.000	-.3871	-.1504
	Navman EZY45	-.1500*	.04758	.009	-.2684	-.0316

Based on observed means.

*. The mean difference is significant at the .05 level.

Scheffe[a,b]

GPS DEVICES	N	Subset		
		1	2	3
iPhone Google Map	32	.2500		
Navman EZY45	32		.4000	
Garmin GPSmap62	32			.5188
Sig.		1.000	1.000	1.000

Means for groups in homogeneous subsets are displayed.
Based on Type III Sum of Squares
The error term is Mean Square(Error) = .036.

a. Uses Harmonic Mean Sample Size = 32.000.

b. Alpha = .05.

- **Running Speeds**

The next step is to test the variable of accuracy against with the running speed (such as Walking and Jogging). Table 5.31 shows that the running speeds impacted the accuracy significantly, and the P value of 0.00 is definitely less than 0.05.

Table 5.31: Statistics for both running speed in Test Stage 3

	Running Speed	N	Mean	Std. Deviation	Std. Error Mean
Deviation	Walking	48	.3354	.15776	.02277
	Jogging	48	.4438	.25591	.03694

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Deviation	Equal variances assumed	21.247	.000	-2.497	94	.014	-.1083	.04339	-.19449	-.02218
	Equal variances not assumed			-2.497	78.215	.015	-.1083	.04339	-.19472	-.02195

Figure 5.7 presents graphically the deviation values for two different speeds (walking and jogging) from the four tests in test Stage Three. The deviation values of these tests followed a fairly set pattern cross all tested GPS devices. The most obvious trend in the graph is that the deviation values rise dramatically when the speed changes from walking to jogging which also means that testing at higher speed will produce lower GPS accuracy. For example, on a rainy day, when I tested Garmin GPSmap62 accuracy at jogging speed in the morning, the deviation value was 0.83 meter, but it was only 0.63 meter at walking speed. The difference was even bigger when the testing was performed in the afternoon on the same day, as the deviation was 0.75 meter at jogging speed, but only 0.48 meter at walking speed. Also in other tests the deviation value at jogging speed was greater than the deviation value at walking speed. There were similar increases for the deviation values on the sunny day, rising from 0.35 meter at walking speed to 0.60 meter at jogging speed when I used the Garmin GPSmap62 in the morning. However, there were some different results from test 2 where the GPS accuracy was lower when the running speed was walking. For example, Navman EZY45 shows better accuracy when the test conducted on a sunny afternoon at jogging speed. This again demonstrates that the running speed is not the only factor that affects the GPS accuracy.

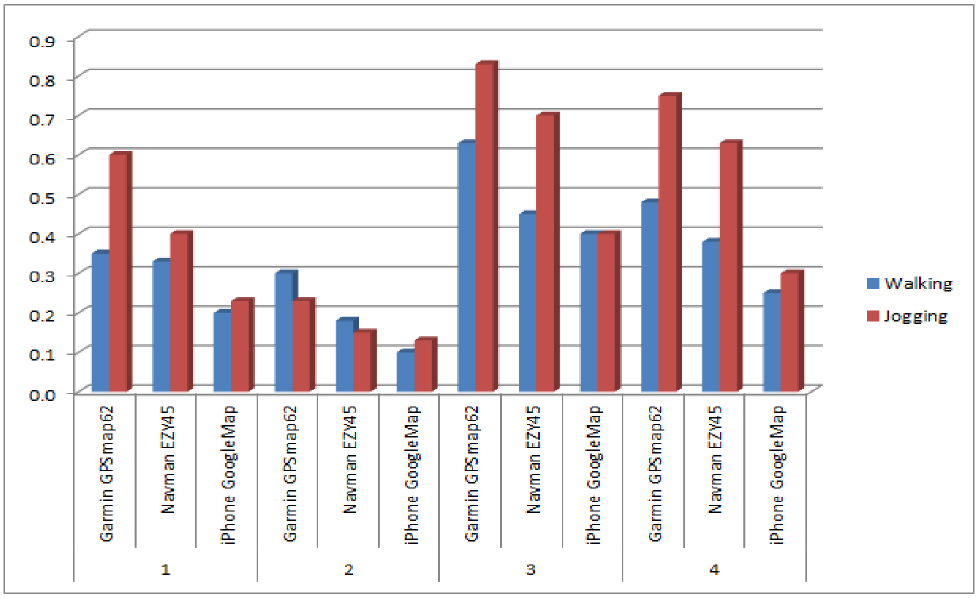

Figure 5.7: Mean deviation for GPS devices tested at different running speeds in Test Stage 3

- **Weather Conditions**

In order to investigate how weather conditions impact GPS accuracy, an independent sample T-test has been run. The results presented in Table 5.32 highlight the fact that the weather conditions have a particular influence on the GPS accuracy with the P value 0.023 which is less than 0.05. Table 5.32 also shows that the mean deviation value on a rainy day was 0.51 meter, compared to only 0.26 meter for the sunny day, i.e. it was reduced by half. This proves that the tested GPS devices have better accuracy in sunny weather.

Table 5.32: Statistics for both weather conditions in Test Stage 3

	Weather Condition	N	Mean	Std. Deviation	Std. Error Mean
Deviation	Sunny	48	.2646	.15087	.02178
	Rainy	48	.5146	.20420	.02947

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Deviation	Equal variances assumed	5.367	.023	-6.822	94	.000	-.2500	.03665	-.32276	-.17724
	Equal variances not assumed			-6.822	86.532	.000	-.2500	.03665	-.32284	-.17716

Figure 5.8 clearly presents and compares the mean deviation values for different weather conditions. Overall, the bar chart provided in this Figure indicates that there were noticeable differences in the deviation values of sunny days and rainy days. The values for rainy days are higher than the values for sunny day in all conducted tests; they are almost 60% higher when I used the Garmin GPSmap62 at jogging speed on a rainy afternoon. , Also, it is interesting to note in Figure 5.8 that there were greater fluctuations in the deviation values for rainy days than for sunny days. More specifically, the highest mean deviation value for rainy days is 0.64 meter when I was walking on a rainy morning and the lowest value was produced at walking speed on a rainy morning when the value dipped as low as 0.37 meter. In comparison, the mean deviation value of the sunny day was approximately 0.26 meter (Part 1 in Table 5.32). The greatest deviation value (0.6 meter) occurred when I tested the Garmin GPSmap62 device at jogging speed, and the smallest value (0.1 meter) occurred when I tested iPhone Google Map at walking speed on a sunny morning. As can be seen in the diagram, the selected GPS devices have a steady accuracy rate for the sunny days.

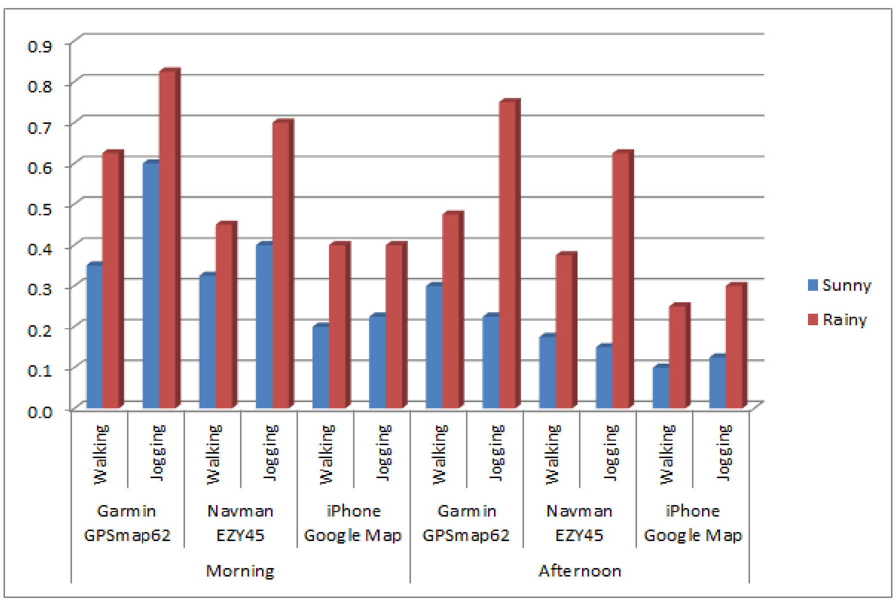

Figure 5.8: Mean deviation values for different weather conditions in Test Stage 3

- **Testing Times during the same day**

The testing times chosen for test Stag Three are morning and the afternoon during the same day. Table 5.33 presents the T-test results and the P value for the causal paths between accuracy and testing time at the significance level of 0.05. The data provided appears to confirm that the relationship between accuracy and testing time was not significant as the P value (0.934) was greater than 0.05.

Table 5.33: Statistics for different testing times in Test Stage 3

	Testing Time	N	Mean	Std. Deviation	Std. Error Mean
Deviation	Morning	48	.4583	.20299	.02930
	Afternoon	48	.3208	.21334	.03079

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Deviation	Equal variances assumed	.007	.934	3.235	94	.002	.1375	.04250	.05311	.22189
	Equal variances not assumed			3.235	93.769	.002	.1375	.04250	.05310	.22190

It is worth mentioning that the deviation value of the testing performed on a sunny morning was significantly greater than the corresponding value for the sunny afternoon when the same GPS device and speed were used. This is clearly illustrated in the graph in Figure 5.9. To be specific, the greatest difference occurred when Garmin GPS map62 was used at Jogging speed, and the mean deviation value was 0.6 meter in the morning, i.e. approximately three times greater than the corresponding value for the tests performed in the afternoon on the same day. Interestingly, the deviation values for the rainy day are quite similar for both morning and afternoon. Excluding the testing performed on Garmin GPSmap62 at walking speed and the testing performed on iPhone Google Map at walking speed, there were greater differences between the mean deviation values of morning and afternoon compared to other tests. In conclusion, although the T-test results (Table 5.33) show the relationship of testing time and accuracy as not significant, the chart implies that the GPS has higher accuracy when the testing is performed in the morning than when it is in the afternoon in test Stage Three.

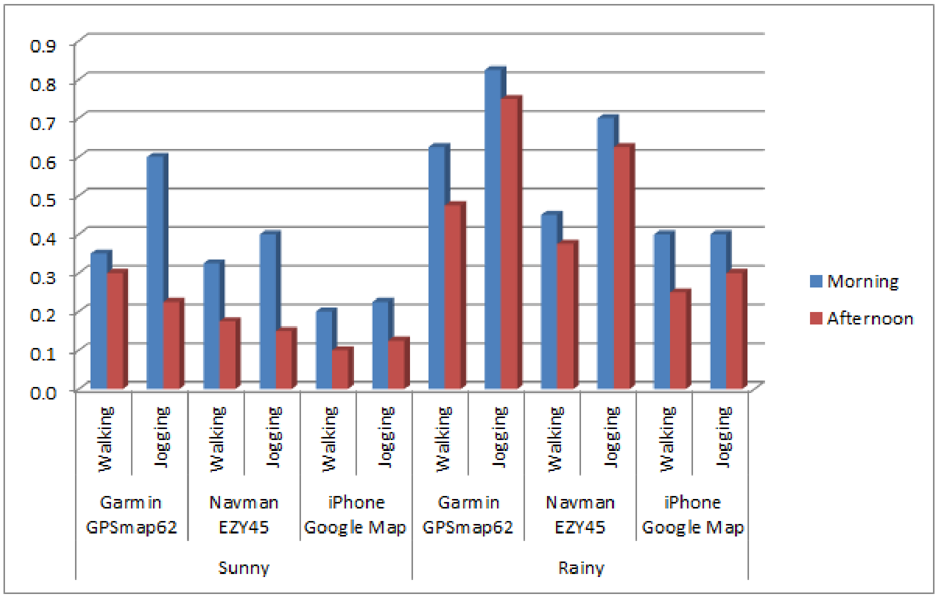

Figure 5.9: Mean deviation values for different testing times in Test Stage 3

- **Tests conducted on different days (Repeated Tests)**

In order to investigate the relationship between the testing time on a different day and GPS accuracy during test Stage Three , the same method as in the above four tests was applied in tests repeated on a different day. (Please refer to Section 4.3.3.5 for more details about the tests). Table 5.34 presents the deviation values and descriptive statistics for these tests. It isn’t surprising that the results are consistent with the findings from the original four tests in test Stage Three.

Table 5.34: Deviation values recorded by each of the GPS devices in the repeated tests in Test Stage 3, and the different statistics used to analyse the accuracy

Test	Weather	Device	Speed	A to B (m)	B to A (m)	A to B (m)	B to A (m)	Mean (m)	Std. Deviation	S.E. Mean
1	Sunny	Garmin GPSmap62	Walking	0.4	0.4	0.3	0.4	0.38	0.05%	0.03%
			Jogging	0.9	0.5	0.5	0.7	0.65	0.19%	0.10%
		Navman EZY45	Walking	0.4	0.3	0.4	0.4	0.38	0.05%	0.03%
			Jogging	0.3	0.1	0.2	0.3	0.23	0.10%	0.05%
		GPS device on iPhone5	Walking	0.2	0.3	0.3	0.3	0.28	0.05%	0.03%
			Jogging	0.3	0.2	0.2	0.3	0.25	0.06%	0.03%
2	Sunny	Garmin GPSmap62	Walking	0.4	0.4	0.4	0.3	0.38	0.05%	0.03%
			Jogging	0.2	0.4	0.3	0.2	0.28	0.96%	0.05%
		Navman EZY45	Walking	0.3	0.3	0.2	0.2	0.25	0.06%	0.03%
			Jogging	0.1	0	0.2	0.2	0.13	0.10%	0.05%
		GPS device on iPhone5	Walking	0.1	0.3	0.1	0.3	0.20	0.12%	0.06%
			Jogging	0.1	0	0.2	0	0.08	0.10%	0.05%
3	Rainy	Garmin GPSmap62	Walking	0.7	0.8	0.7	0.8	0.75	0.06%	0.03%
			Jogging	0.8	0.9	0.9	0.8	0.85	0.06%	0.03%
		Navman EZY45	Walking	0.6	0.7	0.3	0.5	0.53	0.17%	0.09%
			Jogging	0.7	0.6	0.5	0.6	0.60	0.08%	0.04%
		GPS device on iPhone5	Walking	0.6	0.4	0.5	0.5	0.50	8.17%	0.04%
			Jogging	0.2	0.5	0.2	0.4	0.33	0.15%	0.08%
4	Rainy	Garmin GPSmap62	Walking	0.7	0.7	0.3	0.4	0.53	0.21%	0.10%
			Jogging	0.5	0.6	0.7	0.6	0.60	0.08%	0.04%
		Navman EZY45	Walking	0.4	0.6	0.4	0.3	0.43	0.13%	0.63%
			Jogging	0.3	0.4	0.3	0.6	0.40	0.14%	0.07%
		GPS device on iPhone5	Walking	0.6	0.3	0.4	0.2	0.38	0.17%	0.09%
			Jogging	0.3	0.2	0.4	0.2	0.28	0.96%	0.48%
Mean								**0.37**	**0.27%**	**0.03%**

A further analysis of the relationship between the testing time on a different day and accuracy was completed and a summary of the descriptive statistics regarding the tests are shown in Table 5.35. The differences between results from the original tests and the repeated tests are not significant, with the mean deviation values 0.39 meter and 0.4 meter respectively. On the other hand, Table 5.36 presents the results from paired-sample t-test which appears to prove the above point as the P value was 0.491 which is greater than 0.05.

Table 5.35: Comparison of descriptive statistics for original tests and repeated tests in Test stage 3

Test	Mean (m)	Std. Deviation	S.E. Mean	Correlation	Sig.
First Test	0.390	0.22%	0.22%	0.767	0.00
Repeated Test	0.400	0.21%	0.21%		

Table 5.36: Result of paired sample t-test between original tests and repeated tests in Test Stage 3

		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference Lower	Upper			
Pair 1	Deviation - Repeated Test _ Deviation	-.0104	.14760	.01506	-.0403	.0195	-.691	95	.491

Note: Original tests are Test 1, Test 2, Test 3 and Test 4 in Test Stage 3, please refers to Section 4.3.3 for more details.

5.3.2.4 Discussion of Test Stage Four

Test Stage Four was testing in an indoor area, which was in the hallway in my house. Two types of weather conditions were selected for this test – sunny and rainy. Additionally, each weather type was tested in both morning and afternoon sessions. This section presents the testing results and their analysis with the purpose to understand the connection between the accuracy and other factors that might affect the accuracy.

5.3.2.4.1 Analysis of test results

Stage Four testing was conducted indoor and on a short path. Unfortunately, Garmin GPSmap62 was the only GPS device used in this stage. Therefore, there was no data available from other GPS devices for comparison. Moreover, since the tests were performed indoors, walking was the only speed used in this test.

The data analysis focuses on understanding the relationship between variables in test Stage Four. Table 5.37 presents and compares the deviation values for different weather condition produced at walking speed. The mean deviation value for all tests is approximately 1.08 meter and the highest mean value (1.45 meter) occurred in test four when the testing was performed on a rainy afternoon, and the lowest value (0.78 meter) occurred when the testing was conducted on sunny morning and sunny afternoon. According to the data, the GPS device has a steady accuracy on a sunny day compared to that on a rainy day. It is interesting to note that the weather conditions have a considerable influence on the GPS accuracy for small distance and Garmin GPSmap62 produces better accuracy on a sunny day.

Table 5.37: Deviation values recorded by each of the tests in Test Stage 4, and the different statistics used to analyse the accuracy

Test	Device	Speed	A to B (m)	B to A (m)	A to B (m)	B to A (m)	Mean (m)	Std. Deviation	S.E. Mean
1	Garmin GPSmap62	Walking	0.2	0.8	1.5	0.6	0.78	54.39%	27.20%
2	Garmin GPSmap62	Walking	0.8	1.4	0.9	0.1	0.78	53.15%	26.58%
3	Garmin GPSmap62	Walking	1.1	2.4	0.9	0.7	1.28	76.76%	38.38%
4	Garmin GPSmap62	Walking	2.2	0.8	1.3	1.5	1.45	58.02%	29.01%
Mean							**1.08**	**62.77%**	**15.69%**

5.3.2.4.2 Individual Analysis of each factor

The GPS accuracy can be influenced by a number of factors. However, due to the physical limitations of GPS application and other external factors, this analysis focuses on the weather conditions and testing time. The test method used was walking and the GPS device was Garmin GPSmap62. A discussion of the relationship between each variable and GPS accuracy is presented below.

- **Weather Conditions**

I took the deviation value of all the tests and run an independent sample t-test to find out how weather conditions affect the accuracy. Surprisingly, the result of the t-test shows that the weather conditions do not have significant impact on the GPS accuracy as the P value (0.414) is greater than 0.05. On the other hand, Table 5.38 shows that the tests conducted on a sunny day have better accuracy, and the mean deviation value of 0.7875 meter increased by about 40% to 1.3625 when the tests were performed on a rainy day. In summary, weather conditions have a limited impact on the accuracy and it was not a significant factor for small test distance.

Table 5.38: Statistics for different weather conditions in Test Stage 4

Group Statistics

	weather Condition	N	Mean	Std. Deviation	Std. Error Mean
Deviation	Sunny	8	.7875	.49982	.17671
	Rainy	8	1.3625	.63682	.22515

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Deviation	Equal variances assumed	.709	.414	-2.009	14	.064	-.5750	.28622	-1.18887	.03887
	Equal variances not assumed			-2.009	13.252	.065	-.5750	.28622	-1.19214	.04214

- **Testing time during the same day**

The second factor which was tested was the testing time during the same day. Table 5.39 shows that the relationship between testing time and GPS accuracy is not significant as the P value of 0.975 is greater than 0.05.

Table 5.39: Statistics for different testing time in Test Stage 4

Group Statistics

	Testing Time	N	Mean	Std. Deviation	Std. Error Mean
Deviation	Morning	8	1.0250	.67135	.23736
	Afternoon	8	1.1250	.62278	.22019

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Deviation	Equal variances assumed	.001	.975	-.309	14	.762	-.1000	.32376	-.79440	.59440
	Equal variances not assumed			-.309	13.922	.762	-.1000	.32376	-.79477	.59477

- **Tests conducted on different days (Repeated Tests)**

As might be expected the result shown in Table 5.40 are consistent with the findings from the original four tests in test Stage Four. There are a number of similarities between the results from the original tests and from the repeated test. For example, the mean deviation value for all four tests is 1 meter which is nearly the same as the deviation value for the original tests. Also, the data provided in Table 5.40 shows that the GPS accuracy was impacted by the weather conditions as the accuracy of the tested device was better on a sunny day.

Table 5.40: Deviation values recorded in each of the repeated tests in Test Stage 4, and the different statistics used to analyse the accuracy

Test	Device	Speed	A to B (m)	B to A (m)	A to B (m)	B to A (m)	Mean (m)	Std. Deviation	S.E. Mean
1	Garmin GPSmap62	Walking	1.1	0.3	0.2	0.5	0.53	40.31%	20.16%
2	Garmin GPSmap62	Walking	0.8	0.4	0.1	0.2	0.38	30.96%	15.48%
3	Garmin GPSmap62	Walking	0.7	1.8	1.9	1.5	1.48	54.39%	27.20%
4	Garmin GPSmap62	Walking	1.8	1.9	1.4	1.4	1.63	26.30%	13.15%
Mean							**1.00**	**67.33%**	**16.83%**

A further analysis of the relationship between the testing time on a different day and accuracy and a summary of the descriptive statistics for the tests are shown in Table 5.41. The differences between results from the original tests and from the repeated tests are not significant, as the mean deviation values were 1.1 meter and 1.0 meter respectively. Table 5.42 presents the result of paired-sample t-test which appears to prove the above point as the P value is 0.685 which is greater than 0.05.

Table 5.41: Comparison of descriptive statistics for original tests and repeated tests in Test stage 4

Test	Mean (m)	Std. Deviation	S.E. Mean	Correlation	Sig.
First Test	1.075	0.63%	0.16%	0.382	0.15
Repeated Test	1.000	0.67%	0.17%		

Table 5.42: Result of paired sample t-test between original tests and repeated tests in Test Stage 4

		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
					Lower	Upper			
Pair 1	Deviation - Repeated testing_deviation	.0750	.72434	.18108	-.3110	.4610	.414	15	.685

Note: Original tests are Test 1, Test 2, Test 3 and Test 4 in Test Stage 4, please refers to Section 4.3.4 for more details.

5.3.3 Summary of All Testing Stages

The findings obtained from the data analysis for all test stages as described above confirm that a number of factors affect GPS accuracy. The major factors that impact the accuracy the most are: environmental conditions, weather conditions, used GPS device and running speed. Further insights are discussed in the following section which summarises the relationships between each factor and GPS accuracy.

5.3.3.1 Environmental Conditions and Accuracy

The research testing design discussed in Chapter 3 assumed that there is some association between the environmental conditions and accuracy. The fourth hypothesis (Section 3.2) developed in this research stated that the GPS accuracy would be higher if the testing object is located in a wide open area. According to the test results shown in Chapter 4, the GPS devices received stronger signals under the higher percentage of canopy open area which leads to a better GPS accuracy produced by the devices.

Descriptive statistics for the difference in accuracy for the different types of environmental conditions are shown in Table 5.43. The data provided in the table suggests the tests conducted in a wide open field area (such as Highbrook Industrial Park) have the best accuracy; the mean deviation value of 0.4 meter increased three times when the tested object was located indoor (such as inside my house). One particularly interesting fact highlighted in the table is that the tests performed in the city area have the same accuracy as the tests conducted in the open field area. According to existing studies with similar research topic, any objects such as tall building or trees in the zone of the GPS antenna may reduce GPS accuracy noticeably. For example, the GPS devices were performing not very well in some of the tests in Stage Three when the environmental condition was under canopy, with a mean deviation value of 0.52 meter.

However, unexpectedly the accuracy was quite good when the tested object was located in the city area. This suggests that the environmental conditions are not the only factor that affects the accuracy and further studies should be conducted in the future.

Table 5.43: Descriptive Statistics for the different between environmental conditions for all test stages

Test Stage	Environmental condition	N	Mean Deviation	Std. Deviation
1	Under Canopy	24	0.52	23.74%
2	Open Field	24	0.40	24.98%
3	City Area	24	0.40	20.56%
4	Indoor	4	1.08	33.93%

For the analysis of the relationship between environmental conditions and accuracy the significance level was specified to be 0.05. The results from the t-test for these two variables are displayed in Table 5.44. Environmental conditions are shown to have a significant relationship with accuracy as the P value is 0.00 which is less than 0.05. This finding confirms the third hypothesis in this study. Table 5.45 presents the results obtained from tests in different environmental conditions (under canopy, open field area, city area and indoor environment). It can be seen in the table that the mean deviation value for indoor environment is significantly greater than the mean deviation values for the other three conditions. This must be due the GPS signal being totally blocked indoor which impacts the GPS performance.

Table 5.44: Environmental condition Statistics in all test stages

Dependent Variable: Mean Deviation

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1.783[a]	3	.594	10.570	.000
Intercept	15.254	1	15.254	271.219	.000
TEST	1.783	3	.594	10.570	.000
Error	4.049	72	.056		
Total	22.744	76			
Corrected Total	5.833	75			

a. R Squared = .306 (Adjusted R Squared = .277)

Table 5.45: Comparison of mean deviation values for different environmental conditions in all test stages

Dependent Variable: Mean Deviation
Scheffe

(I) Test Stage	(J) Test Stage	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	Upper Bound
Under Canopy	Open Field	.1142	.06846	.432	-.0818	.3102
	City Area	.1267	.06846	.338	-.0693	.3227
	Indoor	-.5592*	.12808	.001	-.9258	-.1925
Open Field	Under Canopy	-.1142	.06846	.432	-.3102	.0818
	City Area	.0125	.06846	.998	-.1835	.2085
	Indoor	-.6733*	.12808	.000	-1.0400	-.3067
City Area	Under Canopy	-.1267	.06846	.338	-.3227	.0693
	Open Field	-.0125	.06846	.998	-.2085	.1835
	Indoor	-.6858*	.12808	.000	-1.0525	-.3192
Indoor	Under Canopy	.5592*	.12808	.001	.1925	.9258
	Open Field	.6733*	.12808	.000	.3067	1.0400
	City Area	.6858*	.12808	.000	.3192	1.0525

Based on observed means.
*. The mean difference is significant at the .05 level.

Scheffe[a,b,c]

Test Stage	N	Subset 1	2
City Area	24	.3917	
Open Field	24	.4042	
Under Canopy	24	.5183	
Indoor	4		1.0775
Sig.		.679	1.000

Means for groups in homogeneous subsets are displayed.
Based on Type III Sum of Squares
The error term is Mean Square(Error) = .056.

a. Uses Harmonic Mean Sample Size = 10.667.

b. The group sizes are unequal. The harmonic mean of the group sizes is used. Type I error levels are not guaranteed.

c. Alpha = .05.

5.3.3.2 Weather Conditions and Accuracy

A number of tests performed in this study were designed to expose the relationship between weather conditions and GPS accuracy. As stated in Chapter 3, the GPS device would be more accurate if the test is performed in sunny weather (please refer to the fourth hypothesis in section 3.2). Table 5.46 shows that the weather conditions can also play a big role in improving the GPS accuracy as the P value is 0.013. On the other hand, Table 5.47 confirms that the GPS devices have higher accuracy on a sunny day than on a rainy day, with mean deviation value of 0.31 meter and 0.63 meter respectively.

Table 5.46: Weather Conditions Statistics in all test stages

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Mean Deviation	Equal variances assumed	6.513	.013	-6.154	74	.000	-.3224	.05238	-.42675	-.21799
	Equal variances not assumed			-6.154	62.823	.000	-.3224	.05238	-.42706	-.21768

Table 5.47: Comparison of accuracy in different weather conditions in all test stages

Dependent Variable: Mean Deviation

Test Stage	Weather Condition	Mean	Std. Deviation	N
Under Canopy	Sunny	.3325	.11887	12
	Rainy	.7042	.16839	12
	Total	.5183	.23739	24
Open Field	Sunny	.2525	.13981	12
	Rainy	.5558	.24652	12
	Total	.4042	.24983	24
City Area	Sunny	.2667	.14002	12
	Rainy	.5167	.18627	12
	Total	.3917	.20561	24
Indoor	Sunny	.7900	.01414	2
	Rainy	1.3650	.12021	2
	Total	1.0775	.33925	4
Total	Sunny	.3105	.17363	38
	Rainy	.6329	.27227	38
	Total	.4717	.27887	76

5.3.3.3 GPS Device and Accuracy

The analysis of test data also reveals that GPS accuracy is highly dependent on the hardware configuration of the GPS device (refer to Table 5.48 where the P value was 0.04). The first hypothesis in Chapter 3 (Section 3.2) stated that the hardware configuration employed would have capability to maximise the accuracy of the GPS. Three GPS devices have been tested in this project and they have different hardware configuration as explained in detail in section 5.3.1. As expected, Table 5.49 shows iPhone5 have better accuracy compared to Garmin GPSmap62. It means the GPS with higher refresh rate on the screen and faster CPU speed will normally have better accuracy.

Table 5.48: Statistics for different GPS devices in all test stages

Dependent Variable: Mean Deviation

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	.491[a]	2	.245	3.352	.040
Intercept	8.862	1	8.862	121.095	.000
DEVICE	.491	2	.245	3.352	.040
Error	5.342	73	.073		
Total	22.744	76			
Corrected Total	5.833	75			

a. R Squared = .084 (Adjusted R Squared = .059)

Table 5.49: Relevant statistic for different GPS devices in all test stages (t-test Results)

Dependent Variable: Mean Deviation

Test Stage	GPS Device	Mean	Std. Deviation	N
Under Canopy	Garmin GPSmap62	.5667	.25546	12
	iPhone Google Map	.4700	.21788	12
	Total	.5183	.23739	24
Open Field	Garmin GPSmap62	.4100	.24933	12
	iPhone Google Map	.3983	.26128	12
	Total	.4042	.24983	24
City Area	Garmin GPSmap62	.4550	.19011	8
	iPhone Google Map	.4200	.27402	8
	Navman EZY45	.3000	.11212	8
	Total	.3917	.20561	24
Indoor	Garmin GPSmap62	1.0775	.33925	4
	Total	1.0775	.33925	4
Total	Garmin GPSmap62	.5464	.31274	36
	iPhone Google Map	.4306	.24302	32
	Navman EZY45	.3000	.11212	8
	Total	.4717	.27887	76

5.3.3.4 Running Speed and Accuracy

The fifth hypothesis (Section 3.2) presented in this study assumed that the GPS receivers should get higher accuracy at a higher running speed. This research found that the relationship between running speed and GPS accuracy is significant (please refer to Table 5.50 where P value is 0.044). According to Table 5.51, lower running speed would degrade the GPS accuracy. Additionally, the experiments performed in the Highbrook Industrial Park when the running speed was riding a bike produced the highest accuracy, with mean deviation value of 0.31 meter. This demonstrates that the running speed is not the only factor that affects the GPS accuracy; there are some other factors that might influence the accuracy.

Table 5.50: Statistics for different running speeds in all test stages

Dependent Variable: Mean Deviation

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	.479[a]	2	.240	3.268	.044
Intercept	14.025	1	14.025	191.252	.000
SPEED	.479	2	.240	3.268	.044
Error	5.353	73	.073		
Total	22.744	76			
Corrected Total	5.833	75			

a. R Squared = .082 (Adjusted R Squared = .057)

Table 5.51: Relevant Statistics for different running speeds in all test stages (t-test Results)

Dependent Variable: Mean Deviation

Test Stage	Running Speed	Mean	Std. Deviation	N
Under Canopy	Walking	.6587	.23443	8
	Jogging	.5288	.22806	8
	Bike	.3675	.17186	8
	Total	.5183	.23739	24
Open Field	Walking	.4963	.29233	8
	Jogging	.4038	.27055	8
	Bike	.3125	.16473	8
	Total	.4042	.24983	24
City Area	Walking	.3375	.14573	12
	Jogging	.4458	.24648	12
	Total	.3917	.20561	24
Indoor	Walking	1.0775	.33925	4
	Total	1.0775	.33925	4
Total	Walking	.5500	.32797	32
	Jogging	.4575	.24420	28
	Bike	.3400	.16509	16
	Total	.4717	.27887	76

5.4 CONCLUSION

Chapter 5 has presented a discussion of the findings from the research testing which was analysed and presented in Chapter 4. The research questions proposed in the Research Methodology (Section 3.2) have been answered and discussed along with the previously asserted hypotheses, and a conclusion was reached regarding the validity of the predicted hypotheses. The findings achieved during the various testing phases in different testing locations, different weather conditions and different testing time were presented and discussed, and the GPS devices were compared based on their hardware and software specifications.

The main research question of the project was to establish the accuracy for different GPS devices in a certain testing period, and to find out the factors that affect the GPS accuracy. Subsequently, a series of tests was formed (Section 3.3) and the testing method was established. During the testing phase, the GPS devices were tested in tree canopies area, urban arterials area, Queen Street and indoor environment, each test was done in both sunny and rainy or cloudy weather. All the tests were repeated under the same conditions but in different time, and it was found that the accuracy would be different if time differed. The findings discovered that the GPS devices were able to achieve high accuracy under certain conditions. Furthermore, the devices had built-in memory or flash memory to store the location data, and could use USB port to output the data. If the location data is accurate, it could be output via an USB cable and preserved in order to be presented to and accepted by the court.

Chapter 6 concludes the whole thesis project and presents a summary of the research conducted and the significant findings that have been established. Limitations to the research are outlined to determine why some aspects of the research could not be addressed. In the closing part, other prospective fields of research within the discipline area will be discussed to highlight the many potential avenues open to future research.

Chapter 6 : CONCLUSION

6.0 INTRODUCTION

In this thesis, the introductory chapter discusses the research topic and the motivation for the research. Over the recent years GPS has been used extensively in the field of digital forensics. The challenges for a forensic examiner when gathering digital evidence from GPS devices were briefly discussed, such as the need to use different handling rules from those used for extracting evidence from PC or VCR. On the other hand, due to the physical limitations of GPS applications and other external factors, another unique issue of evidence collection has been identified which is the lack of veracity and consistency of data collected by GPS measurement. However, there are only few research papers discussing the issues and methods for determining the factors that affect the GPS accuracy. Therefore, it is valuable to identify the most important factors that might impact the GPS accuracy from the forensic investigation perspective.

In order to expand the understanding of the research topic and form the research goal, relevant published studies and literature related to the research area were selected and reviewed in Chapter 2. This chapter looked at the main concepts and working processes of the GPS and at the issues that have a potential to affect the accuracy of GPS measurements. In addition, some existing studies in relation to GPS measurement and location tracking technology were also reviewed.

In Chapter 3, the main research question and sub-questions were identified and a feasible methodology was chosen for this research after evaluating different research methodologies that have been used in existing studies. An essential part of this research is the testing approach for determining the GPS accuracy that has been developed by following the recommendations presented by other researchers. Hence, the main components of the testing methodology include the tools used in the testing; testing steps for accomplishing the examination, the measurement criteria and grounded theory were also discussed. Furthermore, after reviewing the relevant literature, hypotheses associated with each research question were also established.

In order to use the testing methodology, four quasi-experimental test scenarios have been presented. By design, these tests were held in tree canopies area in One Tree Hill, urban arterials in the Highbrook Industrial park, Queen Street and indoor environment; each scenario also included different GPS devices, running speeds and weather conditions in order to get more comprehensive data for investigating the factors that impact on accuracy. The outcomes from these test scenarios and the findings from the proposed research methods were reported in Chapter 4. The results of the testing were outlined based on the proposed research method which included data preparation, data analysis and presentation. The most relevant findings were also identified that the proposed system design was capable of researching the factors that affect the GPS accuracy in a forensic manner.

After the analysis of the test results, a discussion of the research findings for each test scenario was presented in Chapter 5 to provide the answers for the research questions and nullify the associated hypotheses. The main research question was to establish the accuracy of different GPS devices in a certain testing period, and to find out the factors that would affect the GPS accuracy. The research discovered that the GPS devices were able to gain a high accuracy under certain conditions. Additionally, the testing methodology was re-visited and some recommendations for this type of research were documented.

The aim in Chapter 6 is to provide the conclusion for this research by summarising the research achievements in Section 6.1, while the research limitations are outlined in section 6.2. Recommendations for further research are presented in Section 6.3.

6.1 SUMMARY OF KEY FINDINGS

This section reviews the key findings regarding GPS accuracy and the factors affecting GPS accuracy.

6.1.1 GPS Accuracy and Limitations

As discussed in Chapter 2 and Chapter 3, although the GPS navigation applications have been developed to be as accurate as possible, several random and systematic errors still occur in a certain environment and influence the accuracy. According to the results of the experiment, there was a deviation between the GPS location and the actual location of the person/ car. In a situation that a security incident happened, there would be some uncertainties of the GPS location. This research aimed to understand the limitation of the GPS and establish the most significant sources of poor accuracy. There are various factors that cause reduction in accuracy and they include multipath signal reflection, position, number of satellites and dynamic atmospheric conditions.

6.1.2 Factors affecting GPS Accuracy

A number of studies relevant to my research topic have established that a variety of factors impact the level of accuracy of GPS measurement. In this research, each stage of testing presented findings that help to find out what factors affect GPS accuracy the most. The major factors established in this research include surrounding conditions (e.g. environmental factors, weather condition), GPS Technique employed (e.g. hardware configuration, receiver quality) and running speed.

6.1.2.1 Surrounding conditions

The outcomes from the experiments in this study show that the surrounding conditions have considerable influence on GPS accuracy. This study was specifically focusing on two types of surrounding conditions: environmental factors and weather conditions.

Firstly, the tests from the proposed research phases were undertaken multiple times under different environmental conditions in order to get a general idea of the environmental effects. The findings and analysis from the preliminary testing phase illustrate the sensitivity of GPS devices and that accuracy is heavily impacted by these factors. For example, any objects such as tall building or trees that are in the zone of the GPS antenna may reduce GPS accuracy noticeably. To be specific, in test Stage Three, during the tests conducted in Queen Street, the GPS devices sometime produced inaccurate position data and the GPS accuracy was degraded compared to the results from the tests performed in the Highbrook Industrial park. Moreover, some obstructions have the potential to block the GPS signals totally and it will result in the GPS device losing communication with the satellites. For instance, when I tested the accuracy inside my house in test Stage Four, the GPS devices sometimes received fairly weak signals and there were a few locations where signals were unavailable.

Regarding the relationship between weather conditions and GPS accuracy, three different kinds of GPS devices have been tested and tracked at the same time in varying weather. It was additionally noted that weather conditions (e.g. fog, rain, snow and so on) will not adversely influence the GPS equipment but it will cause reduced visibility of the satellite. A series of experiments discovered that the GPS device is able to produce high accuracy when the tests were conducted on a sunny days with a clear view of the sky.

6.1.2.2 GPS Technique employed

GPS accuracy is also highly dependent on hardware configuration of the GPS device. Two types of consumer grade GPS devices and a smart phone were used for testing in this research; the devices had different hardware configurations, such as Central Processor Unit, refresh rate on the screen, chipsets and so on. As expected, different levels of accuracy have been produced by each device. To sum up, more sophisticated hardware equipment is more likely to achieve better accuracy in a given environment. Additionally, the findings from all test stages prove that the quality of the GPS receiver also affects accuracy. The algorithms for processing GPS signals applied to the receiver might be different depending on the model of the GPS device. For applications where the accuracy is of paramount importance, the GPS user should choose the appropriate equipment to achieve the best GPS accuracy.

6.1.2.3 GPS Accuracy and Running Speeds

With the main objective of determining the most significant factors that have effects on GPS accuracy, I examined the test results to find out how the running speeds impact the accuracy. The study found that testing with combinations of the similar weather conditions, environmental factors, and hardware configuration produced different GPS accuracy depending on the different running speeds. However, only a few running speeds have been evaluated in this study; since accuracy was also impacted by a wide range of other factors, the finding indicates that the data patterns related to running speeds were quite dynamic.

6.2 LIMITATIONS OF RESEARCH

This project aimed to explore the potential relationships between a few factors and GPS accuracy by conducting four stages of tests. Although there were a number of limitations of this research, the findings based on the experiments were a considerable success. It is necessary to identify and acknowledge the limitations in order to evaluate the obtained research outcomes.

6.2.1 Scope of the research question

The research topic is very broad and there are many possible factors that may affect the GPS accuracy that are unknown. My research has only covered a few selected factors while other factors identified by other researchers could not be investigated in details. For practical reasons the study was focused on conducting the proposed experiments in order to achieve a broad view on the selected factors, instead of accomplishing an in-depth research of every single issue. Additionally, due to the time and resource limitations for this project, it would have been unlikely to conduct a detailed study of all factors.

6.2.2 Limitations of the research methodology

Certain limitations are inherent in the proposed research methodology. The first noticeable limitation was that the distance between the two observations points which was utilized to estimate the GPS accuracy could not be 100% accurate since restricted budget for this project led to using limited equipment for distance measurement. Consequently, the testing results of preliminary testing show an acceptable deviation between the real distance and the measured distance. Secondly, preliminary experiments in this research indicated that the hardware design of the GPS devices (such as CPU speed, size of memory, refresh rate on the device screen) will impact the accuracy under the same testing conditions. To address this, previous research studies have tested different consumer grade GPS devices to correctly determine the accuracy of GPS measurement. Interestingly, more sophisticated methods have been applied by other researchers who developed software to differentiate the factors related to hardware design and introduced calculations to handle these factors. Due to the limitation of time and budget, this study focused on the test results from three GPS devices available on the New Zealand market. This research includes a critical review of relevant academic literature and previous research studies, but the lack of an established approach for analysing the acquired data is another factor that limits the usefulness of the test results. To overcome this limitation, previous researchers had developed their own algorithms based on the parameters used in their experiments. In order to make use of my own test results, I developed an approach to analyse and interpret the testing data premised on my testing outputs and the mean deviation value was introduced in Chapter 5 to approximately estimate the GPS accuracy.

6.2.3 GPS accuracy is affected by environmental conditions

The environmental conditions have a powerful influence on the GPS signal. This could cause loss of coordinate data and inconsistent data during the data collection phase in this research. The environmental conditions not only include the test location (such as dense urban area, indoor, tree canopy environment and so on), but also include the weather conditions (for example sunny, rainy and so on). Handling data with poor quality has been a challenge in this research area. However, this issue was poorly identified in the existing research papers and it was outside the scope of my project to come up with solutions for dealing with inconsistent or lost data. In order to minimize the impact of this issue in my research, I have used the previous value or an assumed value to fill in the missing data and the case of short test path. Moreover, the test scenarios were repeated to ensure good quality of data. Nevertheless, there were a few arbitrary values in my dataset and the test results may vary had the missing data been present. It will be necessary to attend to the management of data quality in future research.

Additionally, since a student researcher has restricted resources and time, all experiments in my project were conducted in one of the cities in New Zealand, whereas the reviewed studies were drawn on research from several different countries. Auckland's unique climate and geographic conditions limits the scalability of the testing methodology and it was almost impossible for me to collect data in different kinds of environmental conditions, such as performing the tests on a snowy day or testing in the forest. Since it has been important to manage the scope of the testing, this project attempted to simplify the problem statement and used the set of attainable environmental factors defined in other similar research studies to explore the potential associations between these factors and GPS accuracy. As mentioned in Chapter 4, the tests were only held in tree canopies area (One Tree Hill), urban arterials (Highbrook Industrial park), dense urban location (Queen Street in Auckland) and indoor environment (inside my house). The weather conditions within the scope of this research are sunny, cloudy and rainy.

6.3 FUTURE RESEARCH

This study has investigated the potential relationships between a number of factors and the level of accuracy of GPS measurements. During the research, several possible issues for future research were highlighted as discussed below.

6.3.1 Environmental conditions and GPS accuracy

An exceptionally important issue to further investigate in future research is the effect of environmental factors on the GPS accuracy. It is clear from the research findings that the environmental conditions could affect the GPS performance significantly. For example, we know that the canopy environment is arguably the most challenging area to achieve good GPS accuracy. Typically, in a heavily tree-covered area, the GPS signal will be not captured that well, and therefore due to the poor GPS performance there is high probability of data loss. In this research, all experiments have been conducted to investigate the variation of canopy cover in Auckland. Consequently, future research should focus on other environmental conditions affecting the accuracy, especially the worst conditions such storms or conducting experiments in the rainforests. Moreover, it would also be helpful to have further investigation into how these factors impact the GPS accuracy.

6.3.2 GPS and digital forensic investigation

Another major area of much needed attention is the use of the GPS devices for assisting digital forensic investigations. Nowadays, with different hardware and software innovations, GPS applications are becoming more affordable and can be used much more widely. Since GPS devices not only store navigational data, but also contain other historical data (such as user's location, distance, time, running speed and so on) that could be used in a number of ways. In digital forensics context, the GPS records can be used by the forensic investigator to determine the geographical positions of the suspected person on a particular date and time. However, as mentioned earlier in this thesis, GPS tracking and measurement may not be 100 % accurate as the GPS performance is influenced by a number of factors. Additional features can be developed in the GPS devices to improve the GPS accuracy. For example, it would be good if the GPS device could provide additional capabilities such as managing the missing data when the signal lost. Further work is also necessary to ensure that the evidence extracted from GPS devices could be accepted by the existing forensic principles and can be relied upon in court. GPS was not originally designed for digital forensic use and what kinds of information can be acquired form the GPS depends on the capabilities of the devices. Accordingly, forensic investigators will be required to use some basic techniques and standardized approaches as their procedural guidance for the extraction and interpretation of digital evidence from GPS devices.

Another direction for further development that will be useful is the advancement in specific software applications that are able to extract trusted digital evidence from GPS devices based on forensically robust processes. Further study should be undertaken for the development of proprietary applications for the existing GPS devices. Moreover, there are a number of brands and models of GPS devices on the market and these devices are normally region specific. Hence, the market for GPS in New Zealand will be different from the markets in other countries. Additional research could investigate the development of specialized applications for GPS devices that are popular in New Zealand; the outcomes from such research will definitely give some guidance for the New Zealand's forensic investigators. For example, Navman EZY45 was used in this research and the GPS devices of this brand have been widely used by New Zealanders for navigation. While most of the recent forensic studies related to GPS have concentrated on the exploration of TomTom GPS, there have been very few studies related to Navman GPS devices. More laboratory investigation into the use of Navman GPS in forensics will be required in the future research.

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APPENDIX

APPENDIX A: TESTING SETUP

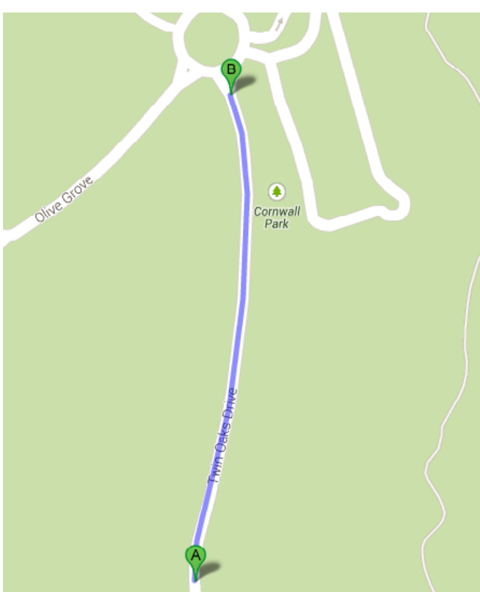
<u>Research Testing: Stage One</u>

Testing Specification:

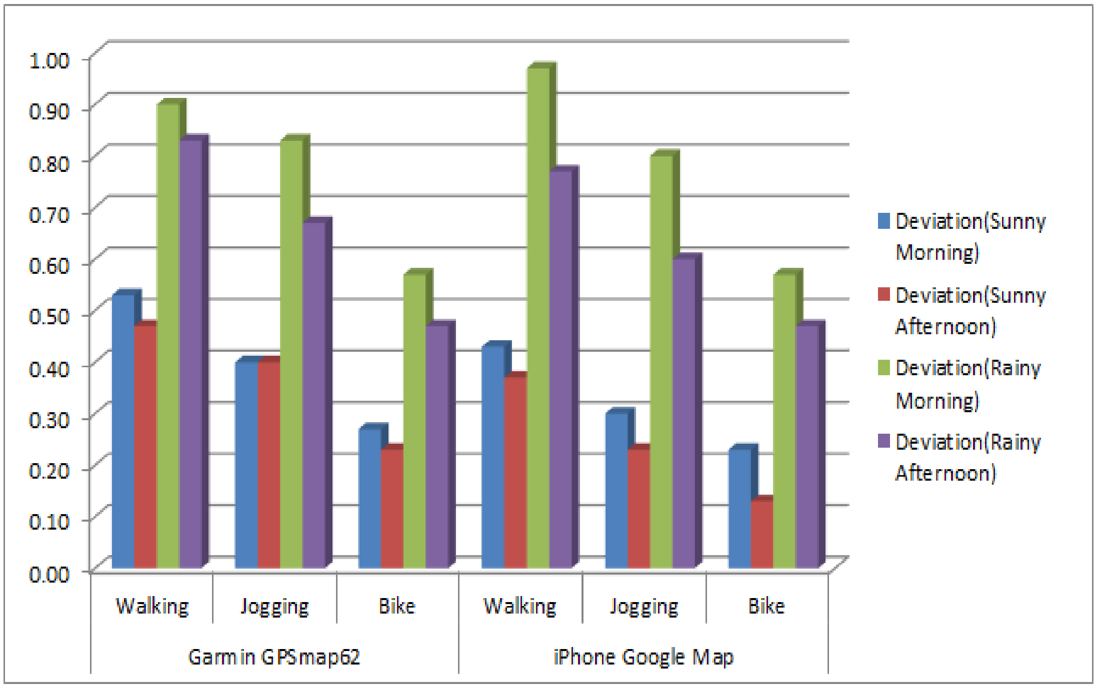
Testing Location	Twins Oak Drive in One Tree Hill
Testing method	Walking, Jogging, Riding a bike
Environmental condition	0% canopy opened (Tree Canopies Area)
Actual Distance	450 Meter
GPS Device Model	Garmin GPSmap62; iPhone Google Map

Test	Weather	Testing Date	Testing Time
1	Sunny	5th January 2013	Morning
2	Sunny	5th January 2013	Afternoon
3	Rainy	17th March 2013	Morning
4	Rainy	31st March 2013	Afternoon

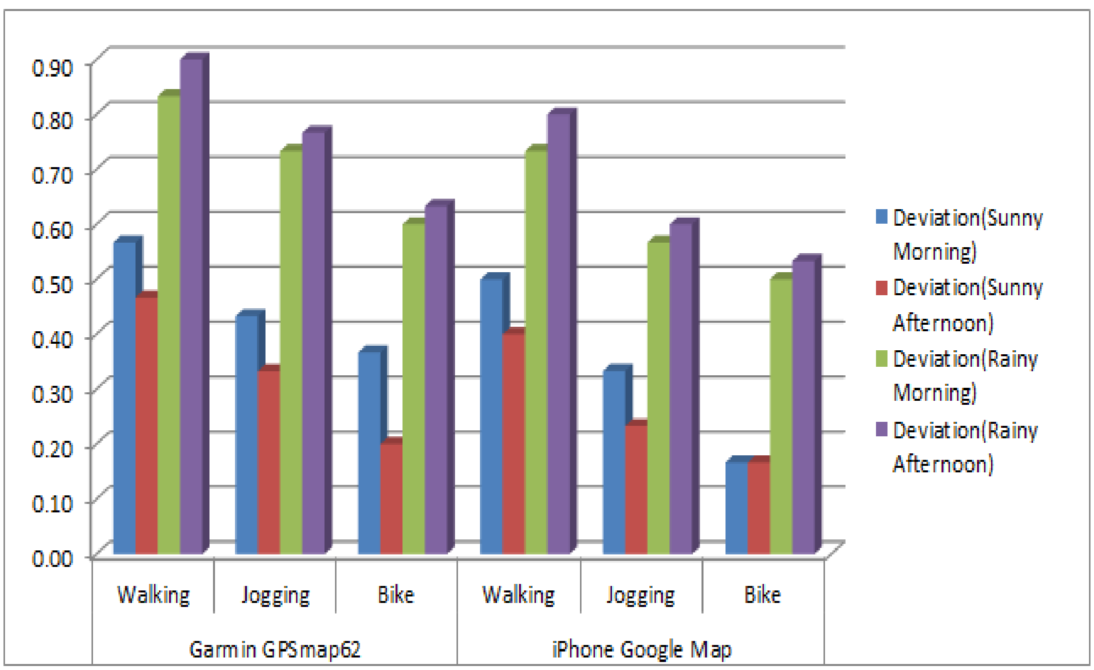
Testing Path:



Comparison of Deviation Values for Test stage 1:



Comparison of Deviation Values for Repeated Test stage 1:



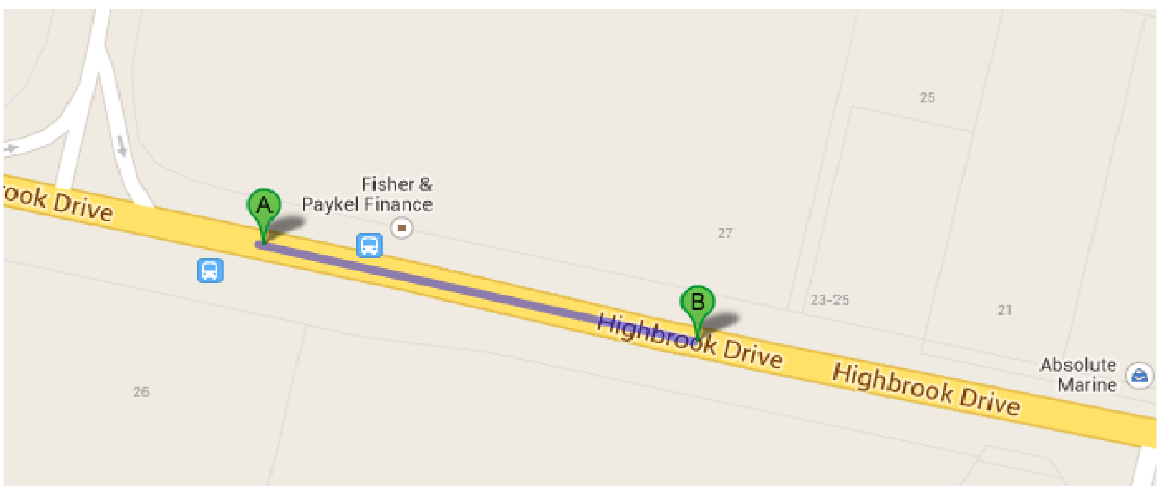
Research Testing: Stage Two

Testing Specification:

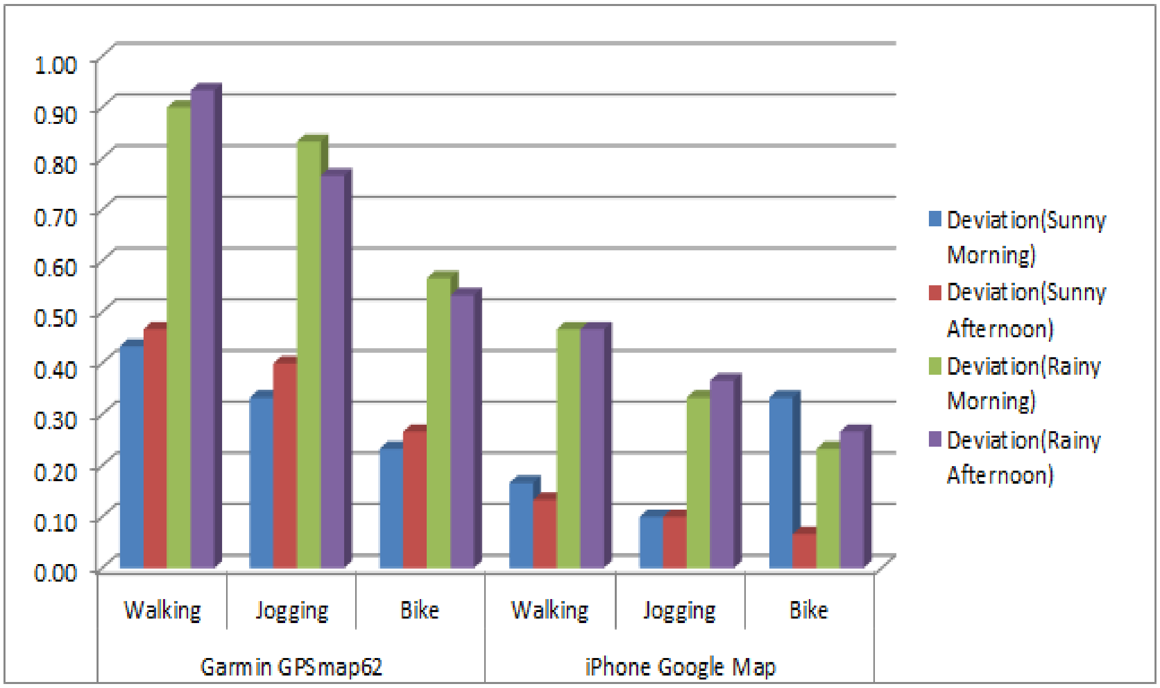
Testing Location	Highbrook Drive in Highbrook Industrial Park
Testing method	Walking, Jogging, Riding a bike
Environmental condition	100% canopy opened (Urban Arterial)
Actual Distance	200 Meter
GPS Device Model	Garmin GPSmap62; iPhone Google Map

Test	Weather	Testing Date	Testing Time
1	Sunny	22nd December 2012	Morning
2	Sunny	22nd December 2012	Afternoon
3	Rainy	4th February 2013	Morning
4	Rainy	10th April 2013	Afternoon

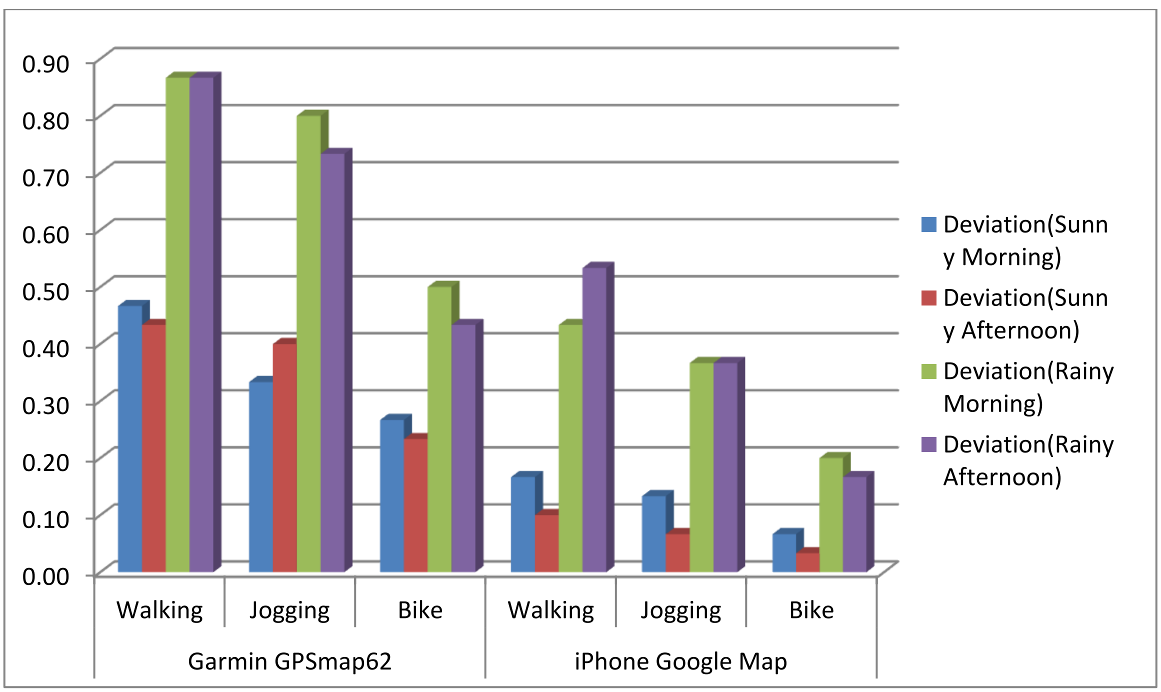
Testing Path:



Comparison of Deviation Values for Test stage 2:



Comparison of Deviation Values for Repeated Test stage 2:



Research Testing: Stage Three

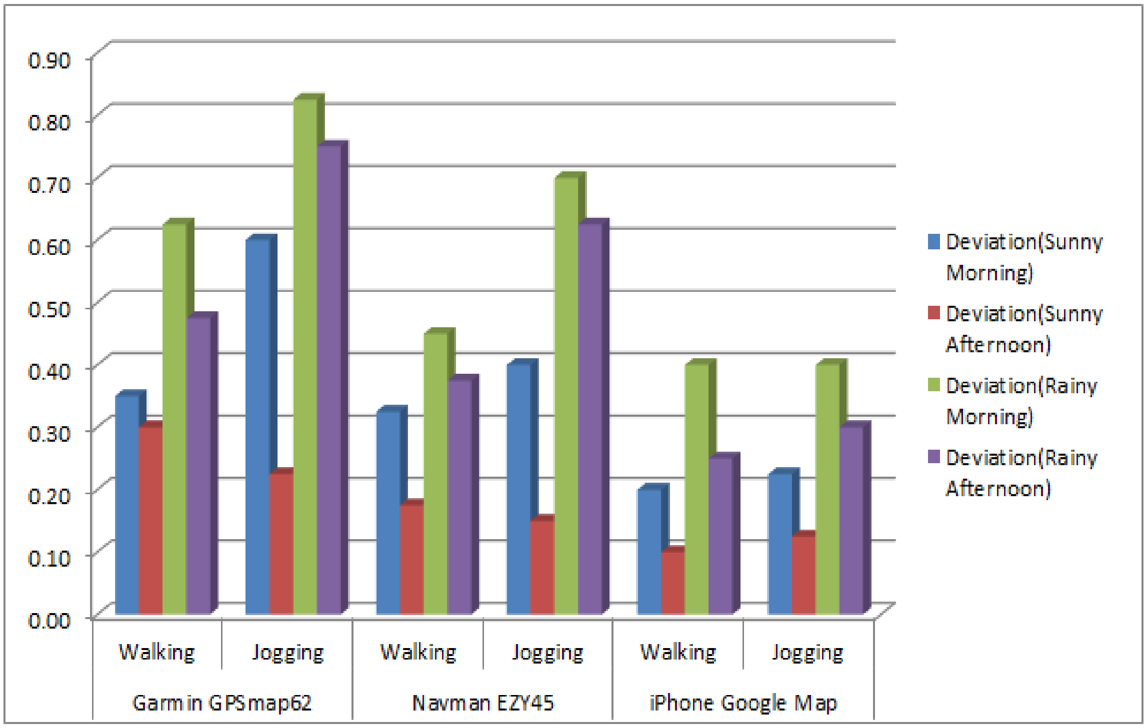
Testing Specification:

Testing Location	Queen Street in Auckland CBD
Testing method	Walking
Environmental condition	In the city which have different percentage of canopy open
Actual Distance	1505 Meters
GPS Device Model	Garmin GPSmap62; Navman EZY45; iPhone Google Map

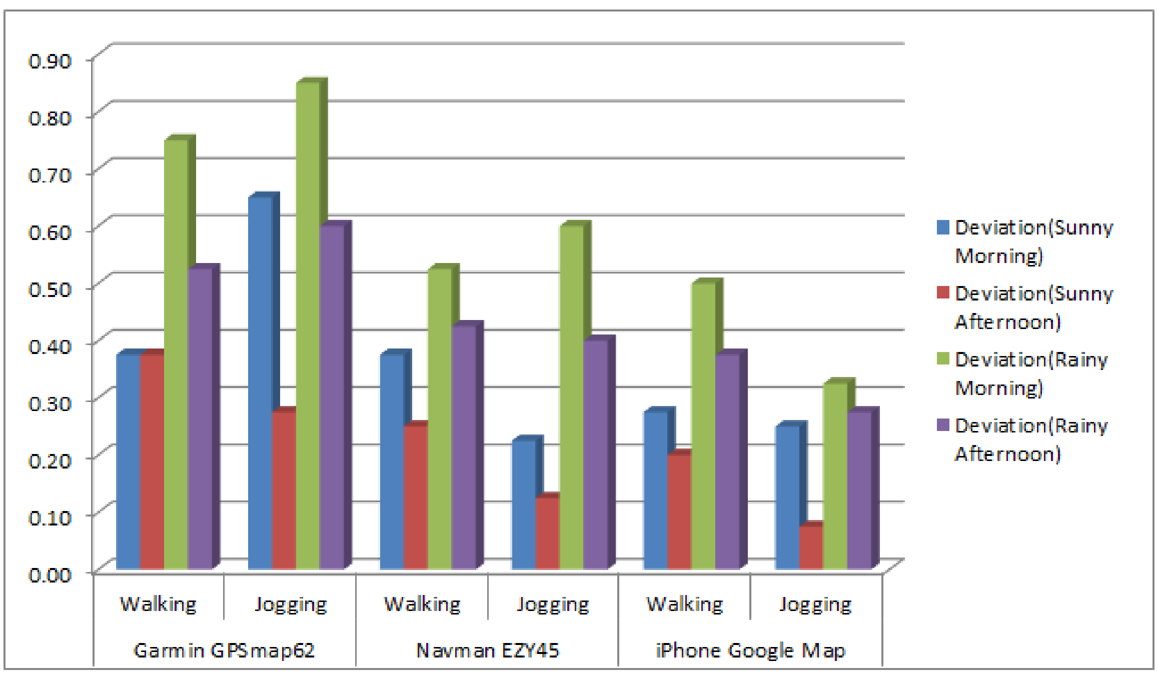
Test	Weather	Testing Date	Testing Time
1	Sunny	1st December 2012	Morning
2	Sunny	1st December 2012	Afternoon
3	Rainy	16th December 2012	Morning
4	Rainy	16th December 2012	Afternoon

Testing Path:

Comparison of Deviation Values for Test stage 3:



Comparison of Deviation Values for Repeated Test stage 3:



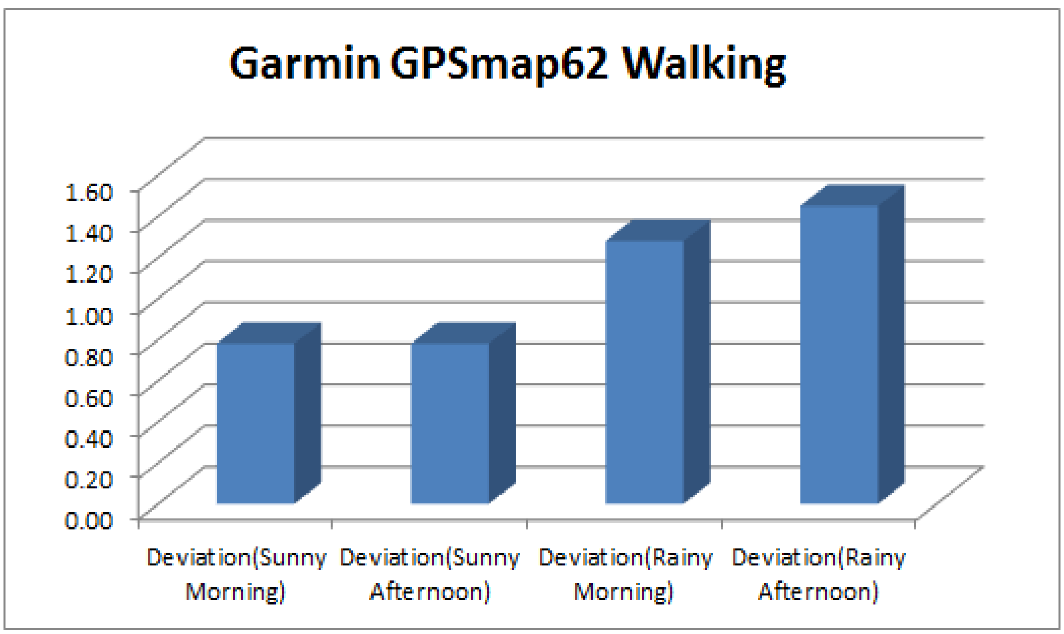
Research Testing: Stage Four

Testing Specification:

Testing Location	Inside my house
Testing method	Walking
Environmental condition	Indoor environment
Actual Distance	6 Meters
GPS Device Model	Garmin GPSmap62

Test	Weather	Testing Date	Testing Time
1	Sunny	8^{th} December 2012	Morning
2	Sunny	8^{th} December 2012	Afternoon
3	Rainy	25^{th} December 2012	Morning
4	Rainy	25^{th} December 2012	Afternoon

Comparison of Deviation Values for Test stage 4:



Comparison of Deviation Values for Repeated Test stage 4: