Precise Positioning in Real-Time using GPS-RTK Signal for Visually Impaired People Navigation System

A Thesis Submitted for the Degree of Doctor of Philosophy

By

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Abstract

This thesis presents the research carried out to investigate and achieve highly reliable and accurate navigation system of guidance for visually impaired pedestrians. The main aim with this PhD project has been to identify the limits and insufficiencies in utilising Network Real-Time Kinematic Global Navigation Satellite Systems (NRTK GNSS) and its augmentation techniques within the frame of pedestrian applications in a variety of environments and circumstances. Moreover, the system can be used in many other applications, including unmanned vehicles, military applications, police, etc. NRTK GNSS positioning is considered to be a superior solution in comparison to the conventional standalone Global Positioning System (GPS) technique whose accuracy is highly affected by the distance dependent errors such as satellite orbital and atmospheric biases.

Nevertheless, NRTK GNSS positioning is particularly constrained by wireless data link coverage, delays of correction and transmission and completeness, GPS and GLONASS signal availability, etc., which could downgrade the positioning quality of the NRTK results.

This research is based on the dual frequency NRTK GNSS (GPS and GLONASS). Additionally, it is incorporated into several positioning and communication methods responsible for data correction while providing the position solutions, in which all identified contextual factors and application requirements are accounted.

The positioning model operates through client-server based architecture consisted of a Navigation Service Centre (NSC) and a Mobile Navigation Unit (MNU). Hybrid functional approaches were consisting of several processing procedures allowing the positioning model to operate in position determination modes. NRTK GNSS and augmentation service is used if enough navigation information was available at the MNU using its local positioning device (GPS/GLONASS receiver).

The positioning model at MNU was experimentally evaluated and centimetric accuracy was generally attained during both static and kinematic tests in various environments (urban, suburban and rural). This high accuracy was merely affected by some level of unavailability mainly caused by GPS and GLONASS signal blockage. Additionally, the influence of the number of satellites in view, dilution of precision (DOP) and age corrections (AoC) over the accuracy and stability of the NRTK GNSS solution was also investigated during this research and presented in the thesis.

This positioning performance has outperformed the existing GPS service. In addition, utilising a simulation evaluation facility the positioning model at MNU performance was quantified with reference to a hybrid positioning service that will be offered by future Galileo Open Service (OS) along with GPS. However, a significant difference in terms of the service availability for the advantage of the hybrid system was experienced in all remaining scenarios and environments more especially the urban areas due to surrounding obstacles and conditions.

As an outcome of this research a new and precise positioning model was proposed. The adaptive framework is understood as approaching an integration of the available positioning technology into the context of surrounding wireless communication for a maintainable performance. The positioning model has the capability of delivering indeed accurate, precise and consistent position solutions, and thus is fulfilling the requirements of visually impaired people navigation application, as identified in the adaptive framework.

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Abbreviations and Acronyms

3G	Third Generation mobile systems
3GPP	3rd Generation Partnership Project
3GPP2	3rd Generation Partnership Project 2
A-GPS	Assisted-GPS
AOA	Angle Of Arrival
bps	bit per second
BNG	British National Grid
BNSB	Brunel Navigation System for Blind
BOC	Binary Offset Carrier
CDMA	Code Division Multiple Access
CN	Core Network
CoO	Cell of Origin
CS	Commercial Service
DAB	Digital Audio Broadcast
DGPS	Differential GPS
DL	Down-Link
DoD	Department of Defence
DOP	Delusion Of Precision
DRMS	Distance Root Mean Square
DR	Dead Reckoning
DS2DC	Data Server to Data Client Protocol
ECEF	Earth-centred Earth-fixed
EC	European Commission
EDGE	Enhanced Data Rate for GSM Evolution
EDAS	EGNOS Data Access System
EGNOS	European Geostationary Navigation Overlay Service
ESA	European Space Agency
ESRG	Electronic Systems Research Group
E-OTD	Enhanced Observed Time Difference
GALILEO	the European global navigation satellite system
GBAS	Ground-Based Augmentation System

GDOP	Geometric Dilution of Precision
GDGPS	Global Differential GPS System
GEO	Geostationary
GIS	Geographical Information Systems
IVE	Ionospheric Vertical Error
GIVE	Grid Vertical Ionospheric Errors
GLONASS	Global Navigation Satellite System
GNSS	Global Navigation Satellite Systems
GPRS	General Packet Radio Service
GPS	Global Positioning System
GSM	Global System for Mobile
GSSF	Galileo Simulation Service Facility
HDOP	Horizontal Delusion Of Precision
HS-GPS	High Sensitivity GPS
HSCSD	High Speed Circuit Switched Data
HSDPA	High Speed Downlink Packet Access
HSGPS	High Sensitivity GPS
HSPA	High Speed Packet Access
HSUPA	High Speed Uplink Packet Access
HTML	Hypertext Markup Language
HOW	Hand Over Word
ICMP	Internet Control Message Protocol
ICT	Information and Communication Technology
IDGPS	Inverse DGPS
IF	Integrity Flag
IGPs	Ionospheric Grid Points Mask
IIS	Internet Information Service
IMT-2000	International Mobile Telecommunication in the year 2000
INS	Inertial Navigation System
IOD	Issue Of Data
IMS	Integrity Monitoring Station.
IPP	Ionospheric Pierce Point
IRM	Intelligent Resource Monitor
ITU	International Telecommunication Union

JPL	Jet Propulsion Laboratory
Kbps	kilobits per second
KB/s	Kilo byte per second
KF	Kalman Filter
LAN	Local Area Network
LADGPS	Local Area DGPS
LBS	Location Based Service
LORAN	Long Range Aid to Navigation
LS	Localisation Server
LTE	Long Term Evolution
MCS	Master Control Stations
MCC	Mission Control Centres
Mbps	Mega bit per second
MB/s	Mega byte per second
MEMS	Micro-Electro Mechanical Sensor
MEO	Medium-Earth Orbit
ME	Mobile Equipment
MI	Misleading Information
MOPS	Minimum Operational Positioning Standards
MoBIC	Mobility of Blind and Elderly People Interacting with Computers
MT	Mobile Terminal
MU	Mobile Unit
Node B	Base Station
NLES	Land Earth Stations.
NMEA	National Marine Electronics Association
NRTK	Network Real Time Kinematics
NSP	Navigation System Precision.
Ntrip	Network Transport of RTCM via Internet Protocol
OGC	International OpenGeospatial Consortium
OS NET	Ordinance Survey network
OS	Open Service
PA	Precision Approach
PDA	Personal Digital Assistant
PDOP	Position Delusion Of Precision

PGS	Personal Guidance System
PE	Positioning Error
PRR	Position Response Rate
PRS	Public Regulated Service
PRC	Pseudo-Range Corrections
PS	Packet Switched
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RDS	Radio Data System
RDG	Raw Data Generation
RFMD	Russian Federation
RFID	Radio Frequency Identification
RMS:	Root Mean Square
RINEX	Receiver Independent Exchange
RNIB	Royal National Institute for Blind
RSSI	Received Signal Strength Indicator
RSA	Russian Space Agency
RTK	Real Time Kinematics
RTCA	Radio Technical Commission for Aeronautics
RTCM	Radio Technical Commission for Maritime
RTT	Round-Trip Time
SAR	Search and Rescue
SBAS	Satellite Based Augmentation Systems
SPS	Standard Positioning Service
SISNET	Signal in Space through the Internet
SISA	Single in Space Accuracy
SISE	Single in Space Error
SISMA	Signal-In-Space Monitoring Accuracy
SINCA	SISNET Compression Algorithm
SLS	Safety-of-Life Service
SMS	Short Message Service
SVS	Service Volume Simulation
TDMA	Time Division Multiple Access
TDOA	Time Difference Of Arrival

TOA	Time Of Arrival
TTFF	Time to First Fix
TVE	Tropospheric Vertical Error
UAS	User Application Software
UDRE	User Data Range Error
UERE	User Equivalent Range Error
UIRE	User Inospheric Range Error
UL	Up-Link
UMTS	Universal Mobile Telecommunication System
UTRAN	UMTS Terrestrial Radio Access Network
VDOP	Vertical Delusion Of Precision
VPL	Vertical Protection Levels
VRS	Virtual Reference Station
WADGPS	Wide Area DGPS
WAAS	Wide Area Augmentation System
WAP	Wireless Application Protocol
WCDMA	Wideband Code Division Multiple Access
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network
WML	Wireless Markup Language
WPAN	Wireless Personal Area Networks
WWAN	Wireless Wide Area Network

List of Symbols

Symbol	Description	Symbol	Description
e_{pos}	Positioning error	a_{f1}	Satellite Clock drift
σ^2	Error variance	β	Baseline matrix
MF	Mapping function	S_{east}	Partial derivatives of the easting error
E	Elevation angle	S_{north}	Partial derivatives of the northing error
X	Vector holding user's position coordinates	S_U	Partial derivatives of the height error
X_0	Vector holding initial user's position coordinates	S_t	Partial derivatives of the time bias
$\tilde{X}$	Vector holding user's corrected position coordinates	w	Pseudo-range weight
$\Delta\tilde{X}$	Position coordinate corrections	$K_{H,NPA}$	Horizontal integrity multiplier
H	GPS observation matrix	$K_{V.Ped}$	Vertical integrity multiplier
P	Pseudo-range measurements	d_{east}^2	Variance in the easting protection distribution
ρ_i	Geometric range	d_{north}^2	Variance in the northing protection distribution
δP	Vector of pseudo-range corrections	d_U^2	Variance in the height protection distribution
p	Pressure	ϕ_{IPP}	IPP latitude
p_m	Pressure at mean sea level	λ_{IPP}	IPP longitude
$PRC\nabla_{i,j}$	linearly interpolated PRC	ψ_{IPP}	Angle between the user position and pierce point.
$PRCsc$	Scalar PRC	R_e	Earth's ellipsoid radios
$PRC_{Integrate}$	integrated PRC	A	Azimuth angles
PRC_{fast}	Fast pseudo-range corrections	A_1	Night time constant

PRC_{iono}	Ionospheric pseudo-range corrections	A_2	Amplitude term
PRC_{tropo}	Tropospheric pseudo-range corrections	A_3	Phase term of cosine wave
PRC_{clock}	Clock pseudo-range corrections	A_4	Period term of cosine wave
h_I	Height of the maximum electron density	F_{pp}	Obliquity factor
h_s	height of the observation station	λ	Water vapor lapse rate
h_d	Height of dry troposphere layer	c	Speed of light
h_w	Height of wet troposphere layer	e	relative humidity
h_m	Height above mean sea level	τ_v	Interpolated GIVE
T_{GD}	Group delay correction	τ_{vpp}	Final interpolated zenith ionospheric delay ($UIVE$)
T	Temperature	τ_{trop}	Tropospheric zenith delay
T_m	Temperature at mean sea level	$\tau_{trop,d}$	Dry component tropospheric zenith delay
Td	Slant tropospheric delay	$\tau_{trop,w}$	Wet component tropospheric zenith delay
ΔT_{ion}	User slant ionospheric delay	ΔI	Filtered ionospheric delay
ΔT_{ion}^{v}	Vertical ionospheric delay (Klobuchar model)	IC	Final ionospheric correction
t_0	Time applicability of the day	x_k	KF process state
t_u	User's time offset	w_{k-1}	KF process noise vector
t_{sv}	SV code phase time	v_k	Measurement-noise vector
Δt_{sv}	SV code phase time offset	p_{DR}	DR position solution
Δt_r	Relativistic effects	v_{DR}	DR velocity solution
t_{oc}	GPS Reference time	z_k	KF measurement vector
a	Matrix holding reference station coordinates	z_{dry}	Zenith dry delay at mean sea level
a_{f0}	Satellite Clock bias	z_{wet}	Zenith wet delay at mean sea level

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Chapter 1

1. Introduction

1.1 Introduction

Mobile and wireless communication technologies are undergoing rapid advancements and moving towards a new age that is characterised by the seamless cooperation of heterogeneous systems; the necessity of high speed communication when being on the move and advanced services with quality guarantees. This has been accompanied by the advancement and evolution of the Internet and satellite communications, and motivated by the increasing demand to access more compressed data.

As a result, mobile technology became a medium not only for voice and Short Messages Services (SMS), but for rich data transmissions such as video, Web browsing, and other multimedia contents. Moreover, in developing countries where people require fast deployment and low expenses for broadband wireless Internet services, hand mobile and wireless communications technology is becoming more crucial. The arrival of broadband and multimedia mobile networks along with effective handsets, embedded with location sensing technologies, has produced a variety of new mobile services. Satellite-based positioning is becoming increasingly important in our lives. It is used currently in many sectors of transport, security, surveillance, industry, research and leisure.

In general terms, navigation service means determining a precise location and providing required guidance on the route to a desired destination. Navigation systems have been found useful in many applications; vehicles, marine navigation, aviation, outdoor recreation, or guidance of visually impaired people.

Several techniques have been developed for position determination over the past century. At the present time it can be said that the most popular techniques are satellite-based radio-navigation systems. Due to the popularity of guidance systems in various applications, many receivers have become smaller, their price has become more affordable, and they provide better performance. Consequently, recent applications in personal navigation systems have become interesting.

There are a number of position determination methods in existence that can be divided into two main categories: network-based positioning systems utilising short and wide range wireless networks, and handset-based positioning systems, such as the Global Navigation Satellite Systems (GNSS). One of the most well-known systems in GNSS is the Navstar Global Positioning System (GPS), developed by the U.S. Department of Defense (DoD, 2004). It is considered to be the most promising and widely-deployed positioning method in use. The GPS can locate and guide you anywhere in the globe with a very high level of accuracy.

However, this situation, the dominance of GPS, is about to change: Russian GLONASS (GLONASS, 2010) is being revitalised after a long period of degradation. In addition, the European Union (EU), together with the European Space Agency (ESA, 2010), has agreed to build its own GNSS, named Galileo (European Commission, Enterprise and Industry, 2010). China has announced plans to continue elaborating its regional BeiDou navigation system (BeiDou, 2010), and it is expected to expand and eventually provide global coverage. Additionally, India and Japan are also establishing their own systems to complement and augment existing and future GNSS.

Several applications require the integration of different technologies to become reality. An excellent example is the vehicle tracking system. This system enables users to track vehicles remotely on a digital map installed on their personal computers. The system requires other types of technologies in conjunction with the GPS, including mobile networks technologies, Geographical Information Systems (GIS), and Information Technologies (IT). All of these technologies have enabled the use of tracking systems (Hunaiti, 2005). Similar to the tracking system idea, a new system has been designed and developed at Brunel University. This system integrates GPS, 3rd Generation mobile technology (3G), and Geographic Information System (GIS). It enables remote tracking of visually-impaired pedestrians based on GPS location and a live video image. The system's primary goal is to assist in navigating visually-impaired people using visually able people as guides. Such a system can also be used in many other highly-complicated applications, such as unmanned vehicles, emergency tracking, fire fighters, battlefield operations and many other applications that need both video imagery and GPS location data (Hunaiti et al., 2004). The positioning performance of GPS and wireless communication is a crucial attribute for the quality of guidance. Therefore, it has become an accepted practice to continually develop new techniques augmenting the positioning services of GPS to advanced and sustainable levels.

The technology behind navigation, jointly with the development of communication services, has received a considerable attention varying from the improvement of positioning techniques, the prevalent and development of geospatial databases, as well as Geo-visualisations and methods of data presentation. This also exploited areas of developing accurate and more sophisticated receivers for position determination using Real Time Kinematic or the Network Real Time Kinematic GNSS.

GPS on its own do not guarantee accuracy in centimetres (Martin et al., 2000). Differential GPS technique is required in order to have more accurate positioning data. This technique allows even centimetre level accurate positioning using the so-called ‘integer ambiguity resolution technique’. The basic concept of differential technique is to mitigate the main error sources, such as ionospheric and tropospheric delay, orbit errors and satellite clock errors by receiving satellite signals at a well-known location. All common errors between this reference receiver and the user receiver are cancelled out (Landau et al., 2001). At the moment, this differential technique is used in real time as well as after the actual processing of data; and real-time data transfer is routinely possible, which enables real time computation of baseline vectors (Hofmann-Wellenhof et al., 1997) and has led to the Real-time Kinematic (RTK) technique**.**

Real Time Kinematic technique or RTK is a GPS mode that is broadly employed for accurate positioning applications. It was invented in 1990’s to find the optimal way of processing reference receiver data, and then providing “correction” information to users, in real time. This practice is known as RTK Surveying (Rizos and Han, 2003). RTK has several requirements such as one reference receiver to be located at a base station whose coordinates are known in a geocentric reference frame, so that the second roving receiver's coordinates are determined relative to this first reference receiver. Algorithms in the mobile control devices merge the reference station data with the roving GPS measurements to resolve the integer ambiguity that is essential for calculating precise ranges from the GPS carrier phase measurements. RTK can provide centimetre position accuracy, though the accuracy and reliability of the standard RTK solution decreases with increasing distance from the reference station (Wübbena et al., 1996). Network-based Real Time Kinematic (NRTK) GPS positioning is regarded as an advanced solution as compared to the previous single reference station based Real Time Kinematic (RTK) GPS positioning technique and satellite orbital and atmospheric biases are greatly affected by the distance reliant errors causing inaccuracy. NRTK GPS positioning uses unprocessed measurements collected from a network of Continuously Operating Reference Stations (CORS) one by one to produce more dependable error models that can tone down the distance dependent errors inside the region enclosed by the CORS. This procedure has been developed and checked significantly in recent years and compared to the usual RTK GPS positioning technique. Its performance is better in terms of precisions that can be achieved, dependability and mobility. This procedure is referred to as augmentation technique.

The augmentation techniques, also known as Differential GPS (DGPS) systems, operate in general over diverse coverage ranges, such as Local Area DGPS (LADGPS) and Wide Area DGPS (WADGPS). By way of using a number of interconnected DGPS references stations, or as Satellite-Based Augmentation System (SBAS), using Geostationary (GEO) satellites, WADGPS can be implemented as network-based DGPS systems. A number of empirical studies have been conducted in order to study the positioning performances achieved after employing these differential systems (Wolfson et al., 2003; Filjar and Huljenić, 2003; Oh et al., 2005; Filjar et al., 2007).

1.2 Motivation and Background

It has emerged that there is severe limitation in mobility found in the visually impaired people, the main reason for this is the major reduction in the ability or the complete inability, as found in many cases, in utilizing the sense of vision in the process of perception and acquisition of the spatial information needed to navigate the environment successfully (Jansson, 1995).

The visually impaired people require parallel support in both of the two basic navigational domains in order to become mobile (Petrie *et al.*, 1997; Guth and Rieser, 1997). In the first place, there is a requirement of some form of assistance in the domain of micro-navigation, which implies that in the immediate travel environment, there should be avoidance of obstacles and other hazards. In the second domain, there is a requirement of a type of assistance in the domain of macro-navigation, which implies the directing of locomotion while being on a route to a destination in a distant and not in the immediate detectable environment (Garaj, 2006).

Over the period of time, there has been several methods proposed in order to provide assistance in the mobility of visually impaired people; for example, *Design of the System for Remote Sighted Guidance of Visually Impaired Pedestrians* (Garaj, 2006) and *A Remote Vision Guidance System for Visually Impaired Pedestrians* (Hunaiti, 2005). Although, up to present, there has not been offered a totally suitable response for their mobility requirements. There are only three methods, which have been established completely as well as been widely utilized, they are the provision of guidance by a sighted human guide and the guidance provided with the use of long cane and a guide dog. For centuries, these three have been in use and also these methods are the oldest mobility-aiding methods.

In order to enable efficient deliverability of a guidance system to mobile users, the demand for reliable and exact position solutions has increased after the proliferation of the wireless technology and the improvement of GNSS in various important applications such as the mobile guides, emergency tracking and even elderly people. This may also involve the delivery on-time of the medical services in various locations and under different conditions. Thus, there is a persistent as well as necessary requirement for assured alternatives and the enhanced positioning services, which are able to deliver current as well as accurate information needed for the fulfilment of the various prerequisites of these essential applications.

Therefore, there has been several research projects carried out for the development of the mobility aids for the pedestrian users, that is for the visually impaired and elderly people, aiming to bring improvement in their mobility (Helal et al., 2001; MoBIC, 2004; Jackson, 2006; Pressl & Weiser, 2006).

Additionally, the Electronic System Research Group (ESRG) at Brunel University was one of the pioneering research groups with its visually impaired guidance navigation project established in 1995 (Balachandran and Langtao, 1995). The idea was to investigate the possibility of using GPS to navigate and guide visually impaired pedestrians based on a client-server-based approach. Accordingly, a novel system was developed, described as Brunel Navigation System for the Blind (BNSB), as shown in Figure 1.1. BNSB consists of two main terminals: a client (mobile terminal), which is located at the site of the visually impaired user and a server (stationary terminal), which is located at the site of the sighted guide who provides the client with location information and the routing to the destination. The client consists of a GPS receiver, a digital camera, a speaker, a microphone and a wireless communication interface. The server consists of a number of workstations equipped with a customised GIS database. The BNSB has undergone several development phases enhancing its usability, user localisation performance and communication quality (Liu, 1997; Shah, 1999; Ptasinski et al., 2000; Jirawimut et al., 2001; Garaj et al., 2003; Hunaiti et al., 2005; Hunaiti et al., 2006; Garaj, 2006 and Al Nabhan, 2009).

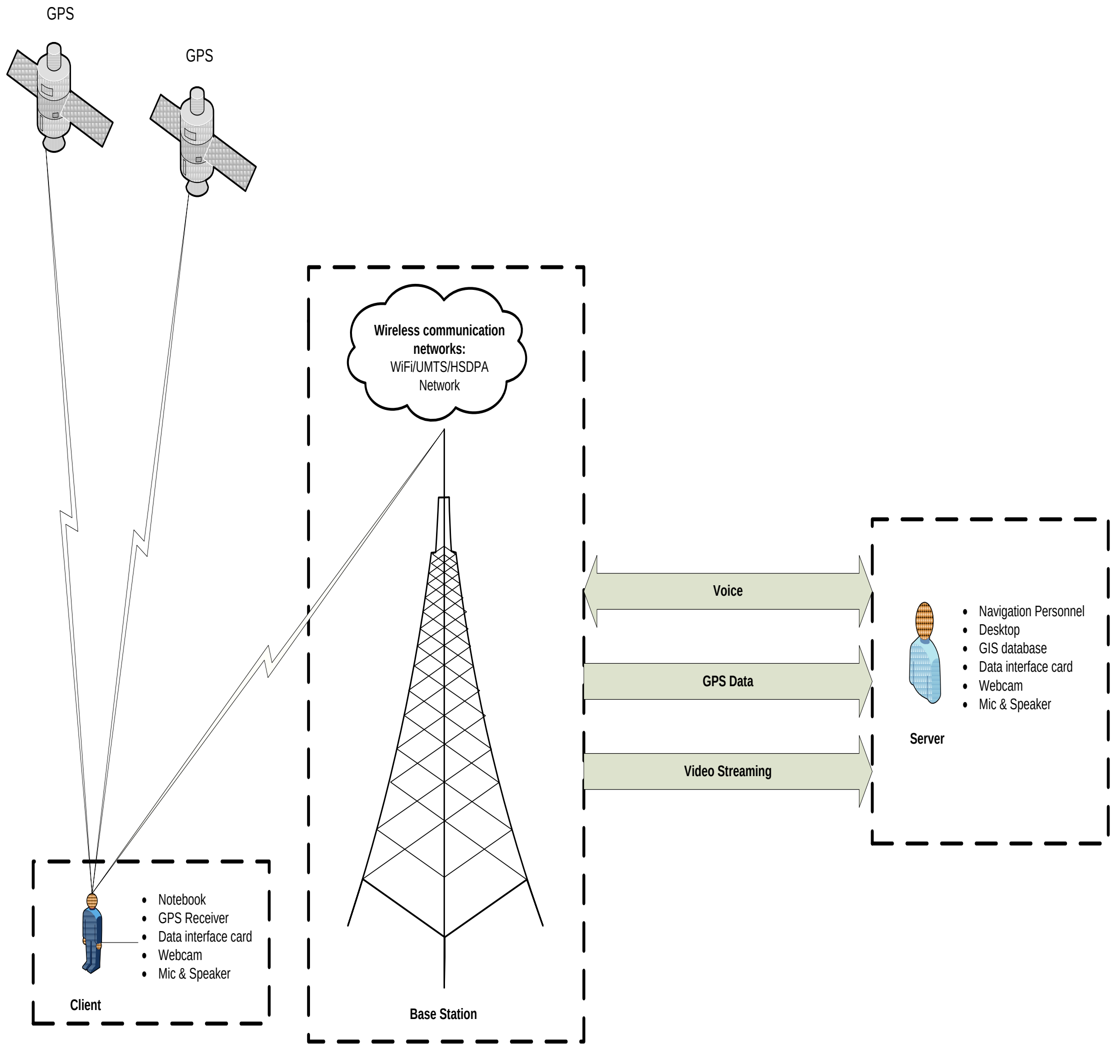

Figure 1.1: Brunel Navigation System for the Blind (BNSB).

In most of these fundamental studies, satellite positioning based on GPS was considered the most widely deployed positioning method according to its service availability and coverage, along with its simple and free accessibility compared to other positioning techniques. However, satellite positioning is affected from the navigation environments and physical surroundings, which limits the availability of line-of-sight satellite signals required for fixing a position solution. A number of augmentation solutions were developed allowing users to achieve different levels of accuracy (Kaplan and Hegarty, 2006). At present, highest accuracies are achieved in the relative positioning mode with observed carrier phases. Processing a baseline vector requires the phases be simultaneously observed at both baseline endpoints. Originally, relative positioning was only possible by post-processing data. These days, it is routinely possible with real-time data transfer over short baselines, which in turn allows real-time computation of baseline vectors, and has led to the Real-Time Kinematic (RTK) technique.

In this research work, the need for a simple and reliable wireless technology and augmentation method, which supports the required positioning performance for crucial and accuracy demanding visually impaired guidance applications, was established. Such a system would assist visually impaired people to access the wider environment and make their life much easier. The system integrates a wireless remote vision facility with a positioning and tracking unit based on the RTK GPS and an application of the GIS into a technological platform enabling the provision of sighted guidance to visually impaired people by remote.

The research evaluated the developed RTK positioning model’s performance under different environments and conditions to measure the advances in the achieved position solutions. Extensive experimental trials were conducted for observing and collecting GPS data in various navigation environments (urban, rural and open space) and in different scenarios, dynamic and static. In addition, a simulation study was conducted in order to investigate future Galileo positioning performance in contrast with the developed positioning model.

1.3 Research Aim and Objectives

The main aim of this study is to pursue a research with an intention to establish and develop a new positioning model, improving the performance of GNSS positioning services and with wireless network to be used to guide visually impaired pedestrians. The developed system can also be used in many other applications, where video imagery and location are required together to perform the guidance. This aim was achieved by performing the following specific objectives:

- A comprehensive literature review of various wireless networks (HSDPA, UMTS, WiFi etc) was conducted, along with a deep focus on the positioning technology GNSS, especially GPS and its augmentation techniques and other high-tech mobility aids for visually impaired people. This provided the required understanding to critically investigative wireless network components with a focus on the performance of satellite-based positioning technology.

- The establishment of an efficient positioning model that incorporates RTK GPS and its augmentation position solutions, fulfilling the identified positioning requirements.

- Carrying out an inclusive investigation and field experiments in such as urban, suburban and rural areas, on the limitations and shortcomings of RTK and NRTK GPS and its augmentation service in these various environments and scenarios. This was followed by identifying a set of background factors affecting the positioning technology performance.

- Performance assessment based on the model (navigation system for visually impaired people) and the existing wireless networks links for use in transferring the navigational information, GPS data, and video and voice data. The performance assessment was focused on the following link features: delay, throughput, jitter and packet loss. The outcomes of the assessments lead to a solution for the communication link, which enabled the optimal performance of the system.

- Utilising a comprehensive evaluation methodology that was designed for the purpose of testing the positioning model using several experimental field trials and simulation sessions.

- Understand the future Galileo navigation systems and investigate its positioning performance.

1.4 Contribution to Knowledge

This doctoral thesis will contribute to knowledge in the following ways:

- **Identification of the limits and insufficiencies in utilising NRTK GNSS and its augmentation techniques within the frame of pedestrian applications in a range of environments and circumstances. As this has not been conducted before, this research attempts to bring light to this aspect and generate a wider insight within this area. By conducting experimental testing in different environment and scenarios the aim is to contribute with more knowledge to the ongoing investigation in the use of these applications, in particular with regards to the mentioned aspects that have left a gap in existing literature up to date.**

- **A new and efficient positioning model which can provide highly reliable and accurate position solutions for guidance and communication applications, below 85 cm in a dynamic urban environment. This included the following:**

    1. The design of efficient and hybrid functional approaches, operating through client-server based architecture consisted of a Navigation Service Centre (NSC) and a Mobile Navigation Unit (MNU). The functional approaches are mainly responsible for establishing wireless connection, processing augmentation and navigation data, and monitoring the availability of the navigation and augmentation information at the MNU (user), which is the main factor for establishing a communication session with the NSC. Also, establishing a connection for the availability of valid augmentation data at the MNU.

2. Establishing the provision of an accurate final position solutions, utilising several positioning and communication methods responsible for data correction and guidance. This include, the corrected positioning data, and video and voice guidance.

- **Designing and deploying an evaluation methodology, summarised as followed:**

  1. Evaluating the overall performance of the developed positioning model, a process taking place in different navigation environments and scenarios.

  2. Evaluating the overall performance assessment of different wireless mobile technologies like (UMTS, and HSDPA) for utilisation in the system. The features selected to be assessed were based on their significant impact on the overall performance of the navigation system.

  3. Investigating the future Galileo system positioning and comparing its achieved performance with the developed positioning model.

1.5 Thesis Structure

The layout of the thesis corresponds to the structure of the work as it was undertaken throughout the PhD project. This thesis consists of eight chapters, the list of references, the list of publications and four appendices, the first of which is an introduction chapter. The following is a brief description of the remaining chapters:

Chapter 2 presents the technical background of Global Navigation Satellite Systems (GNSS) and foundation necessary for the full understanding of this research work.

Chapter 3 provides critical appraisal of all necessary understandings concerning GPS based navigation systems for visually impaired people.

Chapter 4 explains the process of precise positioning in real-time using GNSS. Furthermore, this chapter describes technical features of RTK and NRTK and discusses the potential benefits of the future implementation of the system for the mobility of visually impaired people.

Chapter 5 describes the system design, including its operational architecture, system functions and operational methods.

Chapter 6 provides with the assessment methodology, conducted based on experimental and simulation studies, as a means to assess the positioning model.

Chapter 7 explores the results gained in terms of the positioning performance in different environments of navigation and different measurement scenarios.

Chapter 8 concludes this work, with suggestions for future work.

Chapter 2

2. Technical Background

2.1 Introduction

Global Positioning System (GPS) has been widely used worldwide for a variety of applications such as air, land and sea, and it is the only fully operational Global Navigation Satellite System (GNSS). Due to its several advantages, such as simplicity of use, successful implementation and global availability, this has been considered as the cornerstone of positioning in navigation system applications for the people who are visually impaired (Filjar, 2003). However, due to standalone single frequency service, described in section 2.2.1, the positioning performance has not been sufficient for some accuracy and precision demanding applications (Hughes, 2005; Nabhan et al., 2008; Almasri et al., 2009). The problems of obtaining high accuracy real time positions in the field have led the navigation community to develop a GNSS augmentation system. However, several questions have been raised with this new development, such as how good the new method is? During any satellite configuration, would it be able to provide the accuracy at the same level? In a reliable way, would it be able to replace conventional GPS method?

In this part of the thesis, a detailed review of all necessary understandings concerning GNSS and with a focal point on the GPS, GLONASS, Galileo and Wide Area Differential GPS (WADGPS), is provided.

The chapter is broken up into two interrelated parts. The first one is described in Section 2.2 and offers a systematic overview of satellite-based positioning, focusing on GNSS, WADGPS, modernised and future GNSS. The second part is presented in Section 2.3, and offers comprehensive review of the augmentation and improvement systems, followed by a number of up to date research studies concerning augmentation system in pedestrian applications.

2.2 Global Navigation Satellite Systems (GNSS)

GNSS is the standard general term for satellite navigation systems that provide autonomous geo-spatial positioning with worldwide coverage. Particularly GPS has received considerable attention in navigation applications. Several augmentation systems were developed for the purpose of improving the positioning performance achieved from this technology, and to integrate GPS with another functioning satellite- based positioning system, such as the Russian navigation system, GLONASS. Extensive efforts are currently being directed towards establishing and lunching new navigation systems such as Galileo and the modernised GNSS.

2.2.1 Technical Features of GPS

GPS signals are transmitted in two frequencies, L1 (1575.42 MHz) and L2 (1227.60 MHz). The carrier signals are modulated with a unique Pseudo-Random Noise (PRN) sequence for each satellite. The signals from each satellite are separated by the GPS receiver using CDMA technique. Currently, there are ranges of PRN codes in use, which includes the Coarse/Acquisition (C/A) code, widely used for the civil applications with L1 frequency modulation; secondly, the Precise (P) code, served specifically for military applications, with L1 and L2 frequency modulations and last one is the Y-code, which has been used to replace of P-code if activation of anti-spoofing has taken place. The navigation messages are the modulated data onto these codes and are broadcasted from GPS satellite and the messages received are common to all satellites but unique to the transmitting satellite. The data from the navigation messages includes the time of message transmission, clock corrections, and data relevance to health for all satellites, coefficient for ionospheric delay model, coefficients to calculate coordinated universal time (UTC) and a Hand Over Word (HOW) for the transition from C/Y-code to P(Y). The satellite status could be known through the almanac, which describes the details such as location of orbital, and PRN numbers, which are valid for up to 180 days. The updated version of the almanac is the ephemeris where the information obtained through this could be valid for only four hours but it allows the receiver to calculate the tracked satellite's current position (DoD, 2004).

The GPS receiver estimates the spaces to the tracked satellites, and this is explained as a pseudo-range- the range to the satellite and the receiver's clock offset. These pseudo-ranges are the basic GPS observable that is attained by using the C/A and/or P-codes transformed into the carrier signal. GPS receiver generates a signal similar to the received PRN from the satellite. The generated signal by the receiver keeps shift in time until a correlation is achieved between the two signals (from the satellite and the receiver), but, this time shift is the time taken for the signal to travel from satellite to receiver. As the signal of the satellite is akin to the speed of light, the pseudo-range is established by multiplying the time difference by the speed of light. At least four satellites are required in order to compute a position solution. Based on the pseudo-range measurements (ρ_i), the position calculations are described as the following:

$$\rho_i = \sqrt{(x_i - x_u)^2 + (y_i - y_u)^2 + (z_i - z_u)^2} + ct_u \tag{2.1}$$

Where:

- (x_u, y_u, z_u) are the unknown user receiver position coordinates.
- (x_i, y_i, z_i) are the known satellite coordinates.
- t_u is the offset of receiver clock from the system time.
- c is the speed of light.

At least four pseudo-ranges are required to obtain the unknown receiver's coordinates:

$$\rho_1 = \sqrt{(x_1 - x_u)^2 + (y_1 - y_u)^2 + (z_1 - z_u)^2} + ct_u$$

$$\rho_2 = \sqrt{(x_2 - x_u)^2 + (y_2 - y_u)^2 + (z_2 - z_u)^2} + ct_u \tag{2.2}$$

$$\rho_3 = \sqrt{(x_3 - x_u)^2 + (y_3 - y_u)^2 + (z_3 - z_u)^2} + ct_u$$

$$\rho_4 = \sqrt{(x_4 - x_u)^2 + (y_4 - y_u)^2 + (z_4 - z_u)^2} + ct_u$$

There can be a solution to the above-mentioned equations with the use of iterative techniques or a solution can be arrived at with the use of least squares method. The accuracy of the solution increases with a sophisticated solution and with the use of four satellites. The carrier phase measurements can also be used for computing distances to the satellites and while quantifying using this method, the carrier signal is modulated with the use of C/A code. The number of complete cycles can be decided which have occurred and also the distances of satellites can be measured from the wavelength in addition to the integer uncertainty. Also, satellites are locked while using this method of determination. The quality solution is given with this and also, this is of help while solving ambiguity in integrity.

The number of satellites tracked with a precise geometry is the main factor for deciding the performance of the GPS system. There are three possibilities for the occurrence of error as mentioned by Kaplan & Hegarty (2006). They are:

- Satellite-based
- Signal-based
- Receiver measurement errors

These errors mainly affect pseudo-range measurements and limited satellites visibility. These errors are also described as satellite orbital shifting and clock errors. Atmospheric delays and multipath effects cause errors in interpretation of signals. There are also additional sources of errors like receiver measurement errors are originated by the receiver noise, software resolution and stability. Signal-based errors are the major contributor in the total measurement errors.

These errors escalate in urban canyons and areas with elevated surroundings. These environments lead to signal blockage, causing deficient strong satellites being fruitfully trailed for position calculation. The role of each error source in the calculated position error can be explained in terms of User Equivalent Range Error (UERE). Tables 2.1 and 2.2 show estimates of typical contemporary UERE budgets. Table 2.1 describes a typical UERE budget for a single frequency C/A code receiver. Table 2.2 shows the UERE budget for a dual frequency P(Y) code receiver.

UERE Error Sources	**Error (m)**
Broadcast Clock	1.1
Ephemeris (Orbital Errors)	0.8
Ionospheric	7
Tropospheric	0.2
Receiver noise and resolution	0.1
Multipath	0.2

Table 2.1: GPS Standard Positioning Service typical UERE Budget (Kaplan and Hegarty, 2006).

UERE Error Sources	**Error (m)**
Broadcast Clock	1.1
Ephemeris (Orbital Errors)	0.8
Ionospheric	0.1
Tropospheric	0.2
Receiver noise and resolution	0.1
Multipath	0.2

Table 2.2: GPS Precise Positioning Service typical UERE Budget (Kaplan and Hegarty, 2006).

These values are not fixed and are dependent on the conducted measurements' scenario and conditions.

In recent decades, substantial consideration has been paid to developing Differential GPS (DGPS) (Section 2.2.2). The main aim of the research is to eliminate or reduce the GPS error sources and achieve greater performance positioning. The availability of DGPS systems is wide with different ranges of coverage, different structure, differential data formats and several augmentation data deliverability means. Conversely, Assisted GPS (A-GPS) is one of the DGPS system that has been developed to increase the speed of position fixing, where it helps to provide navigation information using GPS ephemeris from a station, which are remote assisted to GPS users through a carrier network such as mobile network (Hjelm, 2002). Beside, currently in the market, there are High Sensitivity GPS (HS-GPS) receivers available, which are being used in support of positioning accuracy of GPS.

This technology improves the positioning fixing rate and the overall GPS positioning in challenging navigation areas, by enabling the acquisition of weak GPS signals down to -190 dBW level. However, the problems of signals availability are not solved till now, particularly during conditions where the availability of satellites (<4 satellites) is insufficient such as in densely areas and indoor environments (Esmond, 2007; Lachapelle, 2007).

2.2.2 Differential GPS (DGPS) Systems

The Differential GPS (DGPS) is the basic concept of correcting and augmenting the GPS position solution. DGPS is based on the principle that all receivers in the same vicinity will simultaneously experience common errors (Loomis et al., 1995; Haider and Qishan, 2000). There are three elements, where DGPS system is composed of, which includes firstly, at a known location, an antenna or GPS receiver is present (base station), secondly, at an unknown location, another GPS receiver (user receiver) and finally, between these two receivers, a communication medium is present, as shown in Figure 2.1. In a known location, a reference station is present and comparing these known locations, a correction vector could be generated with the calculated measurements at the reference station and these signals in order to be integrated with its position solution are sent to the rover (mobile) receiver. DGPS is applied in the code pseudo-rangers after estimating the corrections or to the measurement domains, which are in carrier phase. The latter process is described as Real Time Kinematics (RTK) (Lachapelle, et al., 2000). However, RTK is an accurate navigation system, expensive and complex and it requires the continuous tracking of satellites. A detailed review of RTK and its constraints and advantages is described in Chapter 4.

In reference to the operational range of DGPS correction information, DGPS systems are separated into two core categories: Local Area DGPS (LADGPS) systems, with restricted coverage from the single DGPS reference station (e.g. baseline <100 m); and Wide Area DGPS Systems (WADGPS), which covers a complete region or country. WADGPS are in general developed providing augmentation services to a large variety of users regardless of their location and distances to the reference stations (baselines).

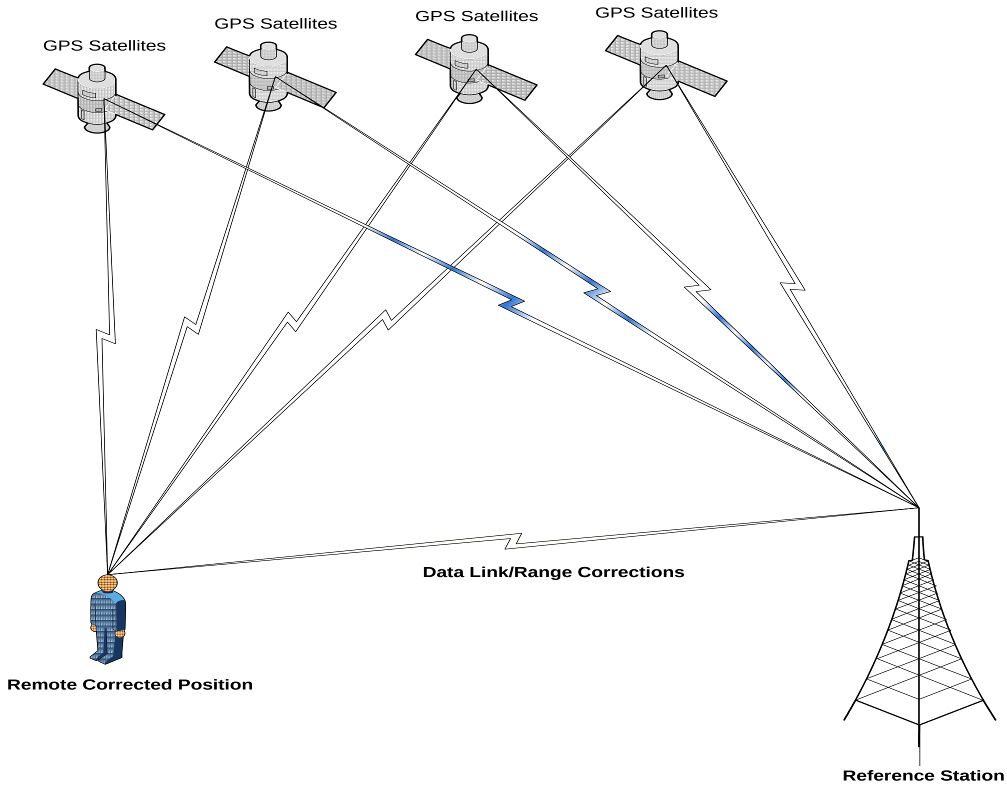

Figure 2.1: DGPS System.

2.2.3 Wide Area Differential GPS (WADGPS)

According to Raman and Garin (2007), in order to form a vector correction for each and every satellite, DGPS extension, which is Wide Area Differential GPS (WADGPS) has been used. This technology uses a broad network of reference stations for the vector corrections which are individual for the ephemeris, satellite clock and ionospheric delay model. The vector correction is considered to be more valid than Local DGPS correction, since it covers wide geographical area. A network-based DGPS system are described as the distribution of DGPS reference stations only at certain geographical places and connected to a centralised point, which forms a DGPS stations network.

One of the WADGPS's core advantages is the possibility to achieve a more consistent accuracy throughout the region with support from the network. In the case of DGPS with only one reference station, the accuracy reduces as a function of distance from the reference station at a rate of approximately 1cm per 1km (Hofmann-Wellenhof et al., 2001). Further advantages with WADGPS are the possibilities to cover inaccessible regions, e.g. large bodies of water. Moreover, the network will still maintain a comparatively high level of integrity and reliability in case of a failure in one of the reference stations, in contrast with a collection of individual DGPS reference stations. A large ground network of real-time reference receivers is employed by DGPS, to trace the GPS civil signals on the L1 and L2 frequencies. Network-based DGPS (Section 2.3.1) augmentation data is broadcasted to users within the coverage capacity through radio and/or wireless communication means; the mobile network is regarded as the main communication means to transport the augmentation data to the user with longer baselines. The Radio Technical Commission for Maritime (RTCM), (RTCM, 1994), is the generic format for transmitting DGPS corrections.

In the UK, there are several network based DGPS and DGNSS (Differential Global Navigation Satellite System) solutions available and examples of such network includes Ordnance Survey GNSS Network (OS Net) and commercial partner Topcon's TopNET+. With the completion of the Ordnance Surveys upgrade to the nationwide Continuously Operating Reference Stations (CORS) network, this covers entire Great Britain DGNSS reference stations of more than 100 reference stations. These stations constantly receive GPS and GLONASS signals from satellites in near earth orbit. Topcon has been collaborated with the Ordnance Survey and using data from OS Net, Figure 2.2 shows the network coverage in UK. Throughout the UK, TopNET+ provides real-time L1 and L2 RTK corrections for carrier phase data for both GPS and GLONASS. With the use of internet, mobile or radio communications, the services from TopNET+ augmentation could be delivered to the authorised users in real time from the central processing station.

Alternatively, raw GPS data in the Receiver Independent Exchange (RINEX) format is available from OS Net RINEX data server for any user (free of charge). RINEX is a data format used to archive GPS navigation and observation data for post-processing purposes (Gurtner and Estey, 2007).

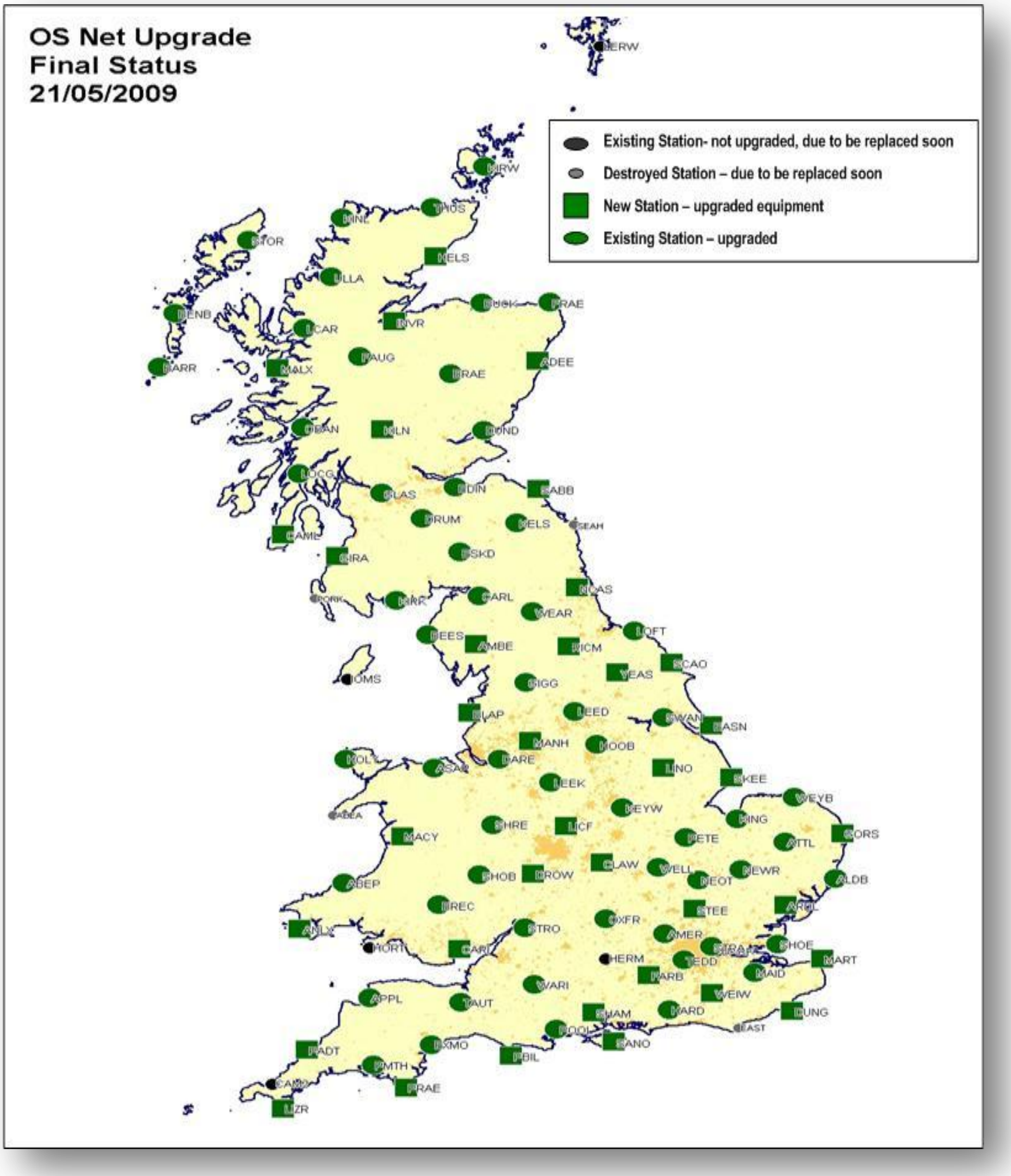

Figure 2.2: OS Net coverage map (Ordnance Survey, 2009).

The use of network as an alternative means for transmitting augmentation data has been possible today mainly due to the increased capability of internet technology. This allowed the development of the Network Transport of RTCM via Internet Protocol (NTRIP), enabling the delivery of RTCM corrections from an NTRIP caster to internet users (RTCM, 2004; Chen et al., 2004; Dammalage et al., 2006).

Using TCP/IP, data streaming over mobile IP network was possible by the HTTP server program of the NTRIP Caster. Through GPRS (General Packet Radio Service) connection, transmission of the corrections from the NTRIP server to the mobile device was also possible for mobile users through a data-enabled mobile connection.

2.2.4 Future GNSS

The enormous demand to further improve positioning, navigation, and timing capabilities for both civil and military users on existing GNSS systems has directed efforts to modernise the GPS and GLONASS system and introduce new systems such as Galileo navigation system.

2.2.4.1 Modernised GNSS

The modernisation program aims at improving positioning and timing accuracy, signal availability and integrity monitoring support capability, and enhancement to control system. GNSS undergoes modification and a transformation process on a routine basis to provide better and sophisticated positioning services for the use of both civilian and military forces.

GPS was launched on a complete basis in 1995, with a constellation of 24 satellites. During the operation of GPS several generations of satellite have come up with improved features. In 2005, a major improvement to GPS infrastructure was made by disengaging old satellites and adding improved satellites. Another new mass of GPS satellites were launched, known as Block IIR-M satellites subsequently (Shaw, 2002; Hughes, 2005). In addition to the above improvements, a new positioning signal described as L2C was introduced meanwhile, but it has to undergo further improvisations before being opened for public use. Block IIR-M includes eight satellites, of these six of them were launched before March 2008. Hence, the total number of GPS satellites orbiting became 31 broadcasting satellites. Meanwhile another feature called the L5 safety-of-life civilian signal was initiated. The final satellite of this block series was effectively instigated in August 2009. By 2012, the civilian L5 signal would be accessible for consumers with the total launch of GPS IIF satellites. Block IIF is the final pushing step in the GPS block series that will highly modernise GPS process (GPS III) (DoD, 2008). This final phase will also consist of twelve new satellites, providing new military code (M-code) and civil signal frequency (L2C).

The Galileo and the Chinese Compass systems will undoubtedly be practical, except these are not expected to be completely operational until beyond 2013 and 2015, respectively (Gibbons, 2008; Gibbons, 2009). In contrast, the GLONASS system is currently being replenished and is nearly fully populated (20 satellites in operation at time of writing).

At present GLONASS uses Frequency Division Multiple Access (FDMA) technology. The long-debated CDMA question is expected to give a final decision imminently, according to Revnivykh (Inside GNSS, 2009). During the modernisation plan, CDMA signals would be established at L1 and L5 frequencies near GPS and Galileo signals, starting with the GLONASS-K generation of satellites that has been launched in 2010. Beyond CDMA, signals would increase potential interoperability with the other CDMA-based systems in user equipment that would be able to process signals from satellites in multiple GNSS systems (Inside GNSS, 2009).

The present process of modernisation of GNSS will improve navigation user capabilities in various ways. There will be additional signals for civil use, which will be more powerful and easier to obtain by receivers. They will also facilitate interoperability between different systems (GPS, GLONASS and Galileo), by transmitting inter-system clock corrections (Gratton et al., 2010). There will be additional ground stations, and satellites will be able to communicate with each other, allowing better ephemeris generation, failure monitoring, and a faster alarm transmission in case a monitor triggers.

One of the predicted improvements is particularly significant to this work is the additional civil signal, and the ability to use a larger number of satellites in view at all times. This will translate into more precise accuracy; ionospheric delay is eliminated using dual frequency measurements, better availability and greater redundancy. In addition, smaller size dual frequency RTK receivers will allow GNSS to be used where DGPS is not practical, e.g. handheld navigation for the pedestrians and visually impaired people. DGPS positioning, which has a standard accuracy of 1-5m, will be mainly replaced by the RTK positioning, which will then offer a better accuracy.

The data rate requirements of DGPS will be decreased, in recognition of the modernisation. RTK applications that now use C/A-code and L1 and L2 carrier will take complete benefit from the supplementary L5-code and carrier and permit distances up to 100 km between the reference station and the rover, even when accuracies of few cm are targeted.

2.2.5 Galileo

Galileo is a system of navigation that is supposed to be Europe’s independent and exclusive navigation system, offering better positioning services globally than standalone GPS. The European Union (EU) and the European Space agency (ESA), under civilian control were instrumental in launching this initiative. This global system would simultaneously co-operate with the existing GPS and/or GLONASS system, allowing users to gain from triple/hybrid satellite constellations services. This kind of availability of two or more collective satellite systems results in escalating the totality of available satellites in the sky. This will also help to augment the overall superiority of the positioning services even in urban areas and/or indoor environments. This will lead to a momentous boost in the number of navigation applications (Richard, 2008).

The central theme of the Galileo space segment is the global constellation of 27 operational satellites over an area of spaced orbital planes, and orbital inclination of 56º to the equator at about 23222 km above the Earth. Each plane comprises of nine satellites, supposedly 40º apart. For each plane there is a plan to keep one non-operational spare satellite, able to provide cover for any failed satellite in that plane. Thus, a breakdown or malfunction in the constellation can be fixed rapidly by substitution of the spare in place of the failed satellite. This can be time saving so that there is no need to wait for a new launch to be arranged, which can take several months and take up a lot of the productive time. The orbit altitude above Earth of 23222 km has been chosen to be appropriate; it would be convenient for the constellation to have a repeat cycle of 10 orbits in 17 days (Kaplan and Hegarty, 2006). The appropriate altitude of the satellites has to be in such a manner that gravitational resonances could be avoided. In this way, subsequent to primary orbit optimisation, station-keeping manoeuvres will not be required during the entire life span of a satellite. The altitude chosen also guarantees a high visibility of the satellites (ESA, 2007).

Satellite operations are supported by Galileo ground segment constructs of a network of ground stations, consisting of sensor stations, control centres and uplink stations. A worldwide network of Galileo Sensor Stations (GSS) will continuously monitor the satellites. The accurate measurements of the navigation signals will be sent to the two major Galileo ground segment. The Galileo ground segment in turn encloses two major control centres, the Ground Control Segment (GCS) and the Ground Mission Segment (GMS).

The Ground Control Segment (GCS) uses a global network of supposedly five Telemetry, Tracking and teleCommand (TT&C) stations to interact with each and every satellite on a plan combining regular, listed contacts, long-term test campaigns and emergency contacts. Data transference to and from the satellites, will be primarily performed through TT&C (Kaplan and Hegarty, 2006). TT&C network is comprised of five ground stations with 13 metre antennas working in the 2 GHz Space Operations frequency bands (S-band). A TT&C station network is mainly involved in overhauling of the Galileo satellite collection and giving access to global coverage. Nevertheless, general standard TTC modulation will permit the employment of non-ESA TTC stations when the navigation system of a satellite is not in process (during launch and early course operations or during a contingency).

The Ground Mission Segment (GMS) implements the functions for providing the main services of Galileo. Galileo Sensor Stations (GSS) supervises the navigation signals of each satellite on a daily basis. The data obtained with these sensor stations will be used for orbit determination, time synchronisation, and integrity monitoring.

The Galileo Sensor Stations (GSS) network will collect one-way pseudo-range raw measurements orientated to a local atomic reference clock with navigation messages received from the satellites. The Galileo Sensor Stations (GSS) network provides this data along with narrow meteorological and other data like monitor and control information and navigation data message to the Ground Control Centre (GCC) (Kaplan and Hegarty, 2006).

The integrity data computed at the Galileo Control Centre (GCC) will be made available to global users since they mainly use the dimensions from the worldwide network of sensor stations.

Galileo will afford 10 radio navigation signals allotted within the following frequency plans (Benedicto et al., 2000; Hein et al., 2001; Zimmermann et al., 2004):

- Four signals in the E5a and E5b bands (1164-1215 MHz), that includes two navigation data signals (the data channels) and two signals carrying no data (pilot channels).
- Three signals in the E6 band (1215-1300 MHz), and one split spectrum and one pair.
- Three signals in the E2-L1-E1, also described as L1 band (1559-1592 MHz), as well as one split spectrum and one pair.

A degree of optimisation is reached by using multiple signals in Galileo to fulfil the requirements of many kinds of applications that are accessed in diverse settings and circumstances, such as indoor, outdoor, static and rapid moving. This is presently unavailable in GPS because only one civilian signal is available and accessible. But this problem would be overcome in the subsequent sophistication of GPS. A particular advantage of having multiple signals in the ionosphere layer is that after adding measurements obtained from at least two different signals, it is possible to cancel the ionospheric delay.

The Galileo navigation signals offer the following advantages to the end users (Benedicto et al., 2000; Hein et al., 2001):

- Open Service (OS).
- Safety-of-Life Service (SoL).
- Commercial Service (CS).
- Public Regulated Service (PRS).
- Search and Rescue (SAR) Service.

Generally, the Open Service (OS) data signals are allocated at E5a, E5b, E2-L1-E1 (L1) bands for either data or pilot channels allowing several signal combinations for the single and dual frequency positioning services. The bottom line of the single frequency OS is that they use signals which are in E2-L1-E1 and might receive the GPS C/A code signal on L1. For enhanced precision, signals in E5a and E5b bands might also be incorporated. The GPS L5 signal is included in dual frequency services. The data carried by the OS signals are not in an encrypted form and are usable for all. The OS service does not offer integrity information, and no signal quality determination is assured to the user.

The safety-of-life (SoL) service relies on the data contained in the OS signals and also uses reliability data carried in a special channel. The Commercial Service (CS) is based on two supplementary signals within the E6 frequency band and the capability of using the OS signals. This pair of signals is in encrypted form offering higher performance for commercial users only. The Public Regulated Service (PRS) operates at all times, even during emergencies, and will be used by governmental authorities such as the police, coast-guards and customs, etc. For this service two additional signals are also allocated, one in E6 band, and the other in the L1 band. These signals are encrypted in order to have access control, so access is restricted to PRS users.

2.2.6 GLONASS (GLObal'naya NAvigatsionnaya Sputnikovaya Sistema)

The GLONASS satellite system is currently under development with new modernised GLONASS spacecraft to replenish the constellation. The GLONASS expect to have 24 satellites in orbit by 2011-2012. The GLONASS system and GPS systems share similar principles in data transmission and positioning methods. The difference between GLONASS and GPS is the segment; GLONASS consists of 24 satellites (21 active and 3 spares) in three orbital planes. The three orbital planes are separated by 120º and the satellites within the same orbit plane by 45º. Each GLONASS satellite operates in circular 19100 km orbits referenced to the Earth's surface with an inclination angle of 64.8º and each satellite completes an orbit in approximately 11 hours and 15 minutes. Two L-band navigation signals are transmitted by the satellites and the Russians are planning to develop and add a third L-band signal near the radio frequency of the new L5 signal planned for GPS (Kaplan and Hegarty, 2006). GLONASS offers two types of services: Standard Positioning (SP) and High Precision navigation signal (HP). SP service offered world-wide with horizontal accuracy of 57-70 meters, the vertical accuracy is within 70 meters (Hunaiti, 2006).

The Russian government has stated that, like GPS, GLONASS is a dual use system and that there will be no direct user fees for civil users. The Russians are working with the EU and the United States to achieve compatibility between GLONASS and Galileo, and Galileo and GPS, respectively (Kaplan and Hegarty, 2006). The functions of the ground control segment of GLONASS are entirely located within former Soviet Union. The ground control centre and time standards are located in Moscow. At various locations across the continent, observations of telemetry data and ranges are made and passed to ground control centre in Moscow. The control information and ephemerides are computed and uploaded to satellites. At least five satellites will be available at any location, at any time worldwide under the full constellation (Miller, 2000).

With only 20 satellites currently operational (at time of writing), GLONASS does not work well as an independent positioning solution for high accuracy applications. However, if it is used as a supplement to GPS and the RTK, GLONASS does provide more reliability, availability, accuracy and more satellites in view throughout the day. The additional GLONASS visibility is often enough to overcome suburban environments or mountainous areas and the standard down times when using GPS-only for RTK.

Nevertheless, the amount of GPS and GLONASS satellites that can be observed is still often rather unsatisfactory for the attainment of a position solution. This is partly due to the requirements of at least five visible satellites to determine a position because of an offset between the timescales of GS and GLONASS to be resolved (Cai and Gao, 2009).

2.3 GNSS Augmentation Systems Positioning Performances

A number of navigation applications have used augmentation and complementary systems for the purpose of achieving enhanced positioning performance. Various researchers have carried out the evaluation of such systems under different conditions and scenarios. The following section presents different evaluation studies, as well as the reported results of positioning performances, taking one main augmentation system into account: the use of network-based DGPS.

2.3.1 Network-based DGPS

A number of regional DGPS networks are functioning worldwide, providing pseudo-ranges corrections estimation based on multi-reference DGPS stations being unified together forming a WADGPS solution. There are many advantages associated with network-based DGPS compared to the standard single-reference DGPS station approach. Several advantages are the advanced reliability of the differential positioning service, increased strength, and higher positioning accuracy levels. These advantages can be achieved for code-based DGPS and RTK measurements (Lachapelle et al., 2000; Park et al., 2003; Raman and Garin, 2004; Oh et al., 2005).

Chang and Lin (1999) described a local navigation system consisting of a medium-range DGPS network developed in Taiwan. The objective of this network was to provide adequate positioning accuracy using GPS observations based on C/A pseudo-ranges collected from a set of reference stations and then processed at the central station obtaining a weighted average of the differential corrections. The developed medium-range DGPS based positioning service has achieved an improvement of 35% in terms of Root Mean Square (RMS) error comparing to the single reference station as shown by the testing results. The use of single reference-based DGPS was very much dependent on the baseline lengths; the horizontal accuracy ranged from 3.1 to 5 meters. However, when utilising three reference stations, these measurements, provided an average of 1.3 meters' accuracy. These were achieved only in static scenario without a hint to the surrounding environment.

The Jet Propulsion Laboratory (JPL) of the National Aeronautics Space Administration (NASA) launched Internet-based Global Differential GPS (IGDG) in spring 2001. A subset of 40 reference stations is available at NASA's Global GPS Network (GGN). These reference satellites allow real-time streaming of data to a processing centre, that determines and subsequently distributes accurate satellite orbits and clocks errors, as global differential corrections to the GPS broadcast ephemerides (as contained in the GPS navigation message) over the open internet. This process could be done on a real time basis. An introduction to IGDG can be found in Mullerschon et al. (2001a) and on IGDG (2004). Technical details in Bar-Sever et al. 2001; Mullerschon et al., 2001b.

The low bandwidth correction data stream can be downloaded into a computer by the internet users. It will then be combined with raw data from the user's GPS receiver. The user's GPS receiver must be a dual frequency and be of geodetic quality so as to extract the full potential from the accurate corrections. The ultimate, but decisive, constituent that offers an end-to-end positioning and orbit determination capability is the navigation software possessed by the user.

Raman and Garin (2005) assessed the performance of the Global Differential GPS (GDGPS) system, provided by JPL, for particular specific frequency C/A GPS receiver. This system makes use of a group of DGPS reference stations which are continuously observing GPS measurements. The NTRIP protocol would be utilised to measure the central processing stations and then to forward the improvement messages to the users. At the processing stations, data is analysed to produce measurement corrections of ionospheric delay and satellite state (orbit + clock corrections). The corrections are then provided as an information vector reliant on the user's location. The improvements in terms of horizontal position accuracy using GDGPS augmentation services were measured in open space conditions. A horizontal accuracy average of 1.5 meters using GDGPS was achieved in comparison to 4 meters using standards local DGPS. Nonetheless, these accuracy levels were decreasing within the distance from the reference stations and when the availability of corrections was reduced at the user side. A linear combination algorithm was also developed by Oh et al. (2005) in order to generate interpolated Pseudo-Range Corrections (PRC), which was the used to enhance the DGPS positioning accuracy. The combination algorithm takes into consideration PRC values from multiple DGPS reference stations sharing the same satellites. The accomplished DGPS positioning accuracy was improved over standard DGPS by 40% in static scenarios. When using PRC measurements from two DGPS stations a position accuracy of 1.8 meters was achieved, and around 1.5 meters when using three or more DGPS reference stations.

2.3.1.1 GNSS Augmentation Systems in Pedestrian Applications

When taking the performance of GNSS and its augmentation methods of pedestrian users into account, in densely urban and indoor environments, a pedestrian navigation project was defined and described by Abwerzger et al. (2004) and Ott et al. (2005). This project was named “Definition and Demonstration of Special Handheld based Applications in Difficult Environment” (SHADE), and was supported by the European Space Agency (ESA) in order to explore different sets of navigation technologies employed for pedestrian applications in difficult environments. Three autonomous navigation prototypes were developed and tested in the SHADE project. The first prototype was formed of an A-GPS received, EGNOS[1] functionality included. The second prototype was composed of and INS[2] module, for the sake of pedestrians (a dead reckoning module), as well as GPS/EGNOS receiver. The last prototype was encapsulated of

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[1] European Geostationary Navigation Overlay Service (EGNOS) is a satellite based augmentation system (SBAS) under development by the European Space Agency, the European Commission and EUROCONTROL. The primary goal of EGNOS is to provide augmentation service for GPS, GLONASS and the future Galileo system.

[2] Inertial Navigation System (INS) is a navigation facility that comprises several motion and orientation sensors (e.g. accelerometers and compasses) which are integrated using a computer application to sense and continuously calculate the position, speed and time.

an Integrated GPS/Loran-C with EGNOS facility. The Long Range Aid to Navigation (LORAN) is terrestrial radio navigation system utilising low frequency radio transmitters. The present development of this technology is presented as Enhanced LORAN (E-LORAN) (Abwerzger &Lechner, 2002; Narins et al., 2004). The operational architecture of SHADE was designed to evaluate and develop the availability of several positioning solutions to operate even in dense urban and indoor environments. Field measurements were carried out under good GPS visibility conditions, during the evaluation of the first prototype, and then under light in-doors (partly covered areas) with a sampling rate of one sample per second. An accuracy of 1.5 meters at 95% was achieved in open space areas when using the first prototype. The worst scenario was noticeable during indoor measurements, in which the achieved accuracy reached 39.22 m at a 95% confidence level. This positioning performance is considered four times higher than GPS SPS horizontal levels (7.8-12.8 m) described by Hughes (2005). Hence, the conclusions were that the first prototype is not suitable for navigation applications taking place indoors. In addition, the second prototype was evaluated permitting position determination to take place in GPS complicated environments, in which a primarily absolute position was determined by the GPS/EGNOS receiver, and constant position samples were compromised from the dead reckoning module as well as the GPS/ENOS receiver using Kalman filtering. However, one of the central drawbacks of the second prototype was the position drift because of the attached magnetometer. The third prototype has made known its capacity to increase the availability of position solutions and surmount the blockage of GPS service in densely urban area. On the other hand, the position solution’s accuracy, obtained from the integrated Loran-C service, was lower than the expectations. Furthermore, upon entering the buildings, the signal strength from all Loran-C stations decreased considerably. Thus, the Loran-C was no longer regarded as reliable.

2.4 Summary

This chapter presented a detailed review of Global Navigation Satellite System (GNSS), such as GPS, GLONASS and Galileo, along with its most widely implemented augmentation technologies such as DGPS and network-based DGPS was presented. Additionally, recent augmentation systems evaluation studies conducted by previous researchers were reviewed, showing the achieved positioning performance. The positioning performance of GPS is affected by the capability and productivity of the linked augmentation systems, at present as result of higher efficiency standards and better coverage competence, the WADGPS systems like the network-based DGPS are the augmentation systems which are mainly successful. However, this positioning performance is based on the availability of up-to-date corrections, which is affected by the data deliverability means, measurement scenario and navigation environments. However, still the positioning performance achieved from GPS augmentation system is considered not sufficient for these applications. Network-based DGPS and DGNSS techniques have still not been looked at and made use of for the aid of utilising GNSS system in significant pedestrian applications.

The analysis of the available methods to support the mobility of visually impaired people also includes the descriptions of technologies employed in the methods, including the GNSS and the augmentation technologies.

The information provided in this Chapter provides the state-of-the art in GNSS and the augmentations technologies, some of which are used in the system described in the next Chapter. Chapter 3 describes important studies with reference to GPS based visually impaired people navigation systems.

Chapter 3

3. Review of GPS Based Navigation Systems for Visually Impaired People

3.1 Introduction

In order to represent the services, in which location and direction are central parameters, the navigation system is used as a concept for visually impaired people. Several technical components, such as technology (to determine position), communication technology, mobile device, application service, data content providers (that includes geospatial database) and Geographical Information Systems (GIS)[3], have been widely integrated in the navigation systems for visually impaired people applications. However, to explore the navigation system development for the applications of visually impaired people, each technical component and its limitation should be attentive for the researcher. The basic positioning technique in the history of navigation system, are mobile communication and satellite positioning, thus, it is essential to focus on those techniques and its limitation for a better understanding.

In this part of the thesis, a detailed review of the basic concepts of navigation system for visually impaired people is provided. The chapter is divided into two interconnected parts. The first one is described in Section 3.2 and offers a systematic overview of the most crucial mobility aids for visually impaired employed up to present. This overview also comprises the analysis of the functionality of the aids as well as the advantages and shortcomings of their application. Section 3.3 describes the user requirements for designing electronic orientation aids. Finally, section 3.4 concludes this chapter and summaries the

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[3] Geographic Information Systems is the term commonly used in reference to a wide range of different applications of information technology with the function to process and manage geographic data in the digital format (Kang-Tsung, 2001).

current limitations of electronic orientation aids with reference to satellite navigation system.

3.2 Visually impaired people’s Navigation system

Over the past few decades, several wide ranges of models using high technology mobility aids has been developed, which is also known as Electronic orientation Aids (EOA) (Farmer and Smith, 1997). These aids were developed using several advanced technologies that varied in purpose, but in common, all these aids have been developed with the motivation for the need of more comprehensive reliable mobility support. Additionally, in comparison to the support by long canes and guide dogs, this technology was supported by independent journeys (Garaj, 2006). Development of applications which are tailor made for guidance delivery and emergency services, particularly for disable and visually impaired people, have been studied by several researchers. However, these applications are considered to be more demanding with regard to positioning performance, due to the sensitivity and need for the timely delivered service. In order to facilitate and enhance their mobility, GPS has played an important role in such applications for the purpose of accurately locating the position of the users.

3.2.1 Electronic Orientation Aids

In 1985, Loomis from the University of California in Santa Barbara, USA, was the first person to submit the first proposals to use the GPS and GIS for visually impaired people in the provision of navigation assistance (Loomis, Golledge and Klatzky, 1998). In addition, the first Electronic Orientation Aid (EOA) prototypes project was designed, developed and tested by Loomis and his research team. Subsequent research was carried out by Brusnighan, Strauss, Floyd and Wheeler (1989), LaPierre (1993), Brunel University processing research (1995 to 2009) (outlined in Section 3.2.2) and Makino, Ishii and Nakashizuka (1996) in the prototype development with relevance to the field of EOA. The research on GPS development was carried out at an early stage and during that period the main concern was poor positioning accuracy and moreover, practical studies were excluded with particular reference to blind subjects (Reginald et al., 2004).

Although, the GPS and GIS systems are potentially very effective technologies for mobility, this has to be improved for better usability (Farmer and Smith, 1997). However, the problems encountered by this technology could be classified into three groups (Farmer and Smith, 1997), which initially includes applied technology limitations, secondly, the system architecture and at last the related user interfacing (Garaj, 2006). The blocking of reception of GPS signals in so-called urban canyon areas and other environmental features such as tall buildings. This will make the system disabled and for similar reasons, the system cannot be implemented for indoor navigation. Moreover, other GPS receivers that are commercially available restrict the reliability and the content of the provided information due to its poor positioning accuracy. In addition, the GIS capacity do not accommodate for dynamic changes that could represent the real life environment and, thus, limited for only certain information (Garaj, 2006). All these problems make the GIS system difficult to utilise by the visually impaired users and therefore, the developed system should be flexible and user friendly rather than simply focusing on content choice and the syntax, in order to suit the needs of visually impaired.

The mobility aids, which were available in the past, were able to offer solutions to the visually impaired pedestrians only to some degree. However, a new developed mobility aid must be able to overcome all the problems, which were not solved by former aids. Thus, two main criteria of usability (Garaj, 2006) should be implemented by a ‘perfect mobility aid’ (Wycherely and Nicklin, 1970).

- First, the effectiveness should be improved. Using the ‘perfect’ aid, visually impaired pedestrian should be able to view identical or a similar level of mobility as a sighted pedestrian.
- Secondly, the ‘prefect mobility aid’ should not be mentally demanding and stressful and it should be as comparable or tolerable by pedestrians of sighted person.

Development of GPS systems with increased accuracy has thrown light on a number of new projects, specifically those addressing development of mobility aid systems.

3.2.2 Brunel Project

In the year 1995, the pioneering research team from Brunel University, The Electronic System Research Group (ESRG), initiated a guidance project for visually impaired people (Balachandran and Liu, 1995). An international patent was granted for the "*Navigation System*" project (Liu and Balachandran, 1998). The aim of the project was to analyse the possibility of utilisation of GPS and GIS using a centralised approach to navigate visually impaired pedestrians. Brunel Navigation System for Blind (BNSB) was the system developed by the team, which consists of two components; Mobile Navigation Unit (MNU), a device carried by the user, and the Navigation Service Centre (NSC) where all users are connected through remote centralised side. In addition, NSC has several features, which include DGPS reference station, routine algorithms managed by a computing facility, digital maps and receiving data to and from the MNU, and a communication interface. In order to monitor the voice guidance information, trained staff was recommended to be located at the NSC. For the use of blind pedestrians, the MNU was simplified by understanding only the voice communication provided by the trained staff at the NSC. MNU is a simple prototype consisting of an electronic compass with microphone, a GPS receiver, and a speaker, using mobile device. These were all integrated for the purpose of examining the communication between the MNU and NSC, mobile channels were utilised (Hunaiti et al., 2004; Hunaiti et al., 2006). Also, as part of the MNU, to allow the system to provide information about obstacles and objects surrounding the user, video camera was introduced (Garaj et al., 2003), shown in Figure 3.1 on a visually impaired participant.

Figure 3.1: The visually impaired participant with all components during a trial experiment at Brunel University (Hunaiti, 2005; Garaj 2006).

Several experimental trials were conducted at Brunel University to evaluate the effectiveness of the System for visually impaired people navigation system (Hunaiti, 2005; Garaj 2006). The visually impaired participant walked along an unfamiliar route supported both by the guide dog and by the sighted participant, who was remotely guiding him through from NSC. A sequence of photographs showing the visually impaired participant walking along the final part of the route, including the moment when he located the building entrance, is provided in Figure 3.2.

Figure 3.2: A sequence of photographs showing the visually impaired participant during the session of the trial (Garaj, 2006).

The visually impaired participant completed the task successfully by locating the building entrance, entering the building and locating the correct door inside the building, and therefore ferrying out the whole route. The map of the walk in the trial session (Taken Route), superimposed on the diagram of the route (Described Route), is described in Figure 3.3 (Hunaiti, 2005; Garaj 2006). The Figure demonstrates the nearness of the walk performed by the visually impaired participant to the described route.

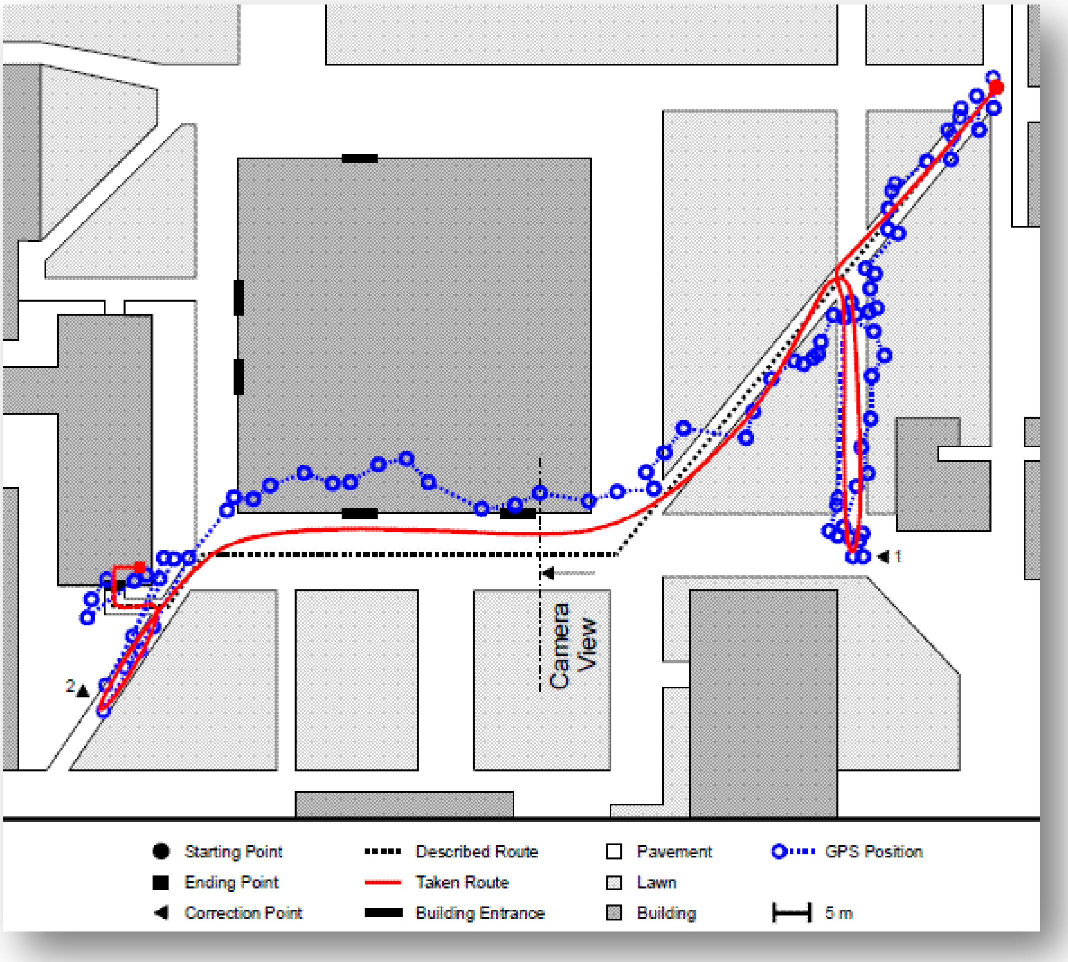

Figure 3.3: The map of the walk in the trial session (Hunaiti, 2005; Garaj 2006).

The visually impaired participant expressed the system as “highly valuable” when asked his opinion on the effectiveness of the system; according to his belief, the system made it possible for him to finish the walk along the route in the session successfully. Moreover, the visually impaired participant pointed out that he perceived the walk in the trial session less stressful than walking along an unfamiliar route, i.e. through the unfamiliar travel environment supported by his dog, thanks to the guidance by the sighted participant. The participant was also in favour of the usefulness of the system in aiding micro-navigation; as the visually impaired participant moved toward the entrance of the building in the ending part of the route, the sighted participant at NSC provided him with a thoroughly verbal description of the entrance layout and helped him locate the door handle on the entrance door. The visually impaired participant qualified the micro-navigational assistance as “impressive”. Nevertheless, when the blind participant was walking along the tall building on his right hand-side, in the second half of the route (Figure 3.3), the accuracy of the GPS positioning decreased considerably. During that section, the blind participant’s position, as traced by the GPS and presented on the guide’s display, was falling within the area of the building on the map (i.e. it emerges as if the blind the blind person is walking on top of the building), which was vague and unreliable information. The decrease of the GPS accuracy (down to 15 metres) occurred as the building in question obstructed the line sight between the GPS antenna carried by the blind participant and some of the GPS satellites that were visible in the preceding part of the route situated in the area of lawn, which was without obstacles. In this case, the guide was able to use the video image of the environment in front of the blind participant in order to determine the correct position of the blind participant.

Compared to other EOA systems, BNSB is easier to use since it includes an option whereby the guidance is provided remotely by a human guide from NSC - in addition to the automated guidance option. The video image of the immediate environment of the visually impaired is vital to be able to provide appropriate instruction by the guide, in order for the visually impaired to avoid obstacles in the route.

Thus, to overcome this problem with positioning performance at BNSB, an improvised method such as local DGPS was introduced along with the use of a Dead Reckoning module, EGNOS/SISNET (Chapter 5, Section 5.6.1) and INS were widely implemented (Shah et al., 1999; Jirawimut et al., 2001; Ptasinski et al., 2002; Al Nabhan, 2009). The newly developed methods were not efficient enough with regard to accuracy levels and the capacity and coverage according to the requirements of the applications. Thus, it has become an established tradition to constantly develop new techniques that augments the positioning services of GPS to sophisticated and sustainable levels. The augmentation systems, also known as Differential GPS (DGPS) systems, operate throughout diverse coverage ranges, such as Wide Area DGPS (WADGPS) (Chapter 2, Section 2.2.3).

WADGPS can be applied as network-based DGPS systems by means of a number of interrelated DGPS reference stations. The purpose of the augmentation system is to condense or eliminate elements that weaken the quality of position, navigation and timing services based on GNSS signals (Das, 2007).

This has led to the identification of new methods that could advance the positioning performance. As noted by Mekik and Arslanoglu (2009), Real Time Kinematic (RTK) and Network Real Time Kinematic (NRTK) (Chapter 4) could be able to provide corrections that are differential in order to produce clear picture on positioning of GPS. Due to its ability of code phase and the carrier phase, observations are faster in accurate positioning compared to the code measurements, and the combination of GLONASS satellites with GPS satellites has been developed so that, simultaneously, five satellites could be easily tracked in urban canyons crowded with high rise buildings. In order to obtain precise results from this method at least five satellites should be observed at the same time, which may be considered as a shortcoming.

The WADGPS are offering augmentation services to a wide range of NRTK users regardless of their location and distances to the reference stations (baselines), which could enhance the performance while navigating particularly in an urban environment. At present, NRTK permits the transmission of coordinate transformation parameters from the operators, which allows users to constantly get hold of the current site grid transformation without any physical loading or localisation on the rover, and consequently a better regularity in the quality of coordinates can be maintained.

Taking advantage of NRTK’s benefits, many NRTK commercial services have been established in various countries in the last few years. TopNET+ has been the example which had achieved very high centimetric precision. TopNET+ is operated in the UK by Topcon (UK) in affiliation with Ordnance Survey Great Britain (OSGB) since April 2009.

In this work, described in Chapter 5, the use of WADGPS Systems and Network NRTK (Chapter 4, Section 4.3) was considered. The studies covered the analysis of actual positional quality with regard to the TopNET+ service from the end user's view point, that have considered accuracy, precision and availability. In addition, how diverse factors such as the number of satellites in sight and their geometry might affect the positioning accuracy. For the aim to evaluate the service's quality, a number of static and kinematic tests have been conducted by using the same sort of equipment and in the same way that the visually impaired people would have used it (Chapter 5 and Chapter 7).

However, NRTK GNSS positioning is especially hold back by wireless data link coverage, correction transmission delay and completeness, availability of GPS and GLONASS signal etc., which could reduce the positioning quality of the NRTK results. Although augmentation services have been implemented widely, due to insufficient accuracy level, particularly in indoor and urban environment, it has been still considered as a problem.

At present, GNSS has been widely used in various applications as the main positioning component, which focuses mainly on delivering vital service with reference to navigation to pedestrian users.

3.2.3 Other Related Electronic Orientation Aids Projects

This section is a review of other related EOA projects that employs the GPS for navigation and orientation of visually impaired people.

Mobility of Blind and Elderly People Interacting with Computers (MoBIC) is one of the major projects funded by the Technology for the Integration of Disabled and Elderly People (TIDE) research-funding programme of the Directorate General XIII of the Commission of the European Union, and the project lasted between the beginning of 1994 and 1997. It was carried out by a consortium of several universities based in the UK, Germany and Sweden (Petrie et al., 1996; Petrie et al., 1997; The MoBIC Consortium, 1997). The project's purpose was to enhance independent mobility for the visually impaired, partially impaired and older people by working out an aid of orientation and navigation that enable them to travel in familiar or unfamiliar environments. The MoBIC project was built on the technologies of GPS and GIS. The MoBIC Travel Aid (MoTA) contained of two fundamental elements: the MoBIC Pre-journey System (MoPS) and the MoBIC Outdoor System (MoODS). The MoBIC Pre-journey System (MoPS) allows the user to explore a map and to sketch their trip in advance. The MoBIC Outdoor System (MoODS) provided direction and navigational data to the user by executing the proposed plan by MoPS. The MoTA is seen as being complementary to primary mobility aids, such as the long cane or guide dog (Petrie et al., 1997). A prototype was constructed, developed and evaluated (Figure 3.4). It consisted of personal computer, DGPS receiver, GIS database, and speech synthetic output. The system was operated by interpreting GPS data from the DGPS receiver to digital map (GIS) via the mobile computer, and then the mobile computer output a speech message to direct the user. The prototype was designed taking into consideration the outcome of a meticulous analysis of the user requirements performed in the opening stage of the project (Petrie and Johnson, 1995; Johnson and Petrie, 1995; Johnson, Bozic and Petrie, 1995; The MoBIC Consortium, 1997).

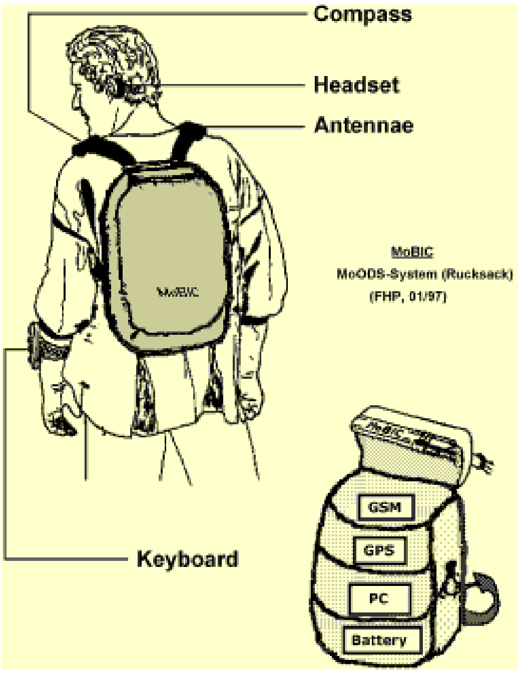

Figure 3.4: The MoBIC electronic orientation aid (Source: The MoBIC Consortium, 1997).

The performance of outdoor field trails was successful, and participants were impressed by the accuracy and navigational data they can receive. MoBIC has also achieved a complete analysis of the specifications, needed to meet the user requirements. Despite successful demonstration the MoBIC system, the designed prototype was never implemented and commercialised. The failure to implement the prototypes is for the most part attributable to the absence of firmly established links between academia, where all the projects were carried out, and the industry that could potentially manufacture and market the EOA emerging from the prototypes. Nevertheless, although the MoBIC project was not introduced in the market, the outcome of the MoBIC was undoubtedly found to be a valuable contribution in the field of mobility aids for visually impaired pedestrians, including the aid developed within this PhD project.

The GPS Talk was the very first EOA made commercially (May, 2000; Misener and Bowers, 2000). The GPS Talk (Figure 3.5) was developed within the industry environment and was release by a small US-based company named Sendero Group. The release of the GPS Talk took place in the beginning of 2000. Nevertheless, the manufacturing and marketing was closed within two years after the release due to unsatisfied sale figures.

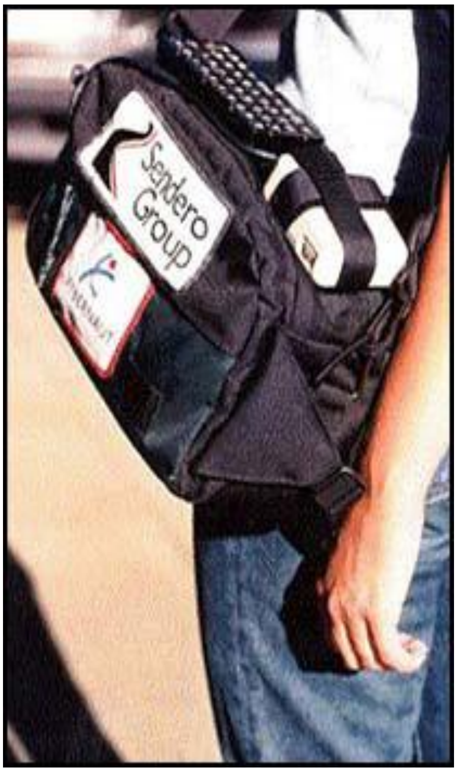

Figure 3.5: The GPS Talk (Sendero Group, 2000).

A wireless navigation system for visually impaired and disabled people was developed by University of Florida, (Helal et al., 2001). This was an additional EOA and was named, Drishti, means *vision* in ancient Indian language Sanskrit. It incorporates a number of technologies, such as mobile computers, voice recognition and synthesis, wireless networks, GIS and GPS (Helal et al., 2001). Drishti system is designed to enable the user to access dynamic and static data, by using a wearable computer from a spatial database server. Drishti enhance related information to the visually impaired and calculates optimised routes based on user preference, temporal constrains and dynamic obstacles. Environmental conditions and landmark information enquiries are provided along their routes from a spatial database on the fly through comprehensive voice signals (Helal et al., 2001; Ran et al., 2004). The GIS database server within the university campus has to be updated continuously through various campus departments such as the University Police, Physical Plant and Special Events, to provide various departments with the ability of inserting and removing dynamic obstacles. Commercial Off-The-Shelf

(COTS) hardware and software were used to implement the Drishti system prototype. The wearable computer along with the GPS receiver and electronic compass are placed in the backpack, the system prototype weights about 3.6kg (8lbs). A head mounted display, for visual tracking, is worn by disabled users and the integrated headset for speech I/O is used by blind persons. Several wireless network connections have been used. Drishti system prototype has been tested around the University of Florida campus. However, Drishti systems require a member of staff to constantly survey and update the remote server, this is costly and unpractical, especially if a wider area coverage is implemented, i.e. covering all dynamic and static obstacles in a city.

NOPPA was a navigation and guidance system for visually impaired pedestrians, aimed to provide the visually impaired and sighted pedestrians with route information. NOPPA was a project run by the VTT Industrial Systems (VTT, 2010) and Ministry of Transport and Communications (MINTC, 2010) in Finland from June 2002 to 2004. The user can access public service databases over internet by mobile devices with capabilities of speech and satellite positioning. A prototype of the NOPPA system was designed to work outdoors by utilising an integrated GPS mobile phone, GIS, communication links (i.e. GPRS), database, internet, and speech recognition (Figure 3.6). In outdoor, the visually impaired passenger will be able to receive navigational data regarding their journey based on the GPS. NOPPA navigation and guidance system for visually impaired pedestrians is useful for providing some information and navigational data during the journey. The navigational data will be delivered to the blind user as a speech message. Nevertheless, this system shares the same weakness as the Drishti system that is mentioned earlier, it’s expensive to use this service, especially for the visually impaired pedestrians who constantly need to access it.

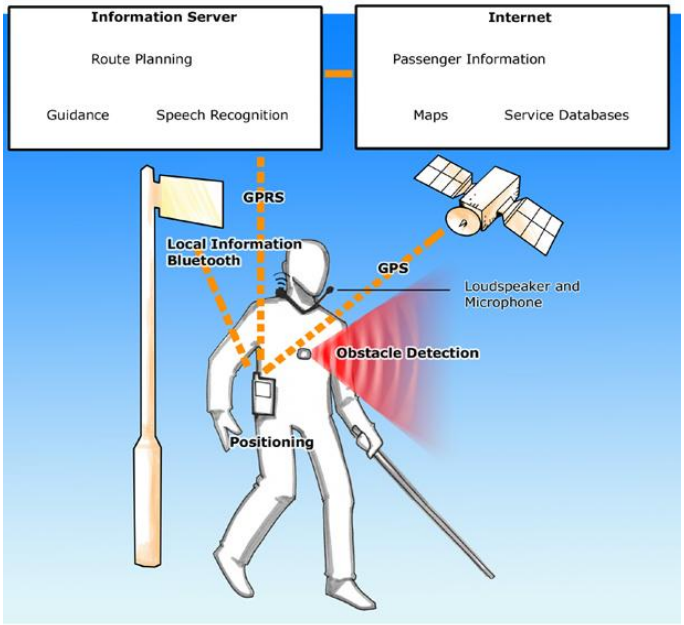

Figure 3.6: NOPPA architecture (VTT, 2010).

The VoiceNote GPS device was made by Humanware (Humanware, 2010) (previously known as Pulse Data International), a company based in New Zeeland. VoiceNote GPS (Figure 3.7) systems with maps were first introduced late in 2003. The device combines computer technology, including digital voicing, with the GPS device, which allows a person to pinpoint his or her location. The device essentially makes an audio map. VoiceNote GPS has two main functions: receiving and recording. In a receiving mode, the device receives signals that determine a person’s location via GPS. Then it connects the user to an enormous database that has pre-programmed points of interest such as, hotels, restaurants and parks. The receiving mode is used mainly for route planning along city streets and previously mapped areas. VoiceNote GPS is subjected to the database availability. However, the system can only provide information about a place if it exists in the database. BrailleNote GPS has the same functions as the VoiceNote GPS with the addition of a Braille display.

Figure 3.7: VoiceNote and BrailleNote GPS (Humanaware, 2010).

The Trekker Talking GPS, designed and manufactured by Humanware (Humanware, 2010) (previously known as VisuAide), was launched in March 2003 and is commercially available right now (Figure 3.8). The system uses GPS and digital maps to help blind persons find their way in urban and rural areas using vocal and written messages. Trekker system provides real-time information finding out such as intersections and area attractions, real-time/offline map browsing, route planning, and access to GPS-enabled location. The system is designed to complement existing navigation aids such as white canes and guide dogs. The system uses off-the-shelf hardware for GPS input and is fully upgradeable. A wide variety of maps can be purchased and updated. Trekker system is reliable to the availability of digital maps; the maps are acquired from a third party.

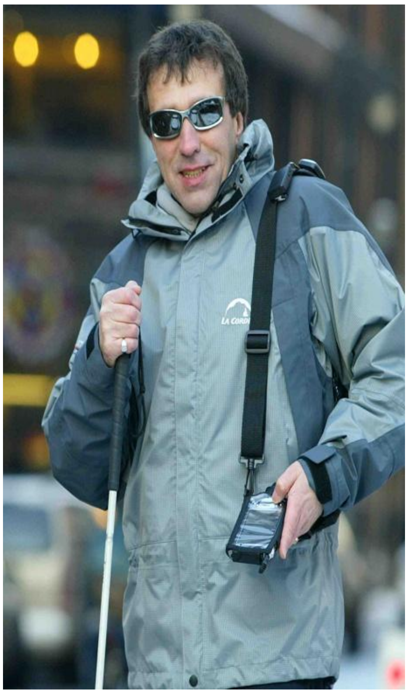

Figure 3.8: Trekker Talking GPS (Humanware, 2010).

Positioning and Navigation of Visually Impaired Pedestrians (PONTES), introduced by Pressl and Weiser (2006), refers to a new system of navigation that helps the visually challenged people to find their direction. Along with GPS, this system of navigation uses features like for example gyrocompass, accelerometer triad, and barometric altimeter. Other advantageous features of PONTES are digital maps, routing and guidance algorithms, and an object recognition function installed utilising a head mounted camera that warns the users about the obstacles in their path. There are also other sophisticated technologies available in order to help the visually challenged people. Organisations like GMV Sistemas and ONCE, the Spanish organization for blind people, have developed a project called MOMO that introduced a mobile phone that can be separately used for the purpose of navigation by pedestrians. This kind of system uses EGNOS positioning data that is maintained with SISNET technology to facilitate enhanced precision (ESA, 2006).

Every EOA that have been introduced so far, together with those developed only to the extent of prototype as well as those that were implemented, are alike each other regarding functionality, system architecture and user interfacing. Moreover, their functionality, system architecture and user interfacing is for the most part comparable to the functionality, system architecture and user interfacing of the mainstream devices for autonomous location and navigation information acquisition based on the GPS and GIS (Vanja, 2006).

The following briefly describes the typical way of utilising EOA during travel. As the visually impaired starts a journey and the EOA is "put on" [4] and activated, the GPS receiver that is integrated in the EOA begins with capturing the signals from the GPS satellites. The EOA processing unit determines the current location of the EOA based on the information controlled by the signals, i.e. the starting location of the journey of the EOA user. In the next step, the location is matched in accordance with the digital map that is included in the GIS application enclosed in the EOA and subsequently presented to the user as a synthesised voice message through the EOA speaker. In general, the location is made available in a format comparable to the first line of the standard postal address. For instance, "You are at 110 Oxford Street." Going along the determined starting position, the users enters the selected location of the journey destination into the EOA utilisation the EOA's keyboard. On the basis of this information, the processing unit together with the route-planning algorithm within the GIS application, set up the most favourable journey route between the starting position of the journey and the destination, and supplies the user with the initial macro-navigational instructions (as a set of exact directions along the route) in order to get on with the journey. In similar ways as the information for location, the instructions are offered as synthesised voice messages.

The EOA constantly updates the user's location as the user walks towards the destination. Furthermore, using the position update and the information in the user's heading, the EOA constantly generates further synthesised voice-based macro-navigational instructions relevant to the launched route and presents to them to the user. The information is either presented numerically, based on the

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[4] EOAs are designed to be wearable in order to allow for hands-free use and thus permit the user to handle a long cane or a guide dog in parallel to using an EOA.

geographical coordinates of several past users' locations, or in some EOA, by the incorporated electronic compass.

Besides enabling the provision of online macro-navigational assistance during travelling (as described above) EOA enable off-line exploration of the digital map contained in the integrated GIS application. An exploration like that, which is supposed to be employed before starting a journey, is intended to facilitate the planning of the journey by way of making it possible for the user to plan specific journey routes as well as construct the cognitive map of the route area before embarking.

The potential of EOA in adding visually impaired people in macro-navigation is unquestionable. The potentiality of this was at first demonstrated through the successful evaluation examinations of the early EOA prototypes (i.e.: Petrie *et al.*, 1997) and this was later re-demonstrated in different assessments of the commercially available EOA, i.e. Humanware, 2010. However, there are a number of "chronic" difficulties attached to the EOA utilisation that requires being resolved in order for the devices to shift from being "gadgets" used by no more than a handful of users- which is the case today- to become a widespread standard mobility aid (Vanja, 2006). Critiques from Farmer and Smith (1997)[5] suggest that the difficulties in question can be separated into two main categories, of which the first refers to the functional problems taking place because of the limitations of the technology applied in the EOA. The second category involves the usefulness and usability limitations linked to the EOA system architecture, operation and maintenance procedures and the macro navigational instructions output of the aids.

The problems in the EOA utilisation concerning the functionality are caused by the technological restrictions of the GPS. The EOA, similar to the mainstream devices, are in the outdoor use within the urban environment often unsatisfactory

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[5] The critique by Farmer and Smith considers only the prototypes of EOAs developed until 1997. Nevertheless, this critique can also be applied to the commercialised EOAs that are presently available at the market because these devices, in terms of the functionality, system architecture and user interfacing domains analysed within the critique, do not differ significantly from the prototypes.

accurate or totally disabled in the provision of macro-navigational information (of varying duration) – because of the blockage of the GPS signal response by objects such as buildings and houses, a large quantity of which exist in the environments of this kind. These problems are principally important to observe and solve since it is in the outdoor urban environment the EOA are suppose to be used most of the time – given the fact that an urban living for the majority of population in general is required for a modern lifestyle, which logically includes the greatest proportion of the visually impaired population as well.

The vital limitation existing both in long cane use and the guide dog guidance is the lacking of dependability in the discovery of obstacles and other hazards within their reach, like steps, tree branches or signs and lampposts. Other difficulties can be dynamic obstacles such as motorcycles and bicycles. Moreover, long canes do not reveal obstacles overhanging the ground at heights above that waist level, since the detection of obstacles range is relatively short (maximum 1m, depending on the type of cane), and mobility supported by a long cane is not efficient either as it is short in gracefulness.

3.4 Summary

This chapter presents the summary of the series of literature review-based studies that were conducted in the early phases of the PhD project. The outcomes of the studies were subsequently implemented as the foundation for the design of the Precise Positioning in Real-Time using GPS-RTK Signal for Visually Impaired People Navigation System.

A comprehensive depiction of the various technologies has been given in this chapter, with its related factors concerning visual impaired navigation. An analysis is presented of the functionality, usefulness and limitations of the, at present, main available methods to support the mobility of visually impaired people and a compilation is provided of the requirements for the design of EOA. The emphasis has been on the positioning technology.

Further research and development work is required in order for the current situation in the area of mobility aids for visually impaired people can be improved. Currently, relevant for the situation is that improvements are in need in aiding both micro-navigation and macro-navigation.

Chapter 4

4. Precise Positioning in Real-Time using Navigation Satellites

4.1 Introduction

Over the years, the GPS has evolved into a significant tool with which to meet civilian navigation and positioning requirements worldwide. All GPS-based positioning techniques operate under a set of constraints. These constraints may be baseline length, attainable accuracy, assured reliability, signal availability, time-to-solution, and so on.

Today, there are different possibilities for the use of satellites for positioning and navigation: not only the well-known American system GPS, but also GPS combined with the Russian system GLONASS or, in future, with the European system GALILEO.

As in all navigation procedures, inaccuracies and even errors, which impair the measured values, occur in GNSS positioning. These effects can be eliminated by the formation of differences. Using Wide Area Differential GNSS (DGNSS) technique, GNSS reference stations installed at a known position, calculates correction parameters and sends them to a mobile GNSS rover over the wireless communication networks.

In order to achieve centimetre- or even millimetre-level accuracies, calculation of a position is based on code pseudo-ranges and carrier phase measurements. However, this Real Time Kinematic (RTK) positioning application is limited by ionospheric errors, tropospheric errors, satellite orbital errors and multipath. During periods of extremely high ionospheric activity, the maximum distance of the rover (user) from the reference station is less than 20 km (Lachapelle 2000). Unlike single reference station RTK approaches, where positioning accuracy decreases while the baseline increases, Network RTK (NRTK) approaches ideally provide positioning with errors independent of the rover position within the network. Moreover, by integrating and optimising the information from multiple reference stations, NRTK covers the desired area with fewer reference stations, compared with the single reference station approach.

This work focuses on NRTK applications related to pedestrian use. The intention is to improve positioning performance and ensure the availability of reliable and highly accurate position solutions, taking into consideration the performance of NRTK GNSS and its augmentation methods for users in various outdoor environments.

4.2 Real Time Kinematic (RTK)

In the mid 1990's investigations related to Real Time Kinematic (RTK) GPS surveying began, focusing on optimal way of processing reference receiver data and then in real-time, providing "correction" information to users (Rizos and Han, 2003). Today, a common surveying and navigation technique is the RTK positioning with GNSS as it enables the utilisation of a static base station at a recognised spot and for real-time data collection utilises mobile rover unit. The process of data are transmitted from the reference station, where in the roving receiver, the computer processor combines its measurement with the data. RTK positioning is a system that allows centimetre level accuracy positioning in real-time. Through efficiently differencing away similar errors and biases that are caused by atmospheric effects and GNSS satellite orbit errors and clock bias in carrier phase interpretation of the receivers at both ends of a baseline, a reference station and a rover.

A conventional RTK positioning system typically comprises of a single reference station which transmits formatted information such as code and carrier phase observations to one or mobile rover units in the field, shown in Figure 4.1. The reference station data is combined with local measurements collected at the rover using proprietary differential processing techniques to yield precise relative coordinate estimates.

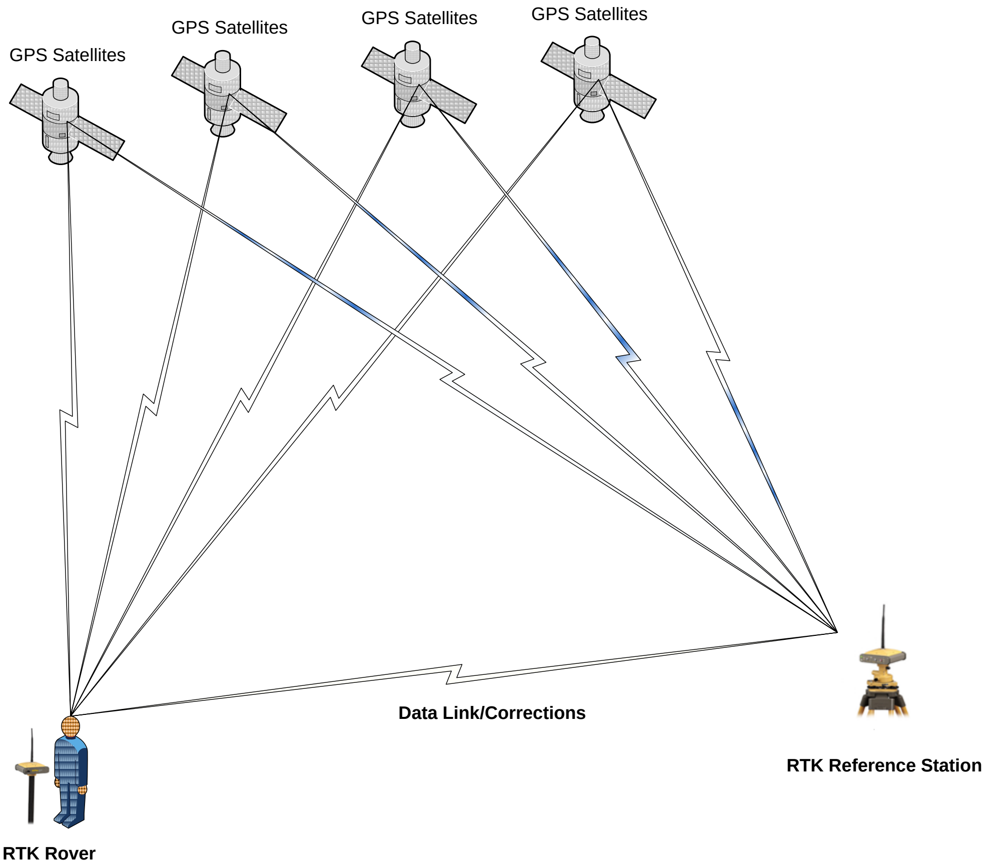

Figure 4.1: RTK system.

The reference station as well as the rover station is equipped with dual frequency receiver. Reference receiver has a radio transmitter to send phase observation corrections to rover receiver which is also equipped with radio modem to ascertain a link with the reference station (El-Mowafy, 2000). The data volume sent by the reference receiver increases because of density if data update rate; as a result of this, RTK GPS requires the data link to have an optimal capacity of 24,00 bps (bytes per second) or at least 9,600 bps or even in some cases 19,200 bps. According to Langley (1997), this kind of data could be supported by the VHF of UHF bands which have a wide spectrum of bandwidths.

An initialisation procedure uses a process called double differencing that the receiver must undergo to begin with and this process helps to aid the unknown number computation of different wavelength between the receiver and a satellite, where measurement of both GPS receiver could be done simultaneously.

According to Roberts (2005), this process of simultaneous measurement was known as “ambiguity resolution”. The rover receiver produces centimetre level position once ambiguities have been resolved, mainly to the base receiver station. From each satellite, the whole number of wavelengths is counted by the receiver in order to eliminate the error sources, which are large enough, particularly addressing the receiver clock bias and satellite. Once a successful initialisation has been performed, the rover is free to move about collecting centimetre accurate 3-dimensional data in real-time. Any loss of lock on the satellites will require the receivers to undergo this initialisation procedure again.

However, this differential positioning method is suitable only for a short baseline lengths (<20 km). The errors from both receivers become less common as the baseline length increases and hence cannot be cancelled out (Wanninger 2004). This sort of occurrence is called spatial decorrelation of errors and is the main restraint of RTK GPS positioning (Aponte et al 2009). Furthermore, due to constraint of a radio modem that transmits the data from the reference station to the rover, the recommended maximum baseline length for RTK GPS is about 10 km (Wegener and Wanninger 2005). These restrictions have constrained the application scope of RTK positioning, for instance, in precise vehicle tracking and pedestrian navigation system where mobility is a priority.

4.3 Network Real Time Kinematic (NRTK)

The drawbacks of RTK are overcome by the Network RTK GNSS, currently a dual system combined of GPS and GLONASS positioning system and it increases the positioning accuracy by precisely modelling the errors that depend on the distance at the rover position using the raw measurements of an array of Continuously Operating Reference Stations (CORS) neighbouring the rover site (Wanninger 2004).

NRTK technology, based on the Virtual Reference Station (VRS) approach, was accepted and became a confirmed technology that is extensively employed today in a great amount of installations all around the world. Developments over the past years (Chen et al., 2003, 2004, 2005; Kolb et al., 2005; Landau et al., 2002;

Vollath et al., 2000, 2001) have resulted in a solution, which is named as GPSNetTM since 1999 (Vollath et al., 2000). By contrast to traditional single base RTK technology, NRTK removes a noteworthy quantity of spatially correlated errors because of the troposphere, ionosphere and satellite orbit errors, hence permits performing RTK positioning in reference stations networks with distances of 40 km or more from the next reference station while supplying, the performance of short baseline positioning (Landau et al., 2007).

The joint use of GPS and GLONASS has attracted an increased interest recently among the navigation community because of the firm progress in the revitalisation of the GLONASS system. Combined GPS/GLONASS navigation can offer many benefits for users of navigation, such as enhanced availability, improved accuracy and integrity. Navigation users are very often in environments with limited satellite visibility such as in urban or mountainous areas. In these kind of situations, navigation users will benefit significantly from the combined use of GPS and GLONASS. However, the amount of GPS and GLONASS satellites that can be observed is still rather often deficient for deriving a position solution partly because an additional unknown has to be solved as there is a system time difference between GPS and GLONASS. As a result, a fifth satellite is necessary for the achievement of navigation solution. The advantages of augmenting GPS with GLONASS are:

- There are two independent systems.
- There is a significant increase in redundancy with the increase in the number of available satellites, and therefore more checks on the integrity/quality of the position solution can be carried out.
- An increase in the number of satellites results in a valid position being computed in more situations, for example when the antenna experiences uneven masking such as by motion, in forest and buildings.
- The geometry of the constellation (PDOP) improves as the number of available satellites increases. The result is an improved consistency in 'valid' position computations over time.

In comparison with standard error budget estimates of a differential GPS system, the accuracies attained when using jointed GPS and GLONASS differential system was favourably. In these cases, dual-frequency measurements can be used to remove the first order effects, thus resulting in better positioning accuracy (Misra and Enge, 2001). Naturally, the more reference and rover stations track satellites, the faster the ambiguity resolution gets and the performance of NRTK solutions in terms of accuracy, availability, reliability improves.

The typical NRTK model comprises of three or more permanent reference stations connected to a central processing facility that estimates the distance dependent errors across the network. Corrections for these errors are combined with raw reference station observations and distributed to users in the field as shown in Figure 4.2.

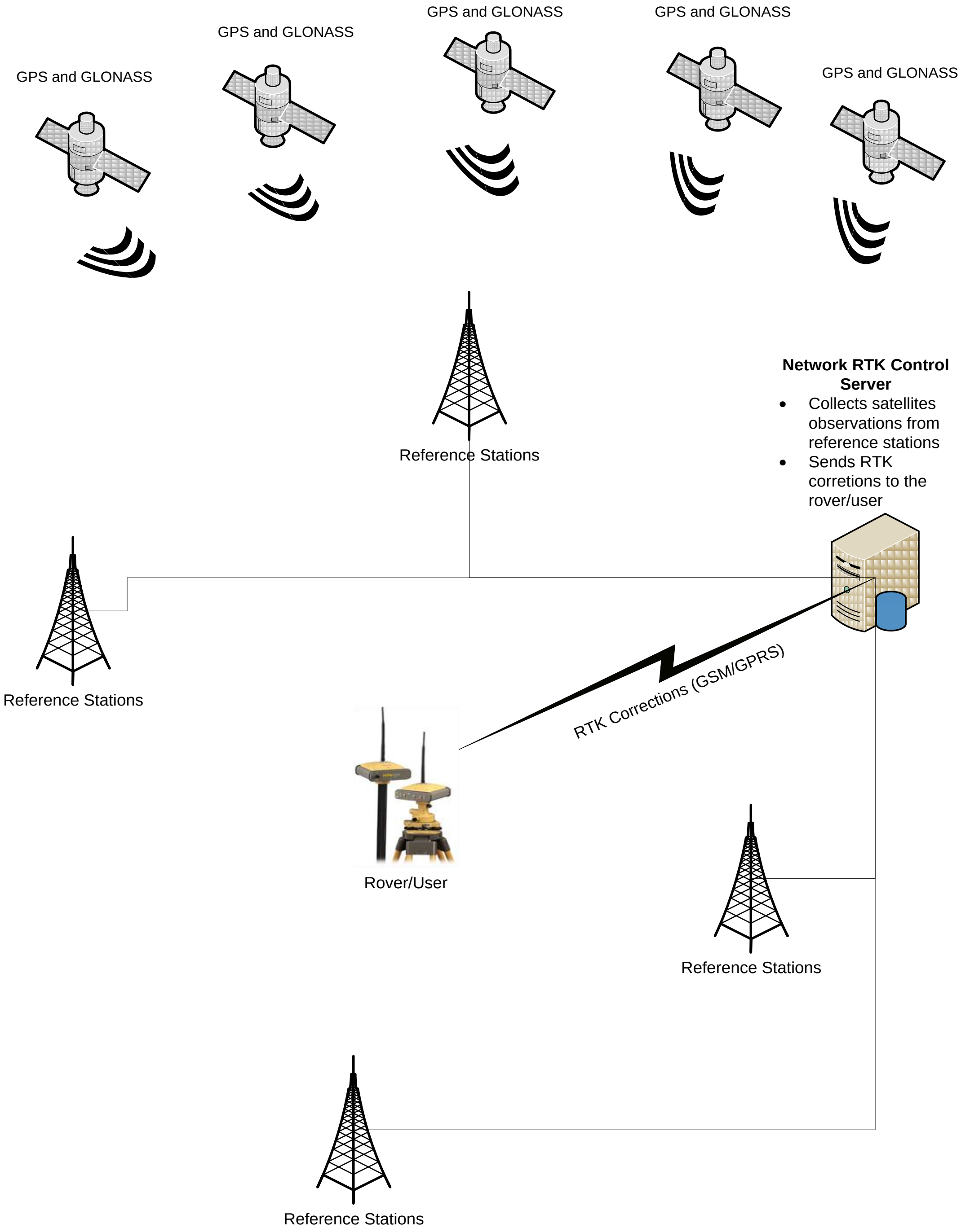

Figure 4.2: Network RTK system.

The information from the network helps to diminish the distance dependent errors viewed at the rover, resulting in more homogenous position accuracy within the region surrounded by the reference stations. The NRTK performance is dependent, to some extent, on the number of available satellites (Takac and Walford, 2006). On the other hand, the network software might not be able to supply with corrections for all satellites in sight. A usual case is low elevation satellites for which the network software has not resolved the corresponding ambiguities. Nonetheless, the raw reference observations still contain valuable information that can be useful for RTK positioning. But, network RTK is usually regarded as an all-or-nothing solution (Alves, 2004). That is to say, raw and corrected observations should not be mixed in the position solution.

In a most favourable solution, the rover software should take into consideration all of the available observation information and account for any residual observation errors remaining after modelling (Takac and Lienhart, 2008).

RTK positioning is a much more complex and vulnerable process, with the intention to achieve the accuracy as high as centimetres with as few as possible data epochs, in real-time for any user in static and dynamic environment. Thus, a better care has to be taken in order to characterise the performance and to address the concern of liability-critical positioning. Users are worried about not only accuracy, but also availability and integrity of the solutions in many applications.

RTK positioning technologies are employed most commonly for outdoor navigation, such as surveying, data acquisitions, machine automation in precision agriculture, mining and construction. However, RTK positioning has not been implemented for pedestrian or visually impaired navigation systems so far (at time of writing).

In this contribution, the novel concept of a precise positioning in real-time using GPS-RTK Signal for visually impaired people navigation system of combining raw and corrected observations in various environments is examined using dual frequency receivers and the TopNET+ network RTK in the UK. The practical benefit of this approach for RTK positioning is tested using real-time data. The results (Chapter 7) demonstrate increased availability of position, better precision and more homogeneous accuracy throughout the network. However, there are some constraints in various environments for both static and dynamic tests.

4.3.1 RTK in Visually Impaired Navigation System

Visually impaired navigation services require constant positioning and tracing of the mobile user with a certain accuracy of positioning and reliability, in particular navigating in urban of the reception of the weak GPS signals being blocked by nearby buildings. As a result, neither EOAs nor the BNSB (Chapter 3) can in such situations provide enough precise macro-navigational instructions. In addition, in some cases, the obstruction of the GPS signal reception is periodically severe to the extent that the location of the user is entirely undeterminable and the macro-navigational assistance can consequently not take place at all. Highlighting the restrictions of EOAs and BNSB components enables a full understanding of matters affecting its QoS. Taking the experienced scenarios with the BNSB into account, several research studies (Hunaiti, 2005; Garaj, 2006; Al-Salihi et al., 2008; Alhajri et al., 2008; Al Nabhan, 2009) have examined the limitations of BNSB to gain an understanding of GPS performance, wireless networks, and mobile devices capabilities, employed in a macro and micro navigation environment. The outcome in toto of these studies shows that BNSB application are still facing a number of challenges linked to the availability of optimal positioning solutions, mobile devices processing, visualising capabilities, and network resources.

With the rapid improvements in satellite constellation and the availability of precise products, such as augmentation services from network-based DGNSS, it should now be feasible to derive accurate solutions for guidance systems utilised by visually impaired people by using NRTK. Aponte et al (2009) conducted several static and dynamic tests using NRTK. The availability of the static NRTK observations without an indication to the surrounding environment was above 97.74%, which ensured an average accuracy better than 5 cm over 98% of the time. Furthermore, dynamic tests showed a much lower availability of the NRTK solution, and resulted in accuracy being better than 5 cm only about 50% of the time. The dynamic test was performed by driving a car around in a mixed route environment surrounded by obstacles, such as flyover bridges, buildings, etc. However, the lack of availability during the dynamic tests was mainly caused by satellite signal disturbances and possibly the interruptions of the GPRS communication link. In addition, multipath and mobile obstacles (e.g. bus, lorries, etc) affected the availability by causing disruption of the NRTK solution. Multipath disturbance affects solutions derived by precise point positioning, relative positioning and dynamic positioning. It is difficult to model multipath disturbance mathematically because of its localised nature and also because of being environmentally dependent.

4.4 Processing Procedures for Real-Time GNSS Positioning

The integer uncertainties in GNSS carrier measurements and the successful resolution of it is important but a challenging undertaking at the same time, in particular regarding RTK positioning. The main issue and challenge for high precision RTK survey and navigation is at the present still the carrier phase ambiguity resolution. The calculation efficiency is of major importance, due to the speed and memory limits, as it can take into consideration the elapsed time prior to the ambiguities can be resolved. The dependability of the ambiguity resolution process is indeed an important concern as well. In order to reach accurate and dependable position solutions under different conditions and navigation environments, the system entails a certain number of procedures. These main procedures are: inter ambiguity resolution in real-time, message decoding, GNSS positioning, navigation and augmentation data availability monitoring, data correction and position calculation.

4.4.1 Message Decoding

The Radio Technical Commission for Maritime Services (RTCM) message decoding handles with every data type separately and afterwards begins with retrieving and synchronizing the necessary data fields, taking in to account the GPS and GLONASS time of the measurements the user receives. These measurements are the position observations of the user, and these are as standard position solutions in the NMEA format. The decoding process of the message comprises of three independent decoding tasks:

- The RTCM message decoding that deals with DGNSS RTCM SC-104 messages received from TopNET+ server.
- The RTCM 10410.1 message decoding, this handles GNSS data corrections from RTCM via Networked Transport of RTCM via Internet Protocol (Ntrip).
- User and navigation data decoding, which deal with satellite ephemeris information and user's measurements.

Several message types are considered while decoding the RTCM messages, containing pseudo-range corrections (PRC), along with the rate of change for the pseudo-range corrections (RRC) for visible healthy satellites observed at the corresponding DGNSS reference station. In addition, another message type is considered for obtaining ECEF coordinates of the corresponding DGNSS station. RTCM messages are made of a number of blocks known as RTCM words, every word is 30-bit length (five RTCM bytes), containing 24 data bits and 6 parity bits (see Figure 4.2).

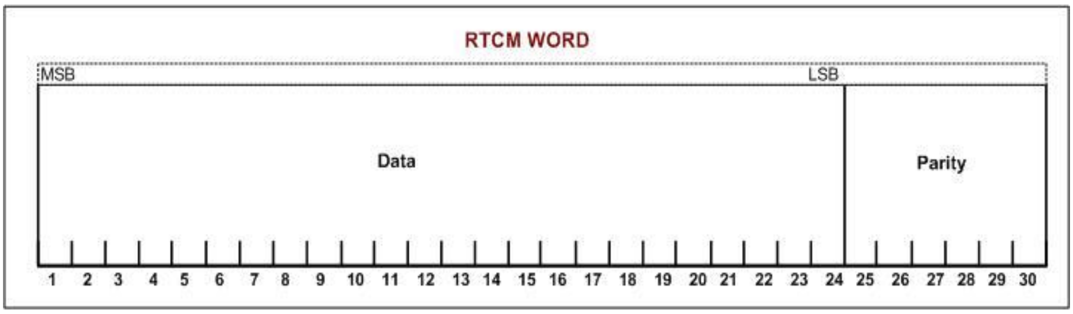

Figure 4.2: RTCM words format (RTCM, 1994).

Each RTCM message consists of a body and a header. While the body keeps data for each corresponding message type, the header is contained in the first and second RTCM words; it composed of message type, reference time, reference station identification, time, and length of message as shown in Figure 4.3.

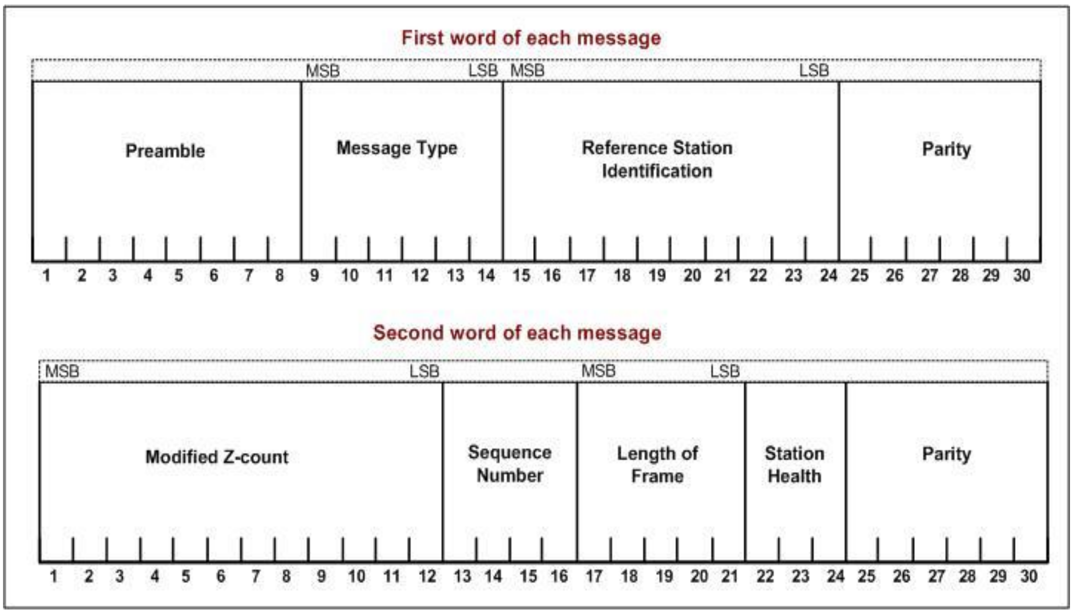

Figure 4.3: RTCM header format (RTCM, 1994).

An RTCM message's length *in toto* rests upon the number of covered and correct satellites. Nevertheless, an integer value in the second RTCM word (Length of Frame) indicates, at all times, the total number of RTCM words that compiles the message. Several versions of RTCM SC-104 data format have been available; these can be summarized as the following:

- **RTCM 2.0:** is only used for DGPS applications (without RTK).
- **RTCM 2.1:** is comparable to version 2.0 but it also contains new messages for carrier phase data and RTK corrections.
- **RTCM 2.2:** additionally to the above, it composes of GLONASS data and associated information which is carried by newly added messages 31-36.
- **RTCM 2.3:** consists of the antenna types in message 23 and ARP information in message 24 as well.
- **RTCM 3.0:** is the most recent version that holds network RTK messages and also accommodates message types for new GNSS systems that are under development, such as GLONASS and Galileo.

The types of messages described in RTCM 3.0 are employed in this work. There are four groups of RTCM 3.0 GNSS RTK messages (RTCM 2004), which are shown below in Table 4.1.

Group Name	**Message Type**	**Message Description**
Observations	1001	L1-only GPS RTK Observables
	1002	Extended L1-Only GPS RTK Observables
	1003	L1 & L2 GPS RTK Observables
	1004	Extended L1 & L2 GPS RTK Observables
	1005	L1 Only GLONASS RTK Observables
	1006	Extended L1-Only GLONASS RTK Observables
	1007	L1 & L2 GLONASS RTK Observables
	1008	Extended L1 & L2 GPS RTK Observables
Station Coordinates	1009	Stationary RTK Reference Station ARP
	1010	Stationary RTK Reference ARP with Antenna Height
Antenna Description	1011	Antenna Descriptor
	1012	Antenna Descriptor & Serial Number
Auxiliary Operation Information	1013	System Parameters

Figure 4.4: RTCM Types.

User’s measurements, as described earlier, obtained at the MNU are in the NMEA. The message decoder merely considers the messages of GGA, which include the GPS and GLONASS essential time and position fixing information. This message contains the list of satellites being tracked and applied for computing the positioning coordinates at the MNU as well.

RTCM has upgraded to Version 2.0 for Networked Transport of RTCM via Internet Protocol (Ntrip), designated as RTCM Standards 10410.1.

The new standard defined by TRCM’s Special Committee 104 (SC104), along with other things, supply a protocol for streaming differential correction data to stationary or mobile users though the Internet. Usually, differential correction have been broadcasted over the radio links from either a single or networked reference stations situated in familiar settings to improve the mobile receivers’ (rovers) real-time accuracy. The majority of these services supply with GPS and GLONASS corrections. The design of Ntrip is to allocate the GNSS streaming data to mobile or stationary clients though the Internet, allowing simultaneous PC, PDA or receiver connections to a broadcasting host. Through the mobile IP networks, such as GSM, GPRS, EDGE, UMTS or HSDPA, Ntrip can support the wireless Internet access.

The navigation message includes a number of data pages, of which each holds five sub-frames. Each and every frame has two data words of 30 bits. In order to extract pertinent information about each observed satellites with respect to the user’s measurement the following sub-frames are considered in the decoding process:

- Sub-frame 1, containing the Satellite Vehicles (SVs) clock parameters. This information is utilised to correct the code phase time received from the SVs, with respect to the relativistic effects. This also permits the compensation of the SVs’ group delay effects.

- Sub-frames 2 and 3 consist of ephemeris parameters which are used to determine the SVs orbits within two hours interval. This information is used in order to calculate the satellites' locations vis-à-vis the time stamps of the user's measurements.

- Sub-frame 4 holds the ionospheric delay coefficients needed for computing the ionosphere delay at the time of measurements by using an embedded ionospheric model.

The information gained from the message decoding procedure is utilised to estimate the user's initial position. Then, before being used in the data *Corrected Positioning Data Computed* process as shown in Figure 5.9 though, the decoded correction information passes through the integrity monitoring and baseline estimation procedures for reliability and validity inspection.

4.4.2 Position Calculation and Data Correction

The position solution, as depicted in Chapter 5, is offered to the user directly from the MNU using the service of NRTK positioning. For the position solutions, coordinate corrections would be set up from the pseudo-range corrections and employed directly to the user's received position solution. This is explained as the coordinate domain positioning.

In contrast to all other current and planned GNSS, GLONASS satellites presently transmit the same variety code signal on different frequencies by means of a Frequency Division Multiple Access (FDMA) technique.

4.4.2.1 Coordinate Domain Positioning

The MNU's receiver offers standard position fixed in NMEA format (Al Nabhan, 2009). A coordinate correction vector ($\Delta\tilde{X}$) is estimated from the pseudo-range corrections (δP) and then straightforwardly added to the user's received position solution. This is attained as follows:

From equation $\tilde{X} = X_0 + (H^T H)^{-1} H^T (\Delta P + \delta P)$ (4.1)

Where:

- H is the observation matrix

- ΔP is a unit vector consisting of the pseudo-range measurements.
- X_0 is a unit vector holding the estimated values of the GPS receiver coordinates and clock bias.

The following is obtained:

$$\tilde{X} = X_0 + \left((H^T H)^{-1} H^T \Delta P\right) + \left((H^T H)^{-1} H^T \delta P\right) \tag{4.2}$$

$$\Delta\tilde{X} = \left((H^T H)^{-1} H^T \delta P\right) \tag{4.3}$$

By substituting equations 4.1 and 4.3 in to 4.2, the following is obtained:

$$\tilde{X} = X + \Delta\tilde{X} \tag{4.4}$$

While X is already extracted from the NMEA GGA messages, $\Delta\tilde{X}$ is the coordinate corrections gained by multiplying the pseudo-range correction vector (δP) with the components of the observation matrix H .

While applying the coordinate domain positioning method, there are two chief points to consider:

- The coefficient matrix H has to be updated constantly. Thus, the satellite ephemeris should be accessible and up-to-date to be able to calculate the tracked satellites' coordinates.

- The standard position solutions contained within the NMEA GGA messages is corrected at the MNU by way of using the receiver internal dual-frequency ionospheric filters.

4.4.2.2 Integer Ambiguity Resolution in Real-Time GNSS Positioning

The difficult part in making an RTK system lies in aligning the signals appropriately. In order to align them easily, the navigation signals are intentionally encoded, but each cycle of the carrier is similar to every other. Thus, this makes it enormously difficult to know if the signals are aligned properly or if they are "of by one" and are hence introducing an error of 20 cm, or a larger multiple of 20 cm. The problem of the integer ambiguity problem can be attended to, to some extent, with sophisticated statistical methods that compare the measurements from the C/A signals and by comparing the resulting ranges between multiple satellites. On the other hand, none of these methods can decrease this error to zero.

The prerequisites for RTK are Integer ambiguity resolution, for instance, as instantaneous ambiguity resolution and ambiguity resolution On-The-Fly (OTF). Along with many specifications of the RTK, three of them are most significant, these are: ambiguity resolution initialisation time, ambiguity resolution reliability and RTK accuracy, which are all related to each other. The ambiguity resolution initial time is important for the real-time applications. The accuracy of the RTK depends on the carrier phase measurement accuracy. Nonetheless, it is still a challenge for the single-frequency case to resolve the ambiguities rapidly and reliably (Han, 1997; Wang et al., 2003). Because of variations in propagation delay of the code and carrier, and those are unpredictable due to the ionosphere and other error sources, it is practically impossible to obtain ambiguity resolution with single-receiver positioning. Consequently, carrier phase measurements are almost always relegated to high-accuracy applications in which errors of such kind are cancelled out by differential operation with a supplementary receiver (base-station) (Mohinder, et al., 2007).

Even though using pseudorange measurements, C/A-code are the most frequently employed a much higher level of measurement precision can be achieved by measuring the received phase of the GPS L1 or L2 carrier. Because of the short period of the carrier waveform (6.35 $\times 10^{-10}$ s at the L1 frequency), the noise-induced error in measuring signal delay by the methods of phase measurements is generally 10–100 times smaller than that encountered in code delay measurements (Mohinder, et al., 2007).

Nevertheless, carrier phase measurements are extremely ambiguous since the phase measurements are simply modulo 2π numbers. With no additional information, such measurements determine merely the fractional part of the pseudorange when measured in carrier wavelengths. Further measurements are necessary to have an effect on ambiguity resolution, in which the integer of wavelengths in the pseudorange measurement can be decided. The link between the measured signal phases ϕ_i and the unambiguous pseudoranges ρ_i can be formualted as (Mohinder, et al., 2007):

$$\begin{aligned} \rho_1 &= \lambda\left(\frac{\phi_1}{2\pi} + k_1\right) \\ \rho_2 &= \lambda\left(\frac{\phi_2}{2\pi} + k_2\right) \\ &\vdots \\ \rho_n &= \lambda\left(\frac{\phi_n}{2\pi} + k_n\right) \end{aligned} \tag{4.5}$$

where n is the number of satellites observed, λ is the carrier wavelength, and k_i is the unidentified integral number of wavelengths contained in the pseudorange. The further measurements needed for determination of the k_i may contain C/A and/ or P(Y)-code pseudorange measurements from the same satellites used for the phase measurements. The range of admissible integer values for the k_i is narrowed significantly since the code measurements are unambiguous. Moreover, phase measurements, made on both the L1 and L2 signals, can be employed to attain a virtual carrier frequency equivalent to the dissimilarity of the two carrier frequencies (1575.42 − 1227.60 = 347.82 MHz). The 86.3 cm wavelength of this virtual carrier reduces the density of pseudorange ambiguities by a factor of about 4.5, facilitating the ambiguity resolution process a great deal (Mohinder, et al., 2007).

GPS ambiguities connected to Double Difference (DD) carrier phase observations are generally resolved in GPS data processing schemes. The double-difference technique efficiently alleviates common errors brought in by the receiver and satellite hardware, together with satellite clocks and the receiver, and also the Earth's atmosphere. By subtracting two inter-station single difference observations, double-difference observations can be shaped (Lee et al., 2005).

Moreover, the inter-state single-difference is derived, by subtracting measurements to the same satellite observed simultaneously at two stations. The single-difference and double-difference involve reference station *m*, rover station *k* and GNSS satellites (Petovello and Takac, 2009), as shown in Figure 4.5.

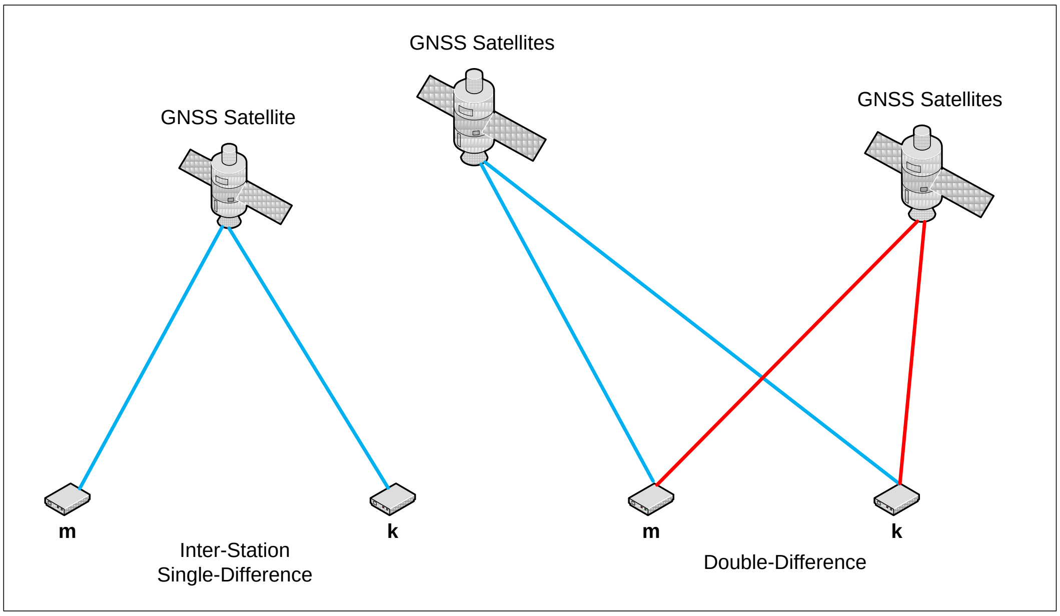

Figure 4.5: The double difference (Petovello and Takac, 2009).

4.5 Precise Positioning in Real-Time using GPS-RTK Signal for Visually Impaired People Navigation System

A reliable navigation system for visually impaired people necessitates the determination of the current position of the user, by means of different components that are integrated into the system design. The below tasks are dealt with:

- The ability to lead the visually impaired user in real-time with the use of diverse suitable location components and to gain an optimal estimate of the present user's position.
- The possibility to find the user in 3 dimensions with high precision.
- The ability to complete a faultless transition for continuous positioning determination between urban, suburban and open field areas.

To achieve above mentioned tasks a novel system has been designed and developed at Brunel University. As mentioned in Chapter 3, one of the weaknesses that prevent BNSB from being standard mobility support is the functional unreliability of the devices deriving in technological limits of the GPS. These limitations rise in urban environments and densely areas since there is a significant possibility for the signals to be jammed and interfered because of high obstructing buildings and difficult landscapes. These boundaries have carried great attention during the last decades attempting to augment GPS positioning services among multiple signal error sources. Consequently, a variety of methods have appeared, such as DGNSS systems allowing GPS and GLONASS signal errors to be reduced or abolished based on pseudo-range or carrier-phase differential correction procedures (Kaplan and Hegarty, 2006). Various researchers under different circumstances and settings have shown that NRTK can achieve accuracy below 5 cm in static tests. However, there are some constraints in dynamic tests, mentioned earlier in this chapter.

This work focuses on a precise positioning in a real-time navigation system related to visually impaired people. The purpose was to improve the positioning performance and ensure the availability of reliable and highly accurate position solutions. This new system, *Precise Positioning in Real-Time using GPS-RTK Signal for Visually Impaired People Navigation System*, was designed by applying the principles of maximum effectiveness in a functioning of a system methodology, following the outcome of the literature review studies that were summarised in Chapters 2, 3 and 4. The conceptual framework for the design of the system was adopted from the Brunel Navigation System for the Blind (BNSB), a mobility aid also developed within the Electronic Systems Research Centre (ESRC) at Brunel University, where this PhD project was carried out.

Precise Positioning in Real-Time using GPS-RTK Signal for Visually Impaired People Navigation System consists of two main terminals (Chapter 5, Figure 5.1). A client, Mobile Navigation Unit (MNU), which is located at the site of the visually impaired user and a Navigation Service Centre (NSC), which is located at the site of the sighted guide who guides the client to the destination using audio communication via wireless networks. The client consists of a high precision dual frequency GNSS receiver (NRTK), a digital camera, a speaker, a hands-free set containing a microphone and earpiece is used by the user for voice communication with the guide and a wireless communication interface (3G/HSDPA). The server consists of a number of workstations equipped with a customized GIS database. It enables remote tracking of visually impaired pedestrians based on NRTK GNSS location and a live video image and voice communication. The system's primary goal is to assist in navigating visually impaired people in macro and micro navigation environment. The positioning performance of NRTK and wireless communication is a crucial attribute for the quality of guidance.

4.6 Summary

This chapter illustrates Network-based Real Time Kinematic (NRTK) GNSS positioning is regarded as an advanced solution as compare to the standalone GPS positioning and previous single reference station based Real Time Kinematic (RTK) positioning technique. NRTK GPS positioning uses unprocessed measurements collected from a network of Continuously Operating Reference Stations (CORS) one by one to produce more dependable error models that can tone down the distance dependent errors inside the region enclosed by the CORS. This procedure has been developed and checked significantly in recent years and compared to the usual RTK positioning technique, its performance is better in terms of precisions that can be achieved, dependability and mobility.

Like any other GNSS technique, NRTK is adversely influenced by the satellite line-of-sight obstructions. Even the most exact orbit and clock data is ineffectual if the user is not able to track particular satellites. By way of using the full range of satellites from both the GPS and GLONASS systems, a best possible service can be warranted if satellite visibility is partially blocked. This can occur in suburban environments, it is a very demanding undertaking since pedestrians move in spaces where no one of the familiar location methods works continuously in standalone GPS/DGPS mode or conventional RTK GPS.

The increase in the number of available GNSS satellites can offer many advantages for navigation users, such as enhanced availability, improved accuracy and integrity.

In this work, a precise positioning in a real-time navigation system for visually impaired people was designed, taking into consideration a set of related parameters affecting the positioning performance. The novel system is responsible for integrating the available positioning methods within the surrounding environment. This system was demonstrated within an efficient positioning model that was designed and developed based on NRTK GNSS services ensuring the availability of reliable, highly accurate and precise position solutions for pedestrian applications in different environments. The latest positioning mechanism developed was adopted as a client-server-based architecture incorporating both the user side known as Mobile Navigation Unit of MNU and the other being the remote one known as the Navigation Service Centre of NSC.

Chapter 5

5. System Design

5.1 Introduction

The main objective of this PhD project is achieving an improved navigation positioning performance to be utilised in applications covering users with a visual impairment. The system, entitled the Precise Positioning in Real-Time using GPS-RTK Signal for Visually Impaired People Navigation System, was designed and its prototype developed within the Centre for Electronic Systems Research (CESR), a research group based at the School of Engineering and Design, Brunel University. This chapter presents the overall process of the system design, the architecture and functionality of the developed system prototype, and the integration of the correction services from network-based DGNSS systems. User-centred system design methodology guided the system design process.

Besides the studies associated with the system design, the architecture, and the functionality of the system and the integration of correction services from network-based DGNSS systems, an extensive study was undertaken of the various technologies with actual relevance to the navigation system for visually impaired people and the technologies deemed as potentially relevant to the novel system. The technologies taken into account include the UMTS and HSDPA (Section 5.3), all belonging to the domain of wireless communication technologies.

Sections 5.1 and 5.2 describe the positioning model’s prototype and components. Section 5.4 presents the main system model operational architecture. The system functions and the operational methods implemented at both the Mobile Navigation Unit (MNU) and the Navigation Service Centre (NSC) are presented in Sections 5.5 and 5.6. Section 5.7 summaries this chapter.

5.2 System Model Prototype

As the prototype of the BNSB, the prototype of the Precise Positioning in Real-Time using GPS-RTK Signal for Visually Impaired People Navigation System comprises one mobile and one stationary terminal. The mobile terminal, the MNU, and the stationary terminal, the NSC, are the two important terminals associated with this new system. The MNU is situated within the vicinity of the visually impaired user, and the NSC is located with the sighted guide who is involved in guiding the user to the destination. These are connected via a wireless two-channel voice and data communication link between the terminals. The prototype system model describing its main components, such as communication links and data transmissions are shown in Figure 5.1.

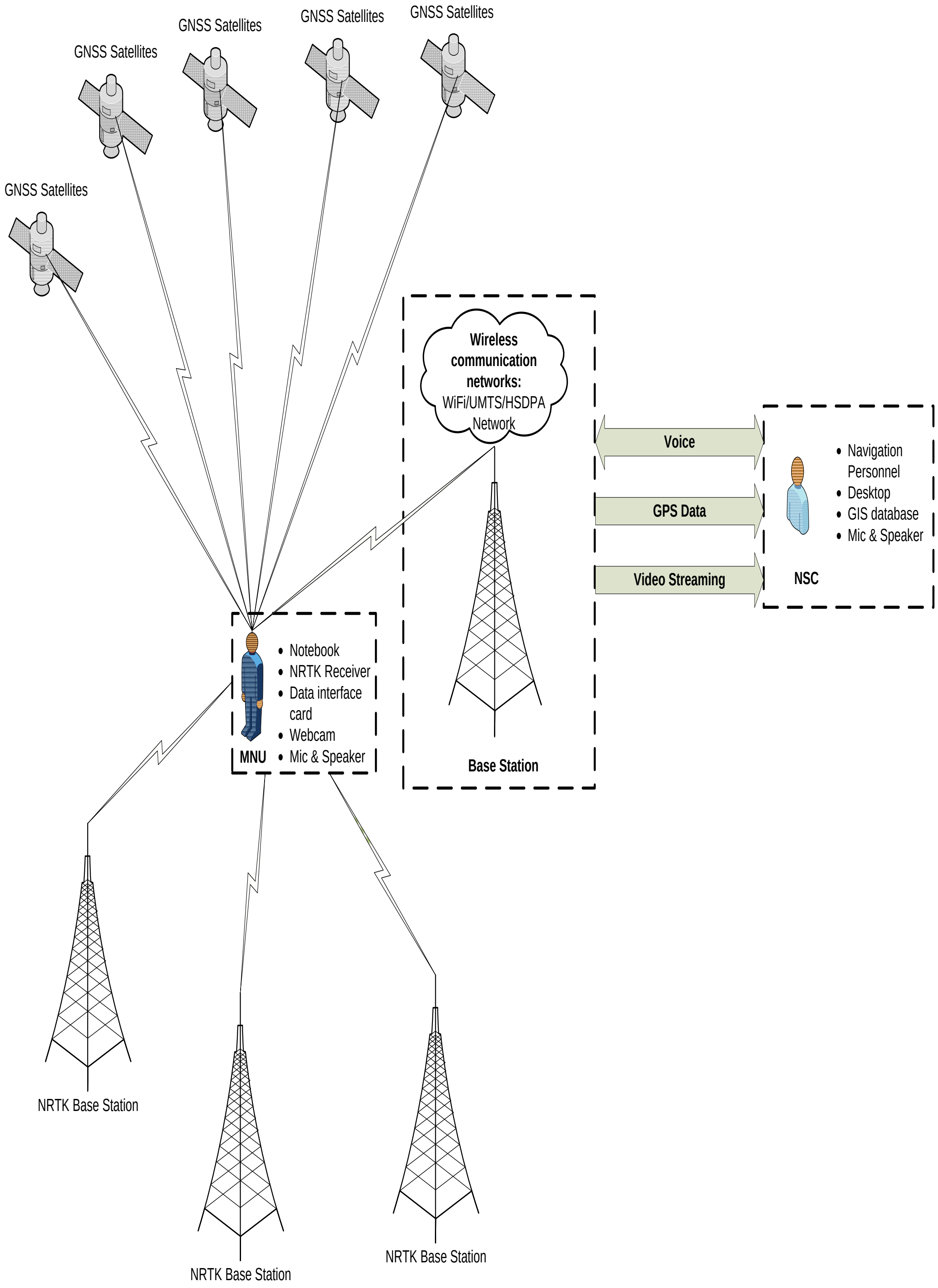

Figure 5.1: System Model Prototype.

The MNU will facilitate the end-user to send the positioning data, video, and voice data to communicate with the NSC through the wireless network. All the individual components composing the MNU are integrated in a wearable single unit. Garaj (2006) conducted an initial study to analyse the user requirements for the design of high-technology mobility aids for visually impaired people. According to the interpretations of this study, it was decided that the MNU should be appropriately designed as a wearable device. The MNU should provide comprehensible and obvious information. The natural senses of the user should not be affected in any way due to the high-technology mobility aid (Hunaiti, 2005). Also, the aid should be in usable condition during all unfavourable climatic conditions. The conveniences that the users should expect are the long-life, state-of-the-art mobility aid and cosmetic applicability, such that their handicap is concealed to a certain degree. It should also be easy to store when not in use. In addition, the presence of the mobility aid unit should not attract the attention of others (Garaj, 2006; Petrie and Johnson, 1995). The MNU consists of a high sensitivity dual frequency receiver for implementing NRTK, a digital camera, a speaker, a microphone and a wireless communication interface.

The NSC is a static service provider and operates automatically once the visually impaired person establishes the link between the MNU and the NSC. The guide at NSC can guide the visually impaired user, as shown in Figure 5.2.

Figure 5.2: The Navigation Service Centre (NSC) (Hunaiti, 2005; Garaj 2006).

The NSC is equipped with a number of services, consisting of a standard personal computer, a communication interface to transmit and receive data to and from the MNU, a customised GIS, and a screen, which displays the GIS applications' contained digital map of the user's travel environment and captured video image simultaneously. The captured video image is transmitted to the NSC from the MNU through a video image transmission channel. In the NSC, the starting location is displayed on the screen, and plotted on the digital map of the user's travel environment together with the received video image (Figure 5.3). In the next stage, the user provides the guide with the details of the travel destination of choice; the provision is carried out verbally through the voice communication channel. The details can be given as an exact location, for example, the address of a particular restaurant in the neighbourhood, or as a description of the destination, for example, the nearest restaurant in the neighbourhood, in which case, the guide determines the exact location. Based on the information on the starting location and the location of the destination, the processing unit in the guide's terminal, in conjunction with the route-planning module inside the GIS application, calculates the optimal route connecting the starting location and the destination. As the route is calculated, the digital map display presents it as a diagram. The dual frequency RTK receiver at the MNU and the GIS application, combined with the digital map display in the NSC, structure the system's positioning and tracking unit. This design simplifies the hand-held device and its user interface using voice communication between the trained navigation staff and the visually impaired person.

Evaluation of the wireless communication features is an important part of the system and could greatly affect the functioning of the Precise Positioning in Real-Time using GPS-RTK Signal for Visually Impaired People Navigation System as a whole, and this is explained in detail in following sections.

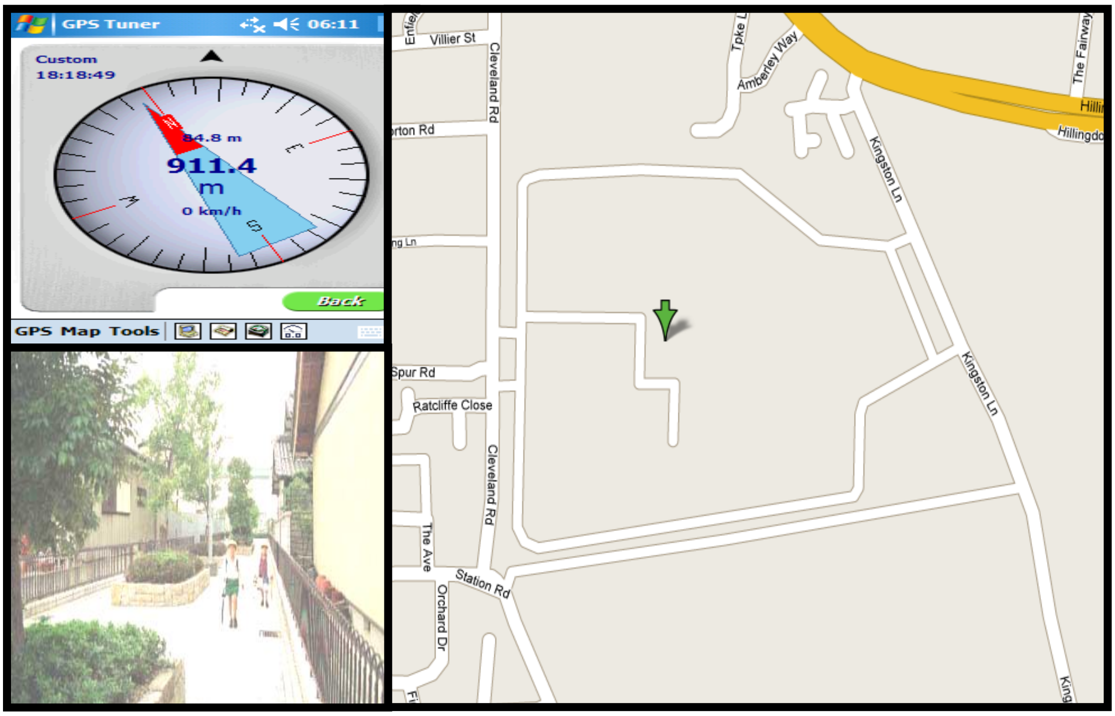

Figure 5.3: Display at NSC.

5.3 Integration between GNSS and Mobile Communications

Generally, the most common guidance systems’ illustration is presented as a client-server-based architecture comprising a mobile device with a positioning capability, which is remotely attached via communication channels to the service providers. The integration between GPS/GNSS receivers and mobile communications is necessary and takes into consideration commercial, as well as technical reasons. Figure 5.4 shows the main components and architecture.

Currently, several companies are integrating a GNSS receiver, computing technologies, and mobile phones into a single mobile device. When there is a need to send the positioning data and messages through mobile units to base stations, the standard mobile networks, such as GSM or third generation mobile technologies (3G) are used.

Generally, a process followed by the application user takes place by sending the service request via a communication network to the application server. For this kind of communication, a mobile network is a commonly used means of communication. The request sent by the user comprises the user's position co-ordinates that the application server has been using. This can be done by retrieving useful information from the databases (Beaubrun et al., 2007; Steiniger et al., 2008). The internet connectivity can become a part of the communication network and is a useful source of displaying information geographically. At the final stage, a service reply is sent back to the user.

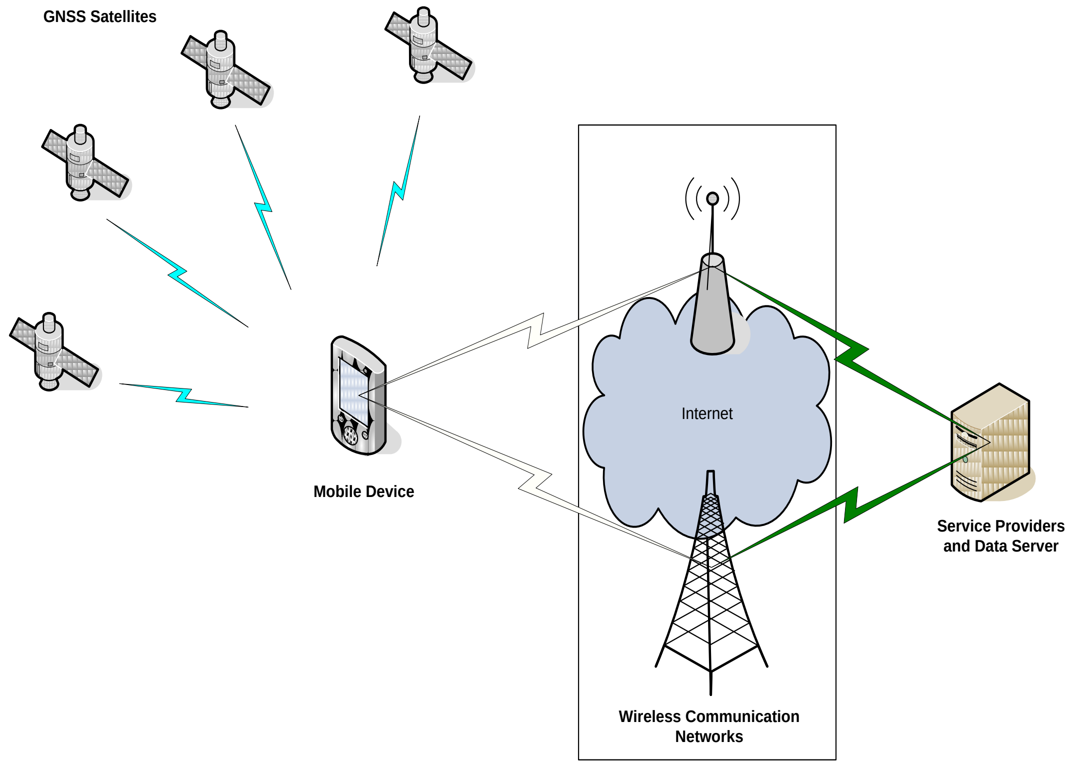

Figure 5.4: The main components and architecture for integration between GNSS receivers and mobile communications.

5.3.1 The Performance of Mobile Networks

The communication link between the NSC and MNU is an important component of the navigation system. The quality of the communication link has a significant impact on the overall performance of the navigation system. The communication between the sites of the visually impaired user's MNU and the site of the guide's NSC is a real-time bi-directional communication, as shown in Figure 5.1. Furthermore, the communication between the NRTK receiver at the MNU and the TopNET+ network for augmentation of the positioning data is also in real-time.

A performance assessment was carried out of different wireless mobile technologies, such as UMTS and HSDPA, for utilisation in the system. The performance assessment focused on the following link features: delay, jitter, and packet loss. Three service provider's networks in the UK, Orange, T-mobile, and Vodafone, were tested at Brunel University's campus.

As reported by Al-Salihi et al. (2007) and Alhajri et al. (2008) the comparison between Orange's UMTS, T-mobile and Vodafone's HSDPA with ITU standard in terms of packet loss, jitter, and delay is presented in Figures 5.5, 5.6, and 5.7, respectively. In terms of packet loss, the only technology that satisfied the condition of ITU[6] standard (packet loss < 150 ms) was HSDPA. In the jitter comparison, the HSDPA matched the standard while the UMTS network was unsuccessful because of very high packet loss. In delay comparison, all of these technologies fitted the standard.

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[6] ITU (International Telecommunication Union), Cisco (Howald, 2003,(Szigeti and Hattingh, 2004), and other organisations define standard requirements for video and voice transmission, as follows:

- **Delay:** < 150ms - acceptable; 150 – 400ms – bordering acceptable (some quality issues may occur); > 400ms – unacceptable.
- **Packet Loss:** should not be more than 1%.
- **Jitter:** < 30ms – acceptable; > 30ms – unacceptable (significant voice degradation).

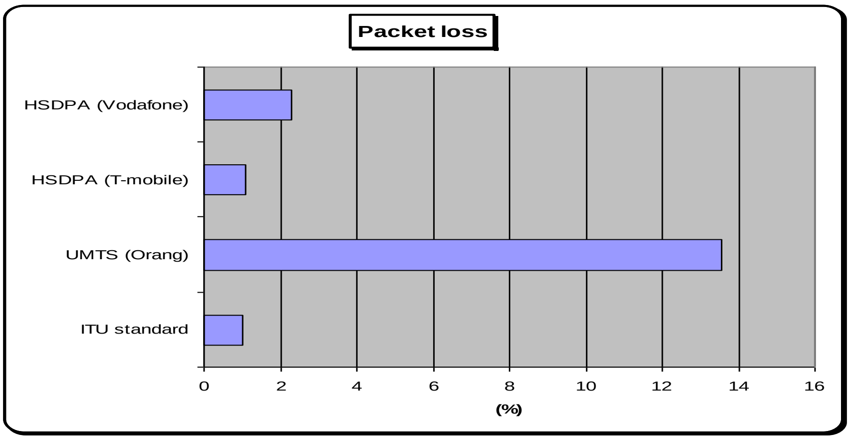


Figure 5.5: Packet loss comparison between different technologies.

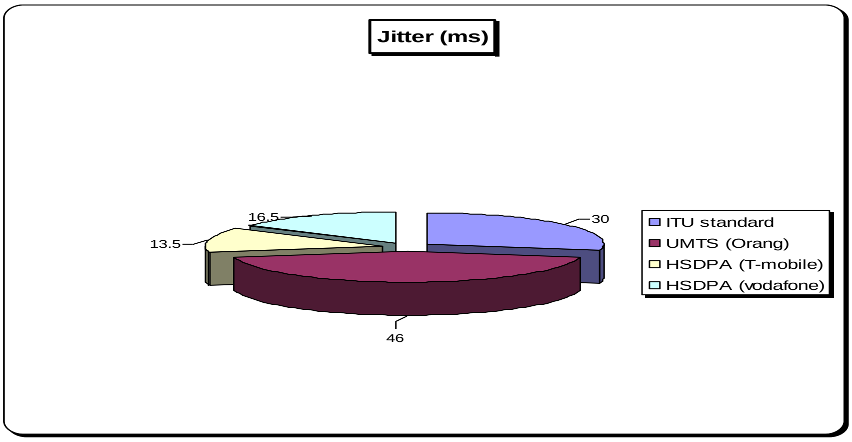


Figure 5.6: Jitter comparison between different technologies.

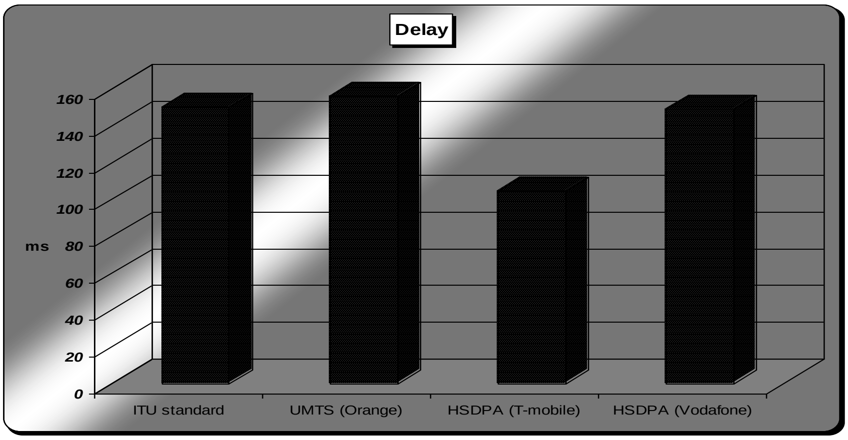


Figure 5.7: Delay comparison between different technologies.

5.4 System Model Operational Architecture

A new sophisticated positioning model, based on the above depicted concept, has been designed and developed as a multi-thread user-server based approach (Figure 5.8). A new provision was introduced at the MNU, described as the Network RTK real-time positioning corrections. The availability of the WADGPS correction data from the network-DGNSS (CORS) system, TopNET+, was received at the MNU for positioning data corrections. This could be attained by way of using wireless devoted communication channels for the corresponding correction sources, such as TopNET+ data servers.

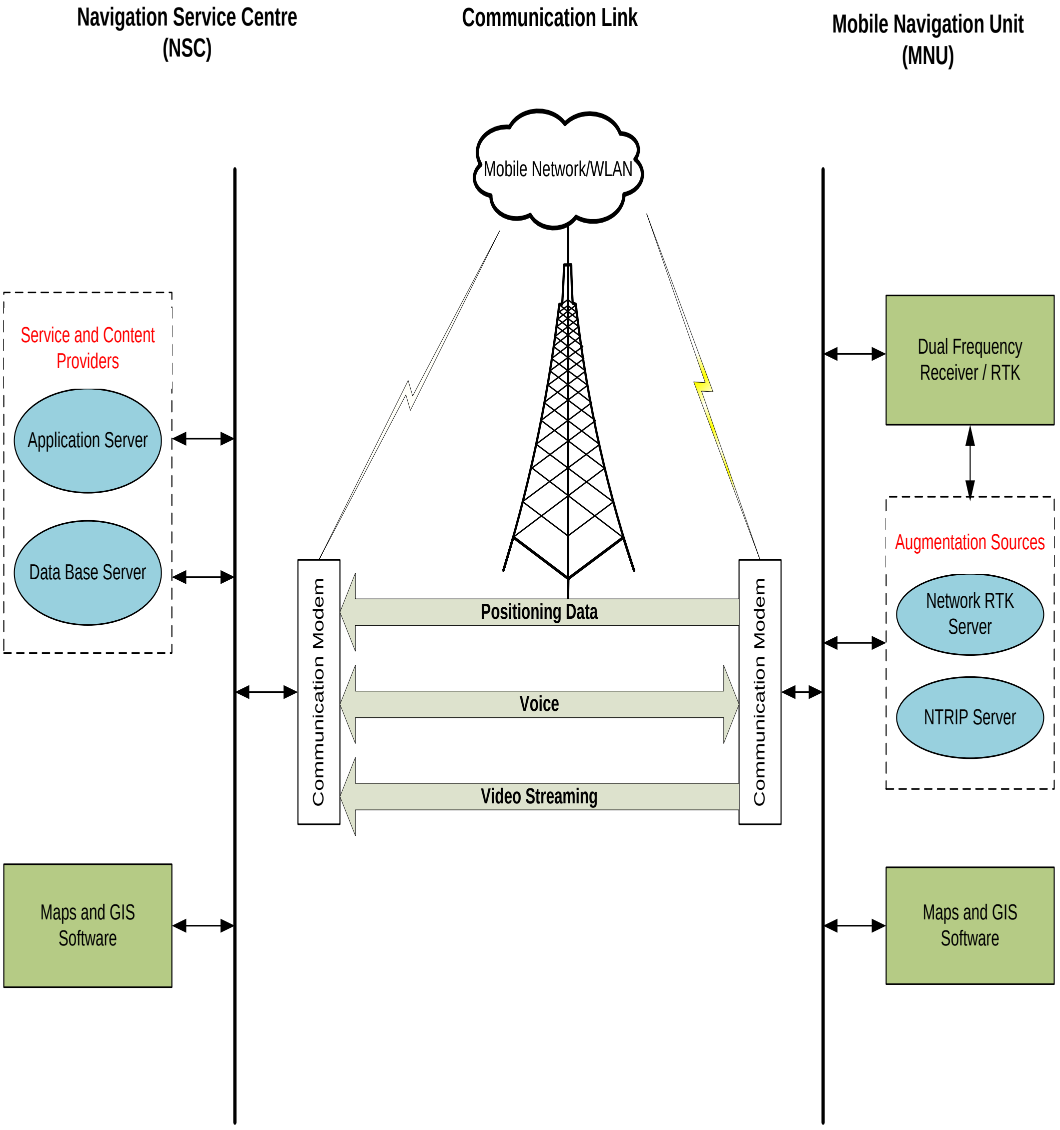


Figure 5.8: System model operational architecture.

As mentioned earlier, the MNU maintains the dedicated wireless mobile connections with augmentation data sources of GPS and GLONASS. The source for the MNU was the TopNET+ NTRIP, and in the RTCM format, a network-based DGNSS correction was provided. Through a wireless connection, transmission of corrections from the server of the NTRIP to the mobile through the GPRS connection would take place using a data enabled mobile connection. TCP/IP connections to the assigned IP addresses handle the communication channels to both sources. This is implemented in this system because accurate positioning information is urgently required to provide critical remote services for a visually impaired pedestrian.

The communication link acts as a middleware element, linking the NSC and its components, such as service and content providers (application server and data base server) with the MNU, allowing the augmentation source directly to utilise the user’s position data, which are available at the NSC. This scenario is mostly implemented when accurate positioning information is required by the application server to track a pedestrian or a car/truck in a non real-time application.

A dual frequency RTK receiver is implemented at the MNU and is used to continuously download up-to-date positioning data from satellites and augmentation data from more than 100 reference stations across UK, shown in Figure 2.2. Components, such as notebook, RTK receivers, data-interface cards, cameras, microphones, and speakers are also attached to the MNU. As explained in Chapter 3 and Chapter 4, these components are responsible for the navigation system contextual adaption.

The most frequently used characteristic features of RTK positioning devices at present are the augmentation functionality, tracking sensitivity, data output formats, the quantity of channels, and the Time To First Fix (TTFF). The focus of this work is on dual frequency RTK GNSS receivers supporting DGNSS capability and corrections throughout the UK. This type of dual constellation tracking (GPS and GLONASS) is an added advantage as it enhances performance, more satellite coverage, and moreover, its precision is improved. Standard GPS positioning format is the form in which receiver data output is being considered (NMEA GGA).

In a scenario where there is an unavailable signal from the satellites, and when the visually impaired person is outdoor in an urban environment, as well as indoor, only video and voice guidance can occur, transmitted through the network of wireless communication. From the MNU, one-way video communication to the NSC and the bi-directional mode for the voice communication would take place. This is described in more detail in Section 5.6.1. Digital maps and GIS resources would be included in the MNU in some cases, depending on the type of navigation applications. Using wireless mobile communication, the MNU transmits the positioning information through the communication link to the NSC. In the case of remote service, the accurate coordinates could be forwarded directly to the application server, where services are remotely delivered to users (clients) from a remote service provider.

5.5 System Functions

The system model is composed of two main functions:

- Data communication
- Data processing

A bi-directional wireless communication link between the MNU and the NSC is utilised by the data communication function. The bi-directional channel is initiated based on positioning data availability restrictions at the MNU; this is described in more detail in Section 5.6. The MNU perceives user and application requirements from the attached profiles and starts supporting the required navigation solution. When the correction data is made available, an advanced positioning method will be performed at the MNU. The MNU can transmit the appropriate coordinates (NMEA GGA data) to the NSC. The data processing level provides a summary of the different procedures taking place at the MNU. These procedures are required for executing the overall positioning model functionality. At the MNU, this includes data acquisition and accessibility verification, data transmission, and corrections. In addition, if only video and voice module was used, then a manual guidance is performed, and this is described in more detail in Section 5.6.1. Finally, the MNU is responsible for providing the navigation service provision to the end-user. This mainly incorporates data filtering, data validity checking, and integrity monitoring, correction data processing, and position correction and computation. Chapter 6 illustrates these procedures in more detail. At the NSC, several procedures are performed in order to efficiently decide users' positioning method selections and to navigate the visually impaired pedestrian to an accurate position solution.

5.6 The Operational Methods of the System

The navigation system model is composed of two main operational methods processes, and both the MNU and the NSC components plan and execute these processes. These approaches are accountable for including both components to obtain a better solution for positioning and to navigate the user at the MNU.

5.6.1 Mobile Navigation Unit (MNU) Operational Method

To find a particular user's location, the MNU largely focuses on the attached dual frequency RTK receiver with DGNSS capability. In case the positioning information and augmentation data at the MNU are unavailable, then an alternative source of direction is utilised, which consists of the NSC and the integration with live streaming video and voice. In Figure 5.9, a flowchart of the MNU operational method is shown, which depicts the order of procedures taking place at the MNU to find out the essential positioning coordinates.

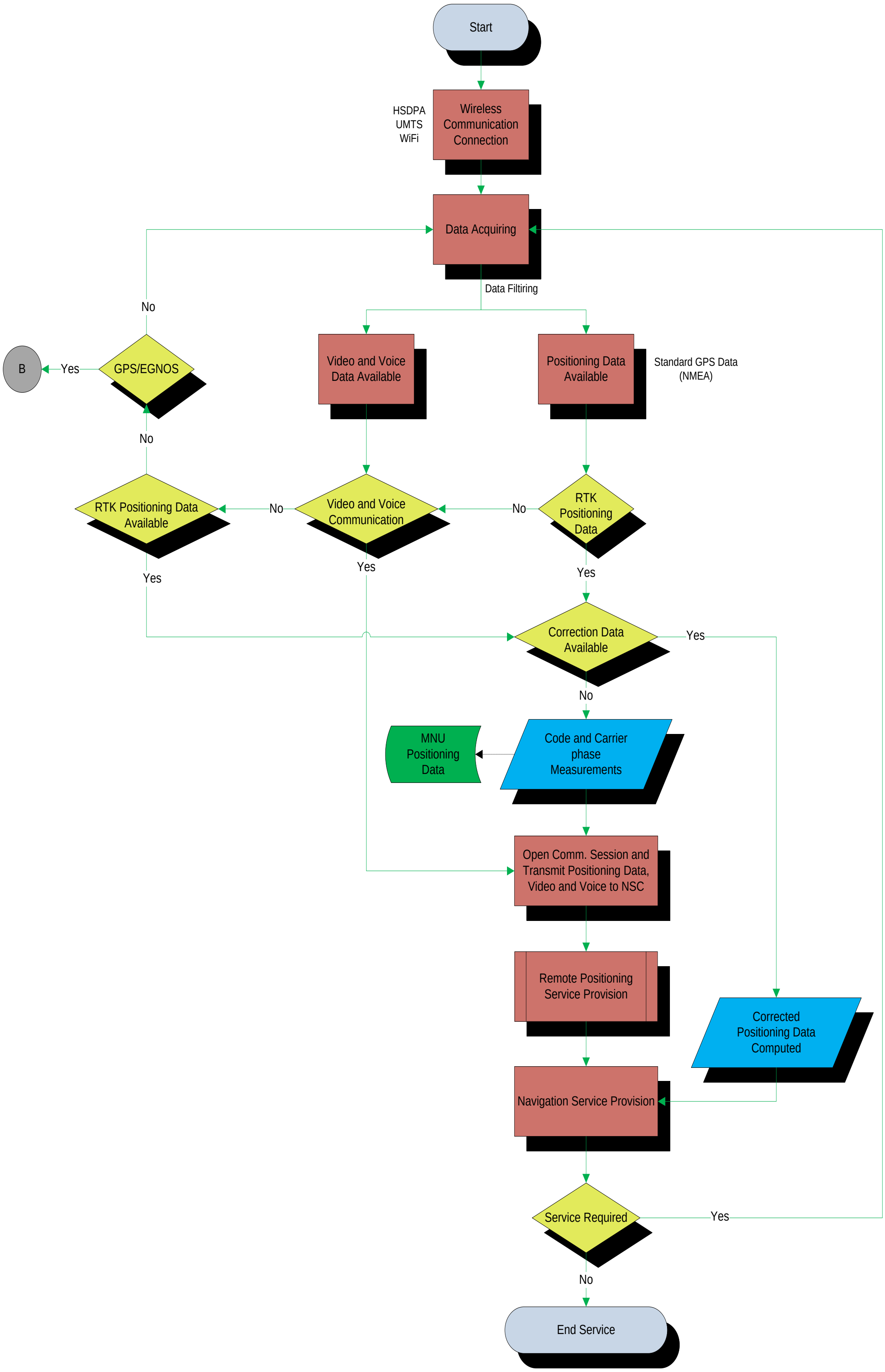


Figure 5.9: The MNU operational method.

As shown in Figure 5.9, the operational method executed at the MNU includes several processes. This starts with connection of wireless communication, which is accountable to search and connect to an existing wireless communication network (e.g., HSDPA or UMTS). Another process is data acquisition, which is involved for acquiring the augmentation data from the dual frequency RTK receiver and video, and the voice data from the intergraded components at the MNU. As mentioned already, two types of positioning data are acquired for the dual frequency RTK receiver: the code and carrier from L1 and L2 of the GPS and GLONASS signals (Chapter 4). The data update rate is 20 times per second (20 Hz). The memory of MNU accumulates these data types and then they are retrieved on the biases of the correction data update time intermissions. Subsequently, two important processes are performed to verify the validity and integrity of the augmentation data and to select the applicable DGNSS reference stations. Based on the user's initial estimated position, this allows only valid and reliable augmentation data to be utilised.

In situations, for example, if inadequate positioning data is available at the MNU or the GPS and GLONASS satellites cannot be seen properly and no applicable DGNSS stations exist, the system gives an alternative directional solution based on video and voice communication. This is called the manual guidance method, and is the second position guiding method proposed by the navigation model system. The MNU would function in a server-based positioning mode, in which a communication session is opened with the NSC to transmit a video image of the immediate environment of the visually impaired person, carry out one-way communication, and to receive voice data from NSC in the bi-directional communication, in order for the visually impaired to avoid obstacles in the route. The video camera built into the user's terminal (MNU) and the video display in the guide's terminal (NSC) make up the system's remote vision facility – utilised to assist in micro-navigation. Both the macro- and micro-navigational assistance (together constituting remote sighted guidance) are provided as verbal macro- and micro-navigational instructions (the guidance instructions). The use of the manual guiding method is not restricted on the GNSS signals availability constraints, only on video and voice communications limitations. However, it can be utilised for reliable and continuous positioning if the user continuously indicates in-door or densely urban environments.

The above descriptions belong to the first and second scenarios. In the third scenario, when NRTK positioning, video, and voice data are unavailable at the MNU, the system has an option to activate a different system for guidance, demonstrated as symbol **B** in Figure 5.9.

The alternative system is the already established *Adaptive, Reliable, and Accurate Positioning Model for Location-Based Services* model, applying GPS augmentation techniques, such as EGNOS/SISNET by Al Nabhan (2009).

The model is based on the single frequency GPS Standard Positioning Service (SPS). The positioning model operates over a client-server architecture, including two main components, described as the Localisation Server (LS) and the Mobile Unit (MU), and the positioning model operates in two position determination modes. The stand-alone mode is used if enough navigation information is available at the MU using its local positioning device (GPS/EGNOS receiver). Otherwise, the server-based mode is utilised, in which the LS intervenes and starts providing the required position solutions. At the LS, multiple sources of GPS augmentation services are received using the Internet as the sole augmentation data transportation medium. The augmentation data is then processed and integrated for guaranteeing the availability of valid and reliable information required for the provision of accurate and precise position solutions (Al Nabhan, 2009).

In Al Nabhan’s (2009) research, the results showed that the LS, through the developed position computation methods, was able to provide position samples with an accuracy of less than 2 m, with high precision at the 95% confidence level. This was achieved in urban, rural, and open space (clear satellite view) navigation environments.

The last position solution used in navigation service provision is received from the NSC using the RTK positioning corrections and the video and voice communication received from MNU. Alternatively, as already mentioned in this chapter, in the absence of a positioning correction or unavailable satellites, the navigation service provision will be obtained from the NSC using the visual image captured and transmitted by the user at the MNU; therefore, employing the manual guiding method solely.

The MNU performs the position calculation by using one advanced method: coordinate domain positioning. In this work, real-time navigation guidance has been used; therefore, the coordinate domain positioning method has been operated. The real-time augmented positioning data is significant for the visually impaired user at the MNU. A detailed description of the processing procedures for real-time GNSS positioning is presented in the following chapter.

5.6.2 Navigation Service Centre (NSC) Operational Method

The NSC is the main component of the positioning model's functioning design. It is primarily for the visually able person to provide direction to the visually impaired person while travelling. The positioning data for every tracked satellite are received from the associated RTK receiver at the MNU. Additionally, the audio and visual data are also obtained. All of these types of data experience dispensation steps so that the user can be guided to the accurate position using the appropriate positioning method. Figure 5.10 shows the flowchart diagram of the NSC operational method.

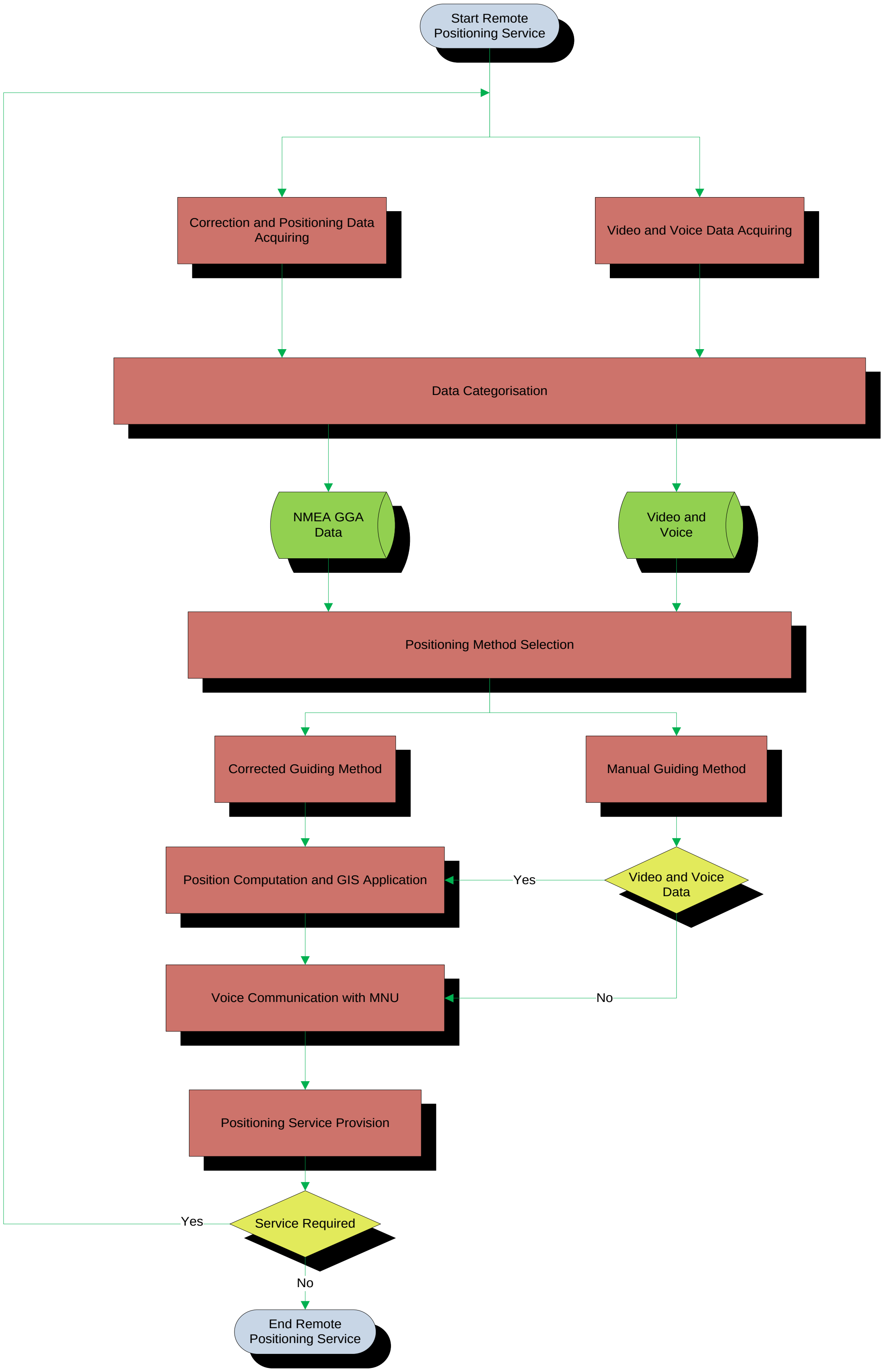


Figure 5.10: The NSC operational method.

The first procedures in the NSC functional approach are responsible for data acquisition and data categorisation. This includes the perception of the data of the audio, visual data, and augmentation data in NMEA GGA formats. This information is then sorted into different corresponding files. The positioning method selection process is responsible for extracting the required data fields from each file. From these, a guiding model will be determined based on the reliance of obtainable augmented positioning data or only video and voice data. This process will automatically choose an appropriate method.

The user's position can be obtained and plotted in the GIS application once all data fields have been attained and positioning method has been selected. The sighted user at the NSC will be able to see the present position on a digital map (e.g. Google map) of the visually impaired person. In addition, the sighed user at the NSC can see a video image of the surrounding area to assist the visually impaired person to keep away from static obstacles located above ground level, such as tree branches, which primary aids (the cane or guide dog) cannot avoid. In order to detect dynamic obstacles, the use of the real-time video image allows the guide to see the environment in front of the user, including moving objects, such as bicycles or new construction work. This was not possible with the other EOAs described in Chapter 3, where static obstacles are pre-programmed in the databases.

5.7 Summary

This chapter describes the process of design of the Precise Positioning in Real-Time using GPS-RTK Signal for Visually Impaired People Navigation System and presents the details of the architecture and functionality of the developed system prototype.

By applying the principles of user-centred system design methodology, the system was designed, following the outcome of the literature review-based studies summaries in chapters 2 and 4. The conceptual framework for the design of the system was implemented from the Brunel Navigation System for the Blind (BNSB), a mobility aid developed within the Centre for Electronic Systems

Research at Brunel University as well, where this PhD project was carried out. The Precise Positioning in Real-Time using GPS-RTK Signal for Visually Impaired People Navigation System has the ability to offer the visually impaired system user with support in micro- and macro-navigation.

The Mobile Navigation Unit (MNU) and the Navigation Service Centre (NSC) are the two significant elements that make up the functioning structure of the positioning model. The new model integrates two functional approaches for switching the MNU from a standalone position determination to a server-based positioning mode in case of positioning and correction data unavailability. The NSC applies in such conditions and starts to provide the the MNU with accurate location solutions and/or physical guidances by verbal methods after obtaining the positioning and visual data of the user. The position correction at the MNU and the NSC is performed using WADGNSS augmentation messages received from the network-DGNSS via TopNET+. Moreover, with a situation of non-accessibility of the positioning data at the mobile device due to a signal blockade, the operational method at the MNU has the possibility of having a manual guidance from the NSC. In view of that, the proposed positioning model offers and maintains an optimal position solution by taking into account all navigation and mobile wireless communication architectural components and the surrounding conditions.

Chapter 6

6. An Assessment Methodology of Network-Based RTK (NRTK) GNSS and Galileo System Performance

6.1 Introduction

This chapter offers a thoroughly portrayal of the assessment methodology utilised in order to make the developed positioning model valid, as presented in Chapter 4 and 5. The methodology has been divided into two sections. The first part involves experimental work; conducting field measurement trials to study and collect Network RTK (NTRK) GNSS data- considering different navigation settings and measurement scenarios. The second part of the methodology included a quantification of the developed positioning model *vis-à-vis* the accurate and reliable positioning services provided by an upcoming Galileo system.

In the first part of the experiment methodology, positioning data measurements were processed and analysed from the performance achieved from the NRTK GNSS positioning service implemented at the MNU. The estimation was conducted in terms of the positioning performance parameters depicted in the section 6.2; this comprises the position solution accuracy and precision as well as the service availability. Furthermore, the experimental performance comparison took place in accordance with the desired positioning performance scenarios and requirements levels summarised in Section 6.2.8 and Table 6.1.

As for the second part, it was achieved by conducting a simulation study using the Galileo Simulation Service Facility (GSSF) software. The GSSF allows the investigative and analysis of future Galileo's Open Service (OS) performance in different scenarios and conditions similar to the experimental work.

The experimental work is explained in the Section 6.3, which elucidates all utilised hardware and software components. Moreover, the section illustrates the settings and locations where the static and dynamic measurements took place. The next section, Section 6.4, presents the simulation part, together with details of the GSSF functionality, and; finally, Section 6.5 summarises the whole chapter.

6.2 Positioning System Performance

A precise definition of performance requirements is critical during the design phase of any navigation system. Accurate requirements elicitation is especially important when selecting an appropriate technology to meet both functional and non-functional requirements. Furthermore, an assessment process of the technical capability is essential to meet performance requirements. The desired system requirements can be quantified by metrics to represent its overall effectiveness. A comparison of these metrics for performance assessment with respect to actual system characteristics assists in describing the system usability and its limitations.

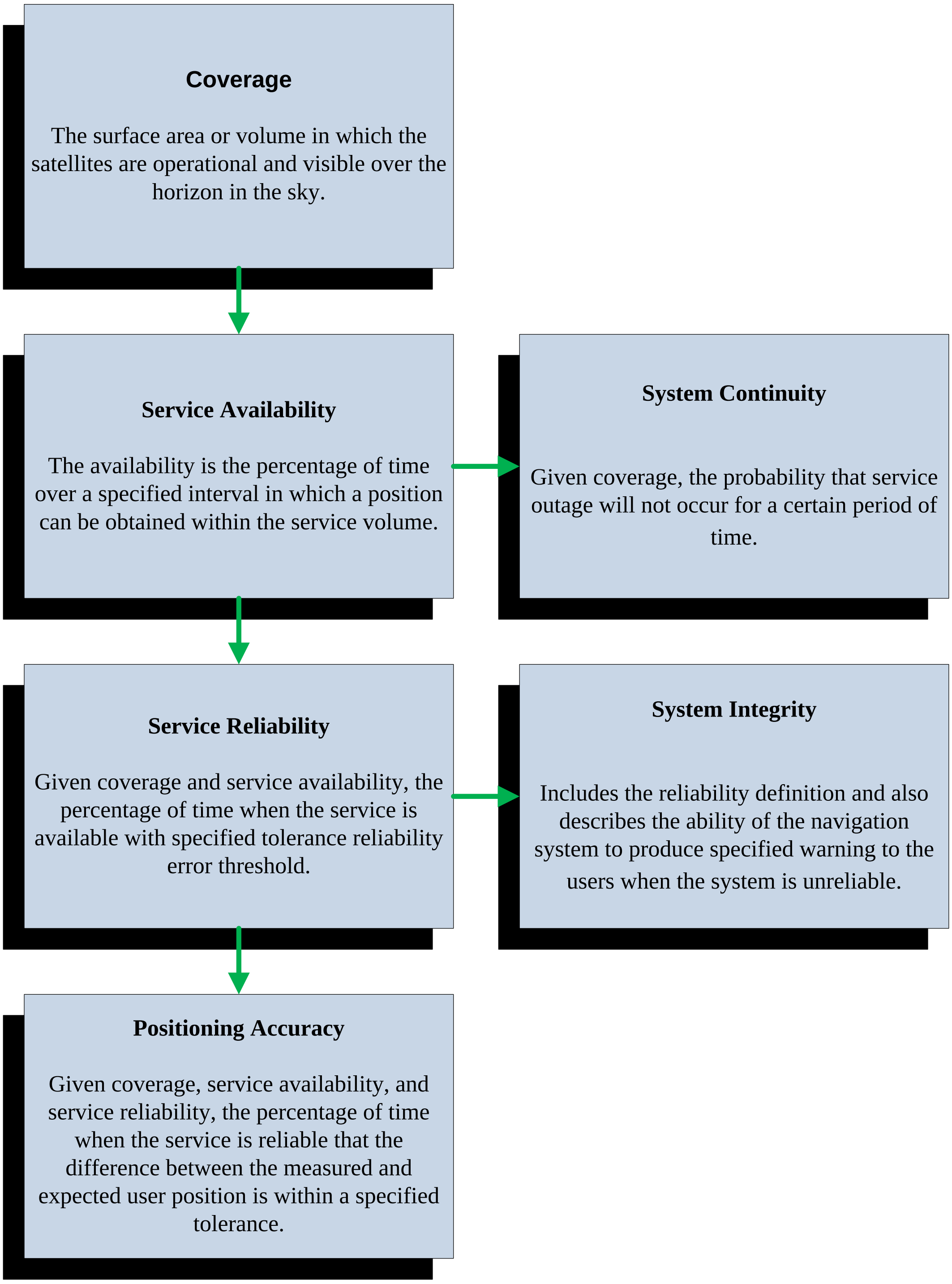
In fact, comprehensive performance standards should provide performance definitions, as well as assessment methodologies. The shortage of performance standards across industries makes the comparison for systems in diverse publication or product specifications very challenging. Hence, a standardised approach for defining parameters is critical for comparing the performances of different navigation systems.

Many ways of assessing and presenting performance parameters do exist, although conversion between them is sometimes difficult. Often, positioning system performance is specified in terms of system availability and accuracy, despite the fact that different parameters are exchangeable by setting different system configuration parameters. This means, for instance, that it is possible to improve precision at the expense of reducing availability and vice versa. Similarly, by modifying the system availability or accuracy, better system reliability can be achieved with certain performance trade-off decisions during the requirement analysis.

6.2.1 Positioning Performance Parameters Definitions

The proposed definition of performance parameters for the end-user side follows the methodology used by the US Department of Defense (DoD, 1996). The methodology defines five primary parameters: (1) coverage; (2) service availability; (3) continuity; (4) service reliability and integrity; (5) positioning accuracy.

All the parameters are organised in successive layers of performance definitions. Performance definition begins with coverage, and each successive one is conditioned on the preceding layers, shown in Figure 6.1. This means that coverage must be provided before the service may be considered available. Similarly, it must be available before it can support reliability and integrity, or reliability must be demonstrated before estimating the accuracy (Ptasinski, 2002; Hughes, 2005).



Coverage

The surface area or volume in which the satellites are operational and visible over the horizon in the sky.

Service Availability

The availability is the percentage of time over a specified interval in which a position can be obtained within the service volume.

System Continuity

Given coverage, the probability that service outage will not occur for a certain period of time.

Service Reliability

Given coverage and service availability, the percentage of time when the service is available with specified tolerance reliability error threshold.

System Integrity

Includes the reliability definition and also describes the ability of the navigation system to produce specified warning to the users when the system is unreliable.

Positioning Accuracy

Given coverage, service availability, and service reliability, the percentage of time when the service is reliable that the difference between the measured and expected user position is within a specified tolerance.

Figure 6.1: Successive layers of performance parameters and their definitions.

6.2.2 Coverage

Coverage represents the area in which the service can be provided, operational of satellites and their visibility over the horizon in the sky. Since the dynamically changing nature of coverage with respect to time affects navigation systems used by various satellite systems, GPS coverage changes must also be taken as a function of time for appropriate correlation. Thus, *dynamic* coverage can be defined as the percentage of time over a given coverage area when the system coverage is provided. For satellite navigation systems, service coverage is provided at a given moment in time and a location, but only if the current position of a given satellite with respect to the user's location enables a fix on the user's position. To obtain a 3D position fix, at least four healthy satellites transmitting usable ranging information should be in the view of the receiver. The fourth satellite is used to account for the delay due to the incompatibility of clock accuracy between the atomic clocks onboard satellites and the mobile receiver clocks. Theoretically, the GPS SPS service provides a global, four-satellite coverage of more than 99% and a global average of 95.87% in the worst 24-hour interval (Al Nabhan, 2009). These locations are predominantly located close to the North and South Poles.

The US Department of Defense (DoD, 1996) provides the definition of coverage as the percentage of time over a specified time interval that a sufficient number of satellites be above a specified mask angle of elevation. They also provide acceptable position triangulation at any point on or near the earth. Satellite visibility is affected by constraints in terms of mask angle and Dilution of Precision (DOP). This is to minimise the possibility of a positioning service generating a marginal position solution. In fact, the values should be selected to support the required level of positioning service performance. The elevation mask threshold values and DOP are correlated to the expected accuracy and reliability of a system, that is, by decreasing the value of the elevation mask, the coverage and accuracy can be improved. Thus, deploying an increased number of visible satellites can provide better coverage and improved DOP for position triangulation. On the other hand, the reliability might be degraded due to the multipath effect, which is increased by the use of satellites with low elevation. Similarly, by increasing the threshold value of the DOP parameter, the cost of degrading the overall accuracy of the system can improve availability.

Whenever GPS is used as a primary positioning sensor, the definition by the US Department of Defense (DoD, 1996) can be useful in the case of a location or navigation system. When considering a positioning system that relies on data transmissions, where a base station serves as a communication node, the coverage of a communication transmission link must also be taken into account in addition to the coverage of the GPS satellites.

In a scenario where the coverage of correction data is not available, the user can choose a stand-alone GPS triangulation system according to his or her needs. The coverage of a centralised system, where remote users can report its location to a base station, is also dependent on data transmission links and its coverage.

A full GLONASS constellation (21 satellites plus 3 active spares) is theoretically designed of providing a global coverage of 94.7% for civilian navigational information. Performance for the Galileo services (Kaplan and Hegarty, 2006) provides statistical coverage of 99.5% and expected minimum coverage with an elevation mask angle constraint of 5°.

6.2.3 Service Availability

Service availability represents the percentage of time that the position can be obtained when the system is in operation. SPS defines availability with a given coverage as the percentage of time over a specified time interval that a sufficient number of satellites are transmitting a usable ranging signal within view of any point on or near the earth. This definition represents a signal in space performance perspective. Taking into account the end-user performance, GPS availability is defined here as the percentage of time over the time when the system is in use that the user receiver can track a sufficient number of satellites. In order to determine a position, these dynamic objects serve as platforms for transmitting usable ranging signals. In this case, certain constraints upon the GPS geometry of the satellites also need to be taken into account.

Just because the satellites are operational and currently visible over the horizon does not necessarily mean that a receiver would be able to determine a position, especially when affected by factors, such as maintenance issues and transmission signal blockage.

6.2.4 Continuity

Continuity expresses the ability of the system to perform its function without interruption during an intended period of operation. Continuity represents in a different way the availability. More specifically, continuity is the probability that the specified system performance will be maintained for the duration of a phase of operation, presuming that the system was available at the beginning of that phase of operation. “Continuity Risk” is the probability that the system will be interrupted and will not provide positioning information for the intended period of time.

This definition was based on the requirement to provide uninterrupted position update considering GPS applications in aviation such as aircraft automatic approach and landing systems. In land navigation or location systems, the positioning module is expected to periodically provide position information with different time intervals. Based on the application, it is important for users to know how long the service may be unavailable. Hence, continuity needs to be determined according to the probability that service outage will not occur for a certain period of time.

6.2.5 Reliability

Reliability is a factor that represents that amount of trust that can be placed in the correctness of the information, taking into account how consistently the system can provide accurate position information. It is defined as the percentage of time when the service is available with a specified tolerance reliability error threshold. The reliability error threshold can be defined as the maximum positioning error.

The selection of an appropriate value is based on an application and the expected user accuracy. However, the threshold must be larger than the practical limit on the normal positioning system accuracy.

Positioning system failure can be caused by factors that include equipment faults and environmental degradation.

Although GNSS system failure is very rare, this system characteristic is important to considering for mission-critical applications. In fact, the system reliability can degrade significantly due to the multipath effects, which requires higher accuracy, when the multipath error is of the order of tens of meters.

6.2.6 Integrity

Integrity represents an aspect of reliability such that the navigation system is able to provide timely warning to users when the system is experiencing faults that compromise functionality. The service reliability standard is based on the assumption that the user does not perform integrity checking. In the case of user equipment that employs integrity checking algorithms, its performance can be described and quantified by using two parameters, namely availability of integrity functions and detection of probability.

Integrity algorithms require the system robustness and additional data, which indicates that integrity functions may not be provided indefinately when the positioning service is available. The availability of integrity is defined as the percentage of time the system can perform integrity functions when the positioning service is considered available. For safety critical applications constraints on service availability may also be used, so it would only be considered available if the integrity functions can be performed. The probability of detection failure multiplied by the probability of occurrence (reliability) yields an overall reliability of the system with integrity checking functions.

6.2.7 Accuracy and Precision

Accuracy and precision describe the quality of the obtained GPS position, where precision is the degree of closeness of covariance in the position measurements to their mean and accuracy being the statistical difference between position measurements and a surveyed position (exact position) with respect to an accepted coordinate system. When discussing accuracy, measurement precision must be considered as it assesses the ability to estimate position samples constantly with similar error budgets during the overall measurement time. Figure 6.2 illustrates both factors.

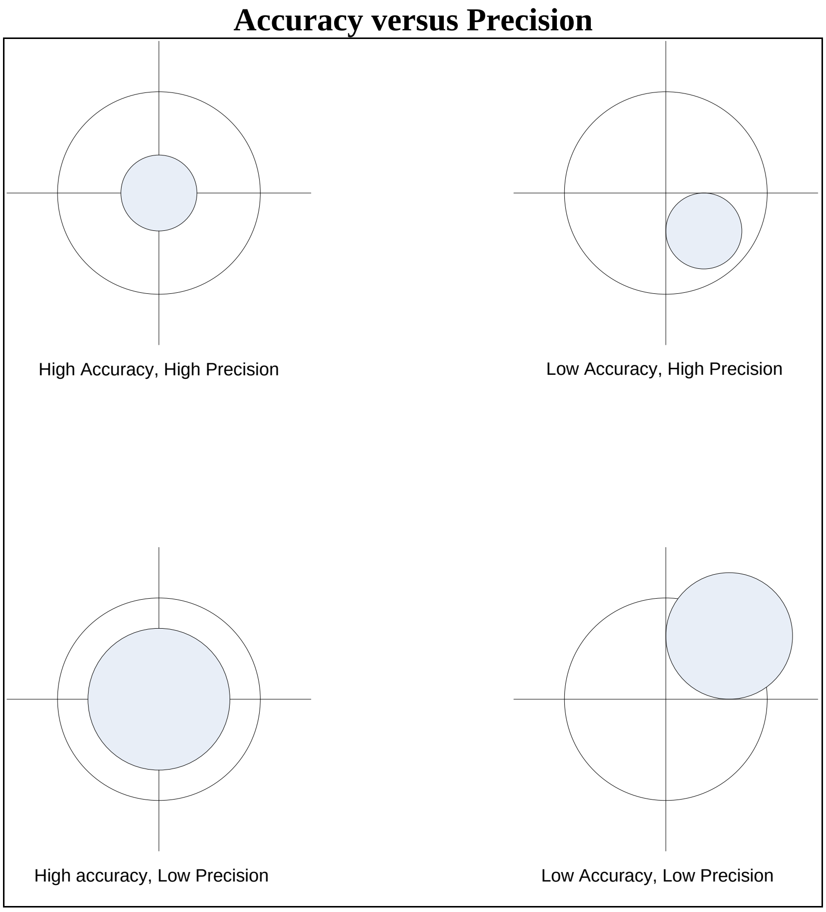


Figure 6.2: Accuracy and precision levels explanation.

Generally, two quantities compose the accuracy of a GPS system; the User Equivalent Range Error (UERE) and the DOP. The total UERE measures the horizontal position accuracy and the satellite, signals, given by user error budgets combined into a single quantity measuring the error in the user-satellite range. The UERE can be calculated as the sum of errors from atmospheric effects, receiver noise, ephemeris and satellite clocks, and multipath error contributions. By taking the square root of the sum of the squares of the measurements errors' standard deviations the UERE can be computed:

$$UERE = \sqrt{\sum_i \sigma_i^2} \qquad (6.1)$$

σ_i is the standard deviation of the i**th** error budget.

The DOP gives a simple characterisation of user to satellite geometry and refers to the position of the satellites in relation to each other with respect to the user. It can be exposed by using measures, such as the Position DOP (PDOP), indicating the error in the satellites coordinates used to triangulate the calculated position; the Horizontal position DOP (HDOP) and Vertical position DOP (VDOP) make up the PDOP. Time DOP (TDOP) can describe a clock-offset quantifier. TDOP and PDOP form the Geometric Dilution of Precision (GDOP) used to represent the geometric strength of the position solution. As the value of GDOP increases, there is a greater possible error in the obtained position. GDOP quantifiers can be used as measures of system availability since most receivers allow the determination of a threshold level of GDOP (e.g. PDOP mask, satellite elevation angle mask) above which data cannot be collected (AL Nabhan, 2009). Here, PDOP is regarded as a measure of availability and accuracy, because it is the only dilution of precision value associated with the horizontal and vertical positional portion of the navigation solution.

The DOP values computation is achieved as follows: As a first step in computing DOP, the covariance of the measurement error can be approximated as (Jirawimut, 2003):

$$E(vv^T) = \sigma^2 I \tag{6.2}$$

where *I* is the identity matrix.

Given the matrix W=I, the least squares estimator is also an unbiased, minimum variance estimator and

$$Cov\begin{bmatrix}\hat{r}_{RX}\\ \hat{b}\end{bmatrix} = \sigma^2(H^T H)^{-1} \tag{6.3}$$

Where $\hat{r}_{RX}$ is the estimate position of the receiver’s antenna and the estimate receiver’s clock bias, $\hat{b}$.

Let D = $(H^T H)^{-1}$. Denote the *i*th entry on the diagonal of matrix D as D_{ii}. Hence, the variances of the estimates can be written as

$$E\{\|r_{RX} - \hat{r}_{RX}\|^2\} = \sigma^2(D_{11} + D_{22} + D_{33}) \tag{6.4}$$

$$E\{b - \hat{b}\}^2 = \sigma^2 D_{44} \tag{6.5}$$

The PDOP is defined as

$$PDOP = \sqrt{D_{11} + D_{22} + D_{33}} \tag{6.6}$$

The clean characterisation of the root mean square (rms) position error in terms of geometry and the measurement error is based on the assumption that the pseudo-range measurement errors are uncorrelated and has a common variance (Jirawimut, 2003). Hence, the rms error of the estimates of single snapshot measurements can be written as

$$rms\{Position\ error\} = \sigma\ PDOP \tag{6.7}$$

The matrix D is in ECEF co-ordinate frame. It is necessary to transform the ECEF co-ordinate frame to the local east-north vertical co-ordinate frame. Denoting the transformed D as $\widetilde{D}$, horizontal dilution of precision (HDOP) and vertical dilution of precision (VDOP) are defined as:

$$HDOP = \sqrt{\widetilde{D}_{11} + \widetilde{D}_{11}}\,, \quad VDOP = \sqrt{\widetilde{D}_{33}} \tag{6.8}$$

and

$$rms\{Horizontal\ Position\ error\} = \sigma\ HDOP \tag{6.9}$$

$$rms\{Vertical\ Position\ error\} = \sigma\ VDOP \tag{6.10}$$

If position is not of interest at all, but time is, the time dilution of position (TDOP) is defined as (Enge et al., 1988)

$$TDOP = \sqrt{D_{44}} \tag{6.11}$$

A simple characterisation of the user satellite geometry is presented in DOPs. The lower DOP means the more favourable geometry and thus the better quality of the position and velocity estimates. The PDOP can be reduced by having more number of satellites. In a receiver that has limited number of channels, the PDOP is often used as a basis for the selection of satellites being tracked. Practically, the high-end receivers now track all satellites in view.

With reference to the horizontal integrity definition, a circle of radius centred at the true position can describe the horizontal accuracy and this can contain observed positions in a horizontal scatter as having an error probability or a confidence level specified in the particular statistical accuracy method adopted. For example, by using R95 or 2DRMS statistical methods, a confidence level of 95% can be obtained. The Distance Root Mean Square (DRMS) can be expressed as:

$$2\text{DRMS} = 2\sqrt{\left(\sigma_x^2 + \sigma_y^2\right)} \tag{6.12}$$

where σ_x and σ_y are the standard deviation of the error along the x and y axes, respectively.

To form a probability density curve or distribution known as a Gaussian distribution, accurate statistical methods require a sufficient amount of observations over a long period. Subsequently, to calculate the error budgets and accuracy levels standard deviation techniques quantify this distribution. A 3D position accuracy level describes the horizontal accuracy and vertical accuracy components. The vertical components are considered as height or altitude values and for land navigations usually the last calculated vertical value are used with infrequent updates.

6.2.8 Positioning Performance Scenarios and Requirements

It is difficult to define specific values for each positioning performance level. However, approximate thresholds were used to define the requirements of each performance level, taking into consideration some cited studies (Ptasinski, 2002; Abwerzger et al., 2004; Ott et al., 2005; Al Nabhan, 2009). Performance assessment is presented for three basic example scenarios of a navigation or location system operation, for which different requirements of the positioning subsystem have been specified:

1. *A person is in need of help (i.e. emergency location service)*
   From October 2001, the Federal Communication Commission (FCC) requires all mobile phones used to make emergency calls be able to determine the caller's position within 50 meters accuracy for 67% of emergency calls, and 150 meters within 95% of calls (FCC, 2007; Kyovtorov, 2003; Ptasinski, 2002). The position update does not have to be provided continuously. If assumed that the position of a pedestrian would not change significantly within 1 minute, the system should provide

a position update without outage longer than 1 minute through 95% of time.

2. *A person is tracked to continuously provide positions (e.g. Police or security personnel tracking)*
   The position has to be updated periodically (e.g. every 5 seconds). Position solution within ≥7 meter of actual true position would allow finding out where the person is currently located. This constraint exists, so that the system can differentiate, between closely spaced roads.

3. *A person is continuously navigated by the system*
   For navigation purposes, the position update should be provided continuously at least every second. If navigation information requires position resolution related to which street the person is currently on, 2 meter accuracy should be sufficient. If the guide is providing more detailed information regarding which side of street, the person is currently walking on, 1-2 meter accuracy would be required. To find the position of a person, e.g. visually impaired people, in relation to a pavement, on which the visually impaired person walks, 0.5-1 meter accuracy is considered necessary.

With reference to each scenario, several positioning performance features were described and appointed for each performance level. The summary of the requirements is shown in Table 6.1.

	Emergency Location	**Individual Tracking**	**Pedestrian Navigation**
Coverage	Coverage of a mobile phone network	Area of service	Area of service
Availability	>95%	Variable	Number of Satellites ≥5 HDOP ≤2 PDOP ≤5
Integrity & Reliability	Variable (Integrity) 99.99% (Reliability)	Variable (Integrity) >99.7% (Reliability)	Variable (Integrity) >99.7% (Reliability)
Continuity		Outage 5 sec less 3%	Outage 5 sec less 1-3%
Accuracy & Precision	125 meter (95%) 50 meter (67%)	≤20 meter	0.5-1 meter

Table 6.1: Navigation service performance requirements level (Ptasinski, 2002; Al Nabhan, 2009).

It is noteworthy to mention that the above values are not necessary for all applications, and only displays a basic method providing initial parameters for evaluation purposes. The high performance level was assigned with specific needs that were extracted from the best achieved values utilising standalone GPS and DGPS services. In opposition, the moderate and low performance levels were assigned variable accuracy because of their flexibility to accommodate diverse performance values.

6.3 Experimental Evaluation

In order to examine the overall performance of the positioning model at MNU, described in chapter 5, the experimental evaluation was used to collect positioning data at the Mobile Navigation Unite (MNU). Several types (accuracy, NRTK availability, PDOP and number of SVs) of positioning data were collected and stored in different files. These include NRTK GNSS position observations with augmented position coordinates.

6.3.1 Configuration of the Experiments

This section describes the experiments' hardware and software components and the configuration of MNU and NSC experimental prototypes. The first prototype implements the MNU, which was mainly utilised in the field measurements. The second prototype describes the NSC, which was used for NRTK GNSS data processing, and the performance of significant guidance.

The experiments for NRTK GNSS were performed using a base and a rover dual frequency receiver, Topcon HiPer Pro, and a Topcon FC-200 controller for logging and analysing the data as shown in Figure 6.3 (see Appendix D for technical specification of Topcon HiPer Pro). These are manufactured by Topcon (Topcon, 2009), which is a Japanese-based manufacturer of GNSS-related equipments. The Topcon HiPer Pro is a dual-frequency and a dual-constellation receiver. In addition to this, it has Bluetooth inherent in the receiver. It consists of 40 channels allowing the tracking of L1/L2 signals from GPS and GLONASS and provides raw measurement along with standard NMEA data outputs (Topcon, 2009). The FC-200 controller has built-in Bluetooth wireless technology that provides cable free connections with the receivers. In addition, the FC-200 also provides wireless LAN and 2.4 GHz spread spectrum radio options for ultra long-range base to rover communications. Using Bluetooth, a mobile phone (HTC Touch Diamond) was connected to the FC-200 controller; a data-enabled mobile connection was used to transmit the corrections from the NTRIP server to the mobile device via a GPRS connection.

Additionally, configuration of these experiments also involved a computer at MNU (Sony Vaio CR420E Notebook, Intel Core 2 Duo, 2.1 GHz, 3GB RAM), which was connected to the RTK GNSS receivers via RS323 cable (serial connection). A full functional diagram is shown in Chapter 5, Figure 5.1.

Topcon Tools application software was utilised as a GNSS data processing and analyser. The MNU internal memory logged three types of GPS and GLONASS position observations: the standard and augmented position solutions in NMEA format and the raw pseudo-range measurements. This software also consists of statistical functions for determining the availability of GPS and GLONASS services and can conduct post-processing of GPS, GLONASS and RINEX data. In addition, during the measurements trials it visualises positions on 2D map, including the calculation of PDOP values and number of SVs.

For the experiments of NRTK GPS, only one of the receivers was required with the hand controller, FC-200. The RTK GNSS receiver was operational in the WADGPS system, receiving augmentation data from TopNET+, via a GPRS connection. The corrected positioning data was processed with Topcon Tools application software and the position of the user was visualised on the screen using 2D map integrated in the software.

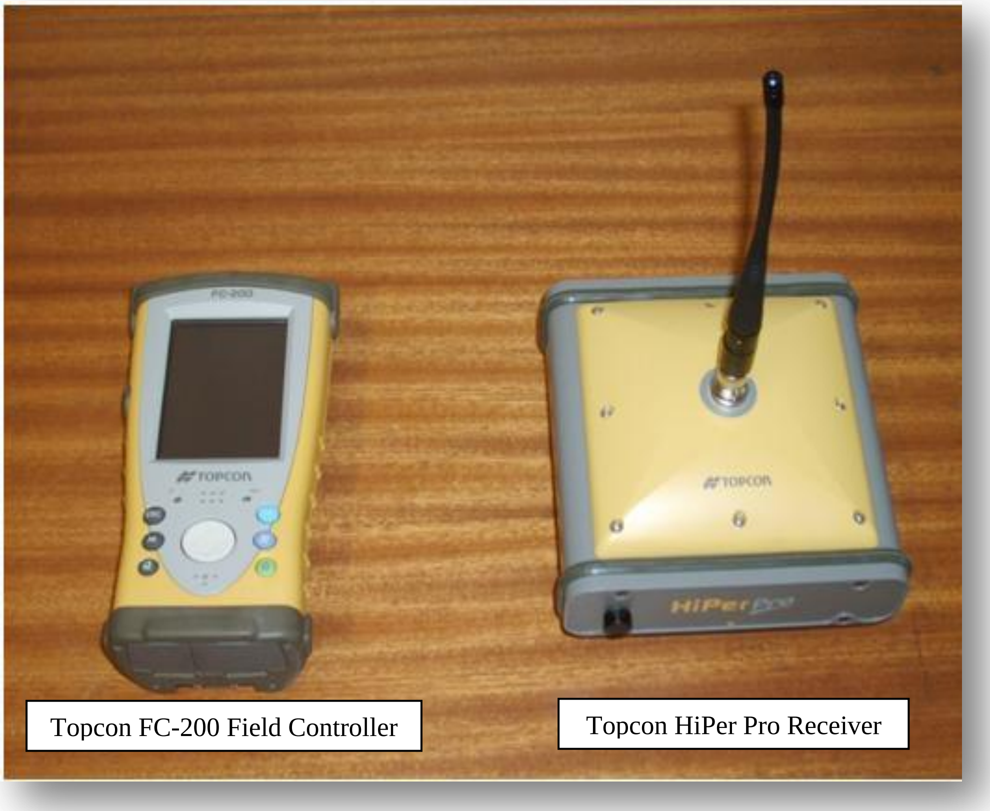


Figure 6.3: RTK GPS measuring units.

The NSC was compiled from the following hardware and software components:

- Intel Dual Xeon computer, 3.2 GHz, 12 MB cache, 1600 FSB, and 8GM;
- Topcon Tools software, as described above.

This configuration can be used in various static and dynamic navigation applications. Positioning data and satellite navigation data were logged directly into the receiver for static and dynamic experiments. The data was transferred from the receiver to a PC for post-processing, or alternatively, real-time positioning with the help of augmentation data from TopNET+, calculated the corrected positioning.

6.3.2 Environment Setup and Quality Assessment Methodology

RTK GPS faces various challenges when being run in environments comprising of different obstacles; especially under and/or near urban environments, thus, creating problems such as multipaths by trees and buildings and signal derangements. Therefore, it is necessary to test the functionality of the NRTK GNSS in a realistic environment, which will bear a purpose in the future. This experimental testing investigates the accuracy performance of NRTK GNSS for pedestrians in real-time scenarios. Realistic environments and real-time scenarios are defined here as locations in which a reasonable person using the NRTK GNSS would position him or herself in. These positions involve various landscapes, which contain a mixture of rural, suburban, and urban areas as these create an ordinary environment in which a GNSS user lives.

To facilitate the evaluation of the positional quality of TopNET+, several static and dynamic tests were carried out. The dedicated static tests were to assess the accuracy, precision, and availability of the TopNet+ NRTK GNSS solutions while the dynamic tests were intended to assess only their accuracy (when compared with a more accurate solution) and availability.

All the tests had a common objective, that is, to examine the influence of several factors, such as the number of GPS and GLONASS satellites in view, their geometry, and the age of the NRTK corrections (AoC) when received at the rover receiver on the TopNET+ solutions.

For the simulation part, similar conditions and scenarios as the NRTK GNSS experimental work were conducted. The simulation experiments were performed using the Galileo System Simulation Facility (GSSF) software, developed by VEGA Group PLC for the European Space Agency (ESA). The GSSF is conceived as a simulation environment that reproduces the functional and performance behaviour of the Galileo satellite navigation system.

The experimental flow chart of the real scenarios and the simulation test consisted of the following components and conditions, as shown in Figure 6.4:

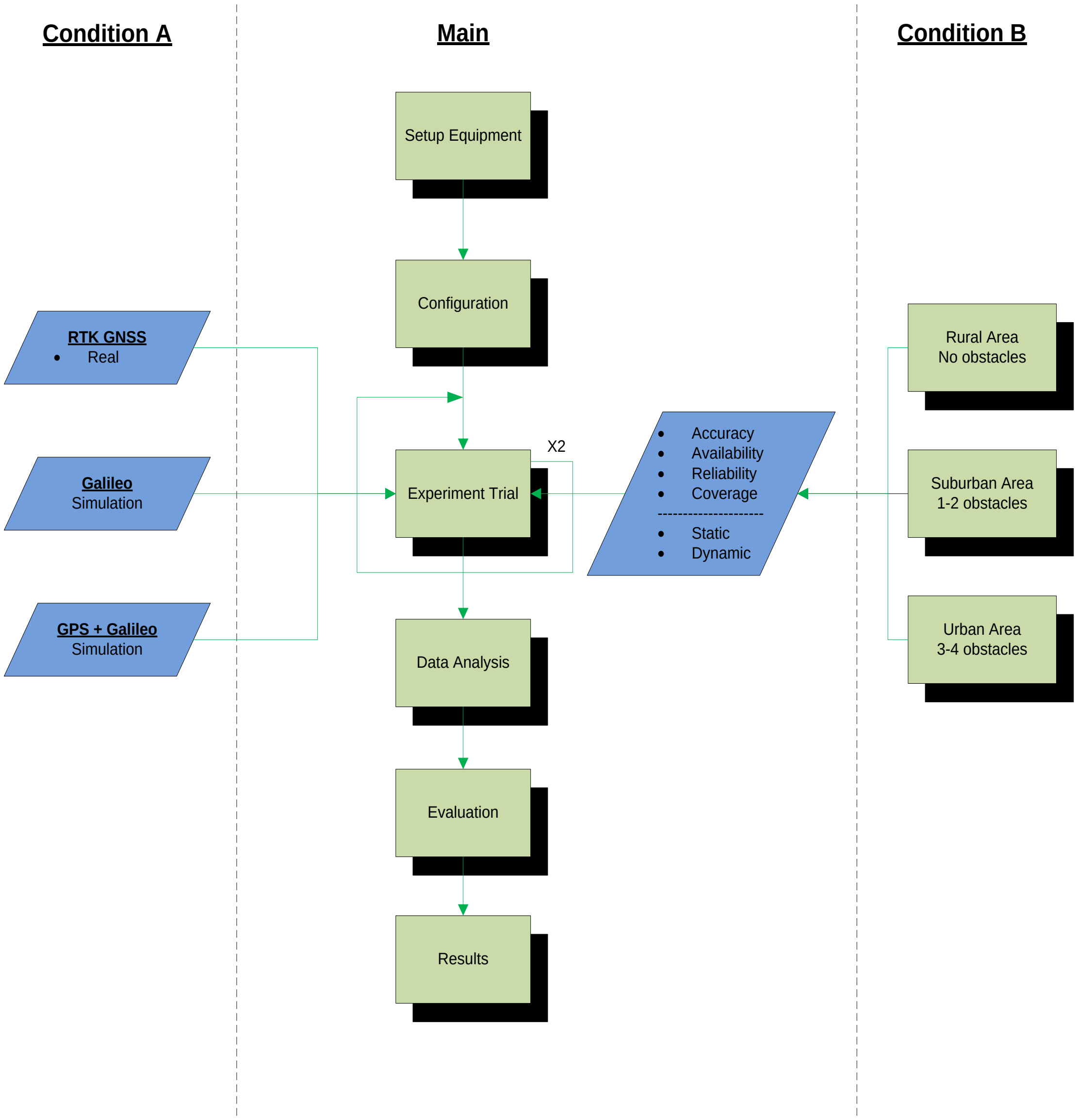


Figure 6.4: Experimental Flow Chart.

➢ Condition A and B:

1. *Real Scenario (RTK GNSS):*

The RTK GNSS signal performance parameters were monitored and computed in different positions and environments. The performance of the signal was evaluated using static and dynamic experiments in rural, suburban and urban areas. It was planned that a participant would walk along a predefined trajectory for the dynamic testing. For the static testing, different positions in various environments were chosen. The experimental environments are described in section 6.3.3.

2. *Virtual Scenario:*

The described experiment above was conducted in a similar manner in simulation software for Galileo and for a hybrid system of GPS and Galileo.

- **Main:**

1. *Setup Equipment:*

Connected hardware (RTK GNSS receiver, laptop, etc.) and communication link.

2. *Testing:*

Various testing performance of hardware and software was undertaken.

3. *Experiment Trial:*

Experiments performed in both real-time and simulated scenarios (static and dynamic) in order to evaluate the four main variables for a comparison between RTK GPS, Galileo and the hybrid system. The variables were accuracy, availability, reliability and coverage.

The trials were arranged to be repeated two times. The first series of trials were intended to be conducted to collect the initial data, whereas the data collected during the second series was used as a reference to determine possible errors in the first series and to approve the repeatability of the experiment.

4. *Data Analysis:*

The outcome of the data from various scenarios was analysed in this stage.

5. *Evaluation:*

With the results from the data analysis, an evaluation of the variables was carried out.

6. *Results:*

In this last step, the results of the experiments were discussed.

6.3.3 Experiment Trials

Using the experimental setup, comprehensive field measurement trials observed and collected RTK GNSS data in static and dynamic scenarios over several dynamic routes and sites. All equipments were during the measurements trials arranged in the same way to ensure a similar testing condition. Two routes (pedestrian paths), three static observation sites and twenty benchmark points (static test) were carefully selected at different locations within Brunel University Campus, Uxbridge, UK (Figure 6.5). The experiential field locations represented diverse navigational environments with a range of diverse conditions, from open spaces to densely built-up areas.

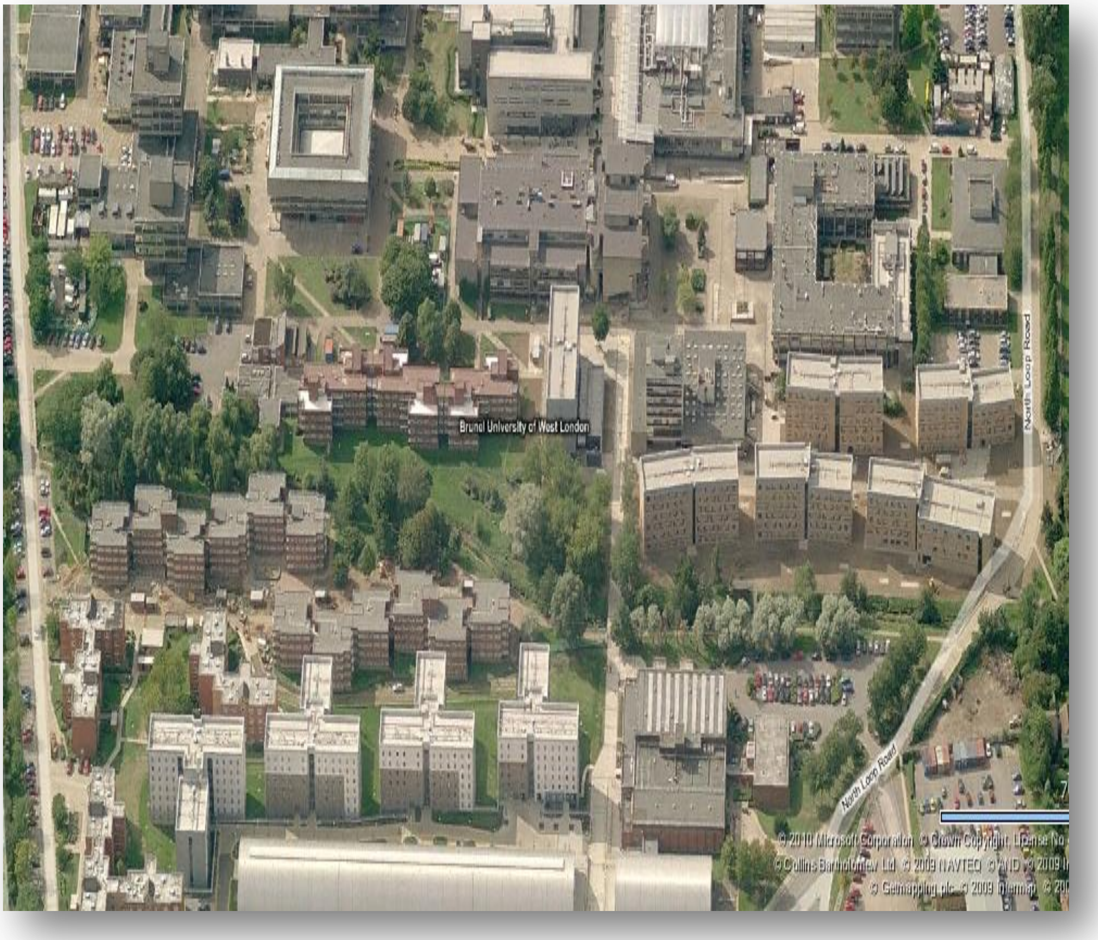


Figure 6.5: Brunel University Campus (Bing Maps).

A static experiment gives an advantage of conducting a long period measurement when a GNSS antenna is placed in an accurately surveyed location and data are collected over 24 hours. When dynamic tests are conducted in a real environment under real scenarios where the system will possibly be used, the tests may give better results. However, it is problematic to conduct 24-hour experiments for practical reasons. Therefore, it was decided that measurements for a specified location be repeated at different times during a 24-hour period, so tests with different satellite configurations could be carried out.

The configuration of GPS satellites continuously changes in relation to each user's position. The satellites complete one orbit in approximately 11 hours and

58 minutes. Since the earth is rotating, the satellites trace a track over the earth's surface, which repeats every 23 hours and 56 minutes. For assessing the accuracy measurement of a dynamic test, a person needs to walk exactly along a marked route assuming a constant velocity. Along this route, different benchmark points (static tests) were marked, accurately surveyed as the reference points over several days at a centimetre accuracy level, using the dual frequency receiver-measuring unit described earlier in Section 6.3.1. When passing by each point, the actual time synchronised with GPS time was logged, together with a group of GPS measurements. This allowed a quantifying of the positional accuracy at each point, as well as along the whole path.

The satellites' elevation mask was set to 5° which is a commonly used value for performance assessment. The elevation mask is a filter, which exclude any signal from a satellite that is under a certain described angle as it is recorded in the satellite's ephemeris. Essentially, if the satellite is below the suggested 5° above the horizon, the receiver will not make use of this satellite in determining the final solution. Because of structural interference, the elevation mask is set to 5° to ward off atmospheric distortion and possible multipath errors. High multipath effects can decrease the time coefficient used to decide the solution and decrease the of data's positional accuracy. The maximum PDOP value was set to 6. Hughes (2005) presented these settings on satellite visibility and they were used to minimise the possibility of having a positioning service generating erroneous position solutions. Table 6.2 also summarises the surveyed points' easting and northing coordinates, with reference to the Ordinance National Grid (OS Net, 2009).

The first testing was carefully selected to simulate a typical rural and suburban area; the tests taking place between different buildings. The distance covered by the dynamic route was approximately 625 meters. As Table 6.2 shows, ten static tests (benchmark points) and the coordinates of the points (Easting and Northing): ST1 to ST10. One of the performance test, ST7, was carried out under a tree canopy. The dynamic test, DT1, were designed to estimate the accuracy and NRTK availability of TopNET+, on a road segment using the static points ST1 to ST10 at Brunel University campus.

Test	Network Service	Obs. Method	Elevation Mask Angle	Environment	Easting Coordinates	Northing Coordinates
ST1	TopNET+	Static	5º	Rural	506143.800	182452.040
ST2	TopNET+	Static	5º	Suburban	506216.007	182474.256
ST3	TopNET+	Static	5º	Suburban	506279.799	182603.845
ST4	TopNET+	Static	5º	Suburban	506204.211	182688.177
ST5	TopNET+	Static	5º	Suburban	506060.601	182688.574
ST6	TopNET+	Static	5º	Suburban	506059.599	182690.407
ST7	TopNET+	Static	5º	Tree Canopy	506050.617	182659.006
ST8	TopNET+	Static	5º	Suburban	506024.638	182573.785
ST9	TopNET+	Static	5º	Suburban	506020.037	182526.405
ST10	TopNET+	Static	5º	Rural	506071.634	182474.018
OS1	TopNET+	Static	5º	Suburban	506041.341	182521.596
OS2	TopNET+	Static	5º	Rural	506024.139	182634.656
OS3	TopNET+	Static	5º	Urban	506178.861	182572.991
DT1	TopNET+	Dynamic	5º	Rural/Suburban	Various	Various

Table 6.2: Performed test details for rural and suburban area.

Figure 6.6 presents the testing points for the static positioning measurements and the distance from buildings. The 2D map of Brunel University campus was in a scale of 1:1000 and was drawn by the Department of Estates at Brunel University. Figure 6.7 provides a general description of the first tests and the surrounding objects in bird view. Furthermore, the route for the dynamic tests (DT1), with Start and End points, are shown in Figure 6.7 (yellow line).

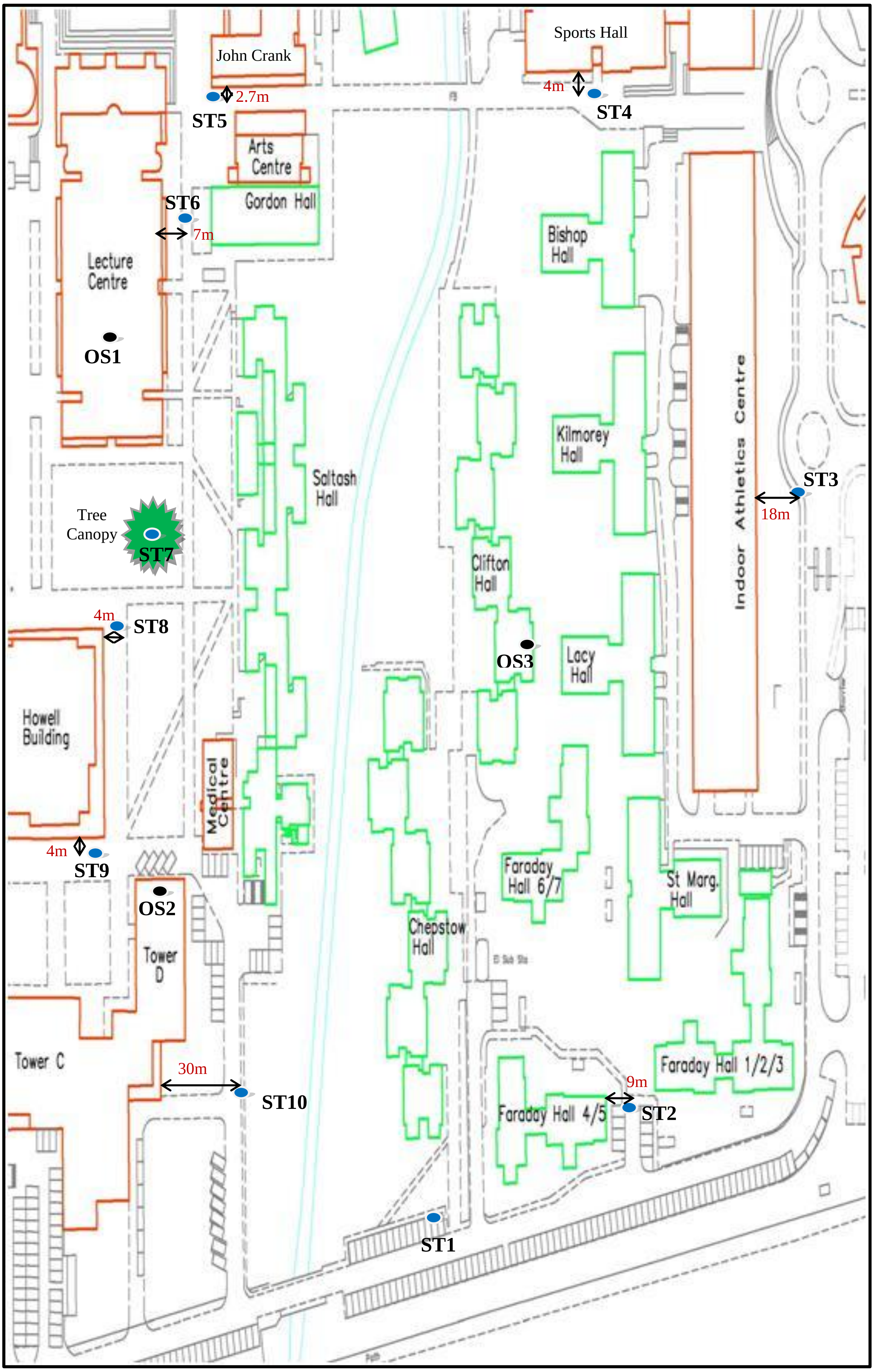


Figure 6.6: Static measurements points in rural and suburban area (Brunel University).

Figure 6.7: Static measurements points in rural and suburban area (Bing Maps).

The second testing for static and dynamic was selected within the most densely sited build-up area, making an urban area in the university campus with parts where signals from the satellites were very likely to be blocked by surrounding buildings. This route was selected in-between eight-storey accommodation buildings (Bishop Complex), shown in Figure 6.9 (yellow line) with Start and End points. The total distance covered was approximately 155 meters for DT2. As described in Table 6.3, several static points (benchmark points) were identified at this route (Brunel University campus) to estimate the accuracy and availability of TopNET+.

Test	Network Service	Obs. Method	Elevation Mask Angle	Environment	Easting Coordinates	Northing Coordinates
ST11	TopNET+	Static	5º	suburban	506216.560	182475.504
ST12	TopNET+	Static	5º	Urban	506202.968	182489.436
ST13	TopNET+	Static	5º	Urban	506205.629	182528.122
ST14	TopNET+	Static	5º	Urban	506205.499	182543.571
ST15	TopNET+	Static	5º	Urban	506199.274	182555.494
ST16	TopNET+	Static	5º	Urban	506188.092	182555.569
ST17	TopNET+	Static	5º	Urban	506176.996	182542.357
ST18	TopNET+	Static	5º	Urban	506157.267	182527.110
ST19	TopNET+	Static	5º	Urban	506157.774	182475.201
ST20	TopNET+	Static	5º	suburban	506158.624	182452.968
DT3	TopNET+	Dynamic	0º	Urban	Various	Various

Table 6.3: Performed test details for urban/suburban area.

Figure 6.8 demonstrates the static points in urban area and the distance to buildings in a 2D map. The bird-eye view landscape illustrates the general description of the second test and its surroundings as shown in Figure 6.9.

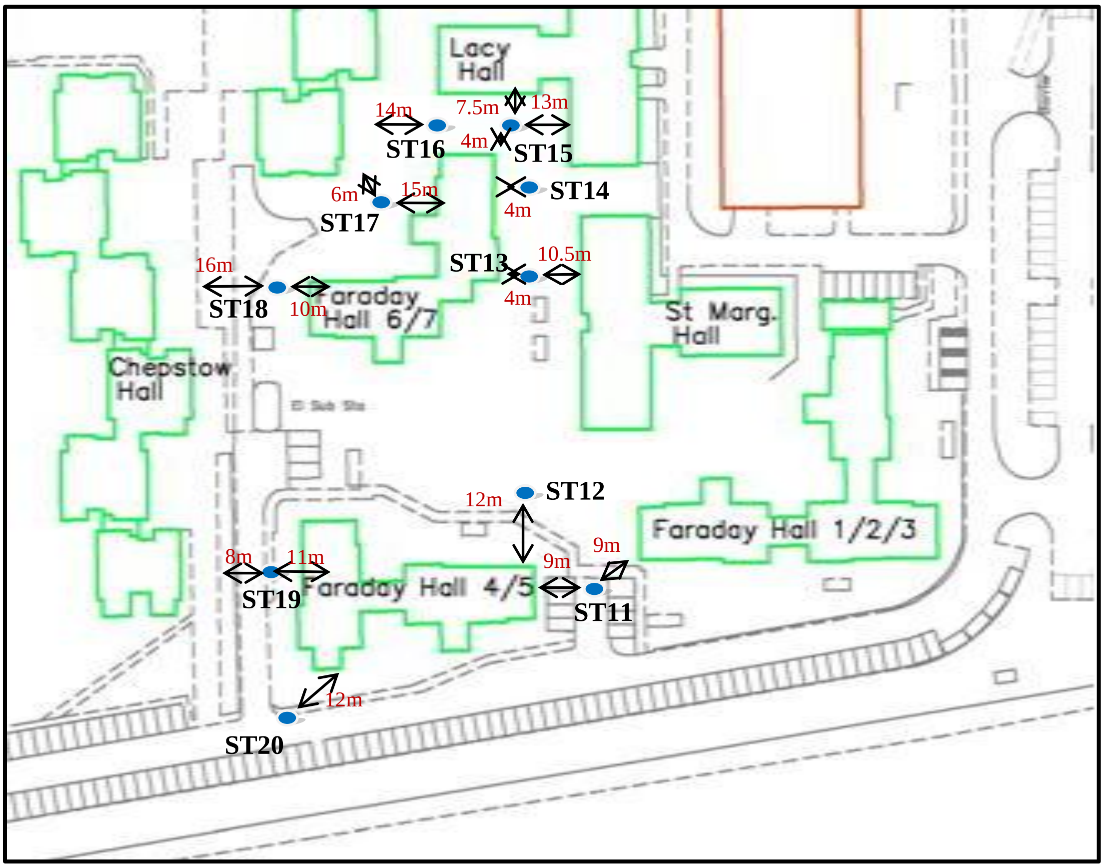


Figure 6.8: Static measurements points in urban area (Brunel University).

Figure 6.9: Static measurements points in rural and suburban area (Bing Maps).

During the static measurements three Observation Sites, OS1, OS2 and OS3, were selected which represented different navigation environments, shown in Figure 6.6. These sites were on top of three university buildings: Lecture Centre, Tower D and Clifton Halls. In order to conduct 24 hours of measurements, the RTK receiver was positioned during different days at these static sites. The first observation site, OS1, which is located within a rural environment. Here, the receiver's antenna was placed on top of Lecture Centre with no obstruction (clear line-of-sight). The second observation site, OS2, was within a typical suburban environment. Here, the receiver's antenna was fixed on the lower part of Tower D (one-storey building) surrounded by two buildings, of which one is an eight-storey building and the other one is a 5-storey building. The third observation site, OS3, was situated within a typical urban environment, in which the GPS receiver's antenna was mounted on top of a four-storey building (Clifton Halls) encircled by two eight-storey building. This location experienced severe signal blockages.

Appendix A shows photographs taken from different locations in both the static sites and dynamic measurements routes.

These tests were primarily planned to evaluate the quality of the TopNET+ services from the end users' standpoint; thus, the majority were conducted using the service as is. This means that as TopNET+ is a commercial NRTK service in Great Britain the corrections arriving throughout the tests were the same as any other subscriber would have received if using the service at the same location and time.

Figure 6.10 shows the TopNET+ CORS (described in Chapter 2, Section 2.2.3) configuration used during the tests for rural, suburban and urban environments. The nearest Reference Station (RS) to the rover site at Brunel University campus (yellow circle) was the station at Teddington (TEDD) and was located about 15 km away, the farthest (STEE) located at about 45 km. This could be considered as a typical configuration for a NRTK GPS application.

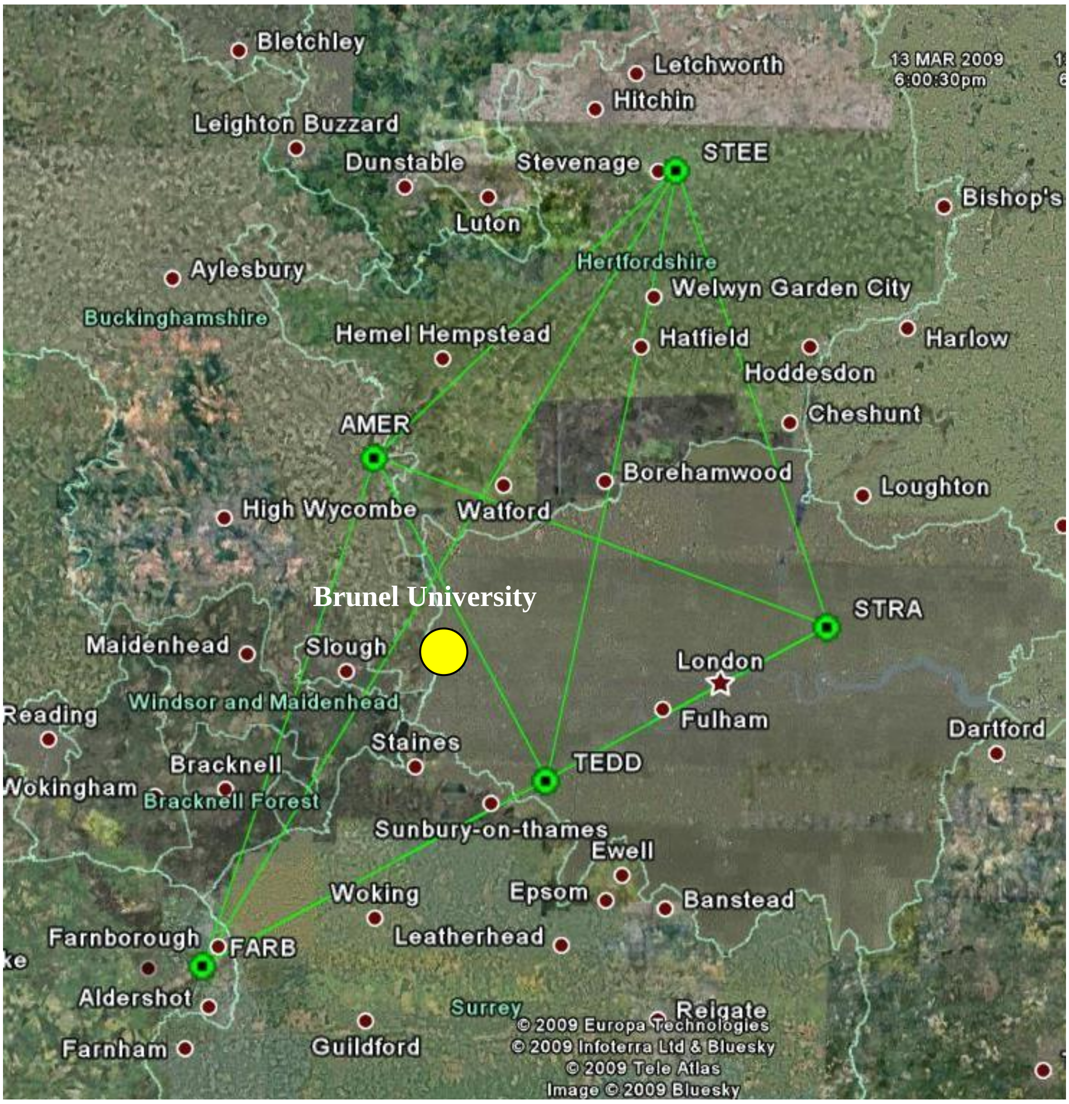


Figure 6.10: TopNET+ reference stations.

Static and dynamic tests were all carried out by means of the service within Brunel University campus buildings with selected experimental points that represented different navigation environments within the campus. The receiver for the static and dynamic tests was a Topcon Hiper Pro dual frequency GPS and GLONASS receiver, which can receive NRTK corrections from TopNET+ via GPRS data linkage. Orange, which is a well-established UK mobile phone company with good coverage in the west London region, provides this GPRS service. The Topcon Hiper Pro receiver was logging real time NMEA GGA data onto the memory of the receiver and the configuration for static and dynamic tests was similar. During all static and dynamic testing trials, the navigation messages and augmentations data were simultaneously downloaded and stored at the NSC. The stored data files were processed at the NSC and these considered data types, navigation environments and measurement scenarios. To assess the performance levels achieved the computed position solutions were analysed and exported into an Excel file.

6.4 Simulation Evaluation Methodology

The GALILEO System Simulation Facility (GSSF) was used to conduct the simulation study. An international consortium lead by VEGA (GSSF, 2004) on behalf of ESA/ESTEC was responsible for primarily developing this tool. Quantifying the developed positioning model performance against accurate and reliable positioning services that Galileo and GPS wish to offer in the future was the goal behind the simulation study. This also helped to identify areas of compatibility and integration between the developed model and the future navigation system.

6.4.1 The GALILEO System Simulation Facility (GSSF)

The GSSF was developed to support the understating of the definition stages and longer-term development phases of the Galileo project. The GSSF V2.1.11 is the current version and allows the simulation of Galileo’s functionalities and performance behaviour during different reference scenarios. The GSSF allows the implementation of real system components, including the space, ground and control segments to be integrated for the support of Galileo system understanding and validation. It operates in two main capability modes: Service Volume Simulation (SVS) and Raw Data Generation (RDG), (GSSF, 2005; Zimmermann et al., 2004).

The RDG is responsible for generating raw data that is used in validating the GSSF’s processing algorithms. By including all navigation signals and satellite constellations within the simulation scenario, the SVS offers the flexibility of combining GPS, EGNOS and Galileo navigation systems. By using predefined

UERE error budgets and integrity factors, different sets of error interferences can be added into these systems (GSSF, 2005 and 2006).

Using two modes, standard and stand-alone, the SVS allows analysis of the data and this will measure the positioning performance achieved from simulating Galileo and GPS. In stand-alone mode, the analysis was conducted manually without running the simulation again. However, in the standard mode several analysis functions are available which allow automatic data processing. The following is a list of standard analysis functions:

- **Visibility Analysis:** provides satellite visibility information, including the number of satellites in view of the user or ground segment at each time step during the simulation time. This process looks at the elevation angle to see if the receiver can see the satellite.
- **Coverage Analysis:** describes the number of ground stations in view for the satellite locations.
- **Geometry Analysis:** responsible for computing the geometry components between the ground receivers and the corresponding satellite at each time step, including elevation, azimuth angle determination and the geometric range.
- **Dilution of Precision (DOP) Analysis:** responsible for computing all DOP quantifiers for each user or ground segment element.
- **Accuracy Analysis:** this option includes two main parts:

    1. **Navigation System Precision (NSP):** describes the dispersion of user’s estimated position around its mean. This is ascertained from the UERE budgets identified within simulation environment. Time NSP (TNSP), Horizontal NSP (HNSP), Vertical NSP (VNSP) and overall NSP (ONSP) can be computed by this function for each user over the simulation period.

- **Signal-In-Space Monitoring Accuracy (SISMA):** determines the level of accuracy described by the satellite’s Signal-In-Space Error (SISE) at each simulation time step.

- **Integrity Analysis: th**e user can select from a number of integrity parameters and equations describing relevant integrity monitoring approaches. The GSSF integrity monitoring concept includes the computation of the Probability of Hazardous Misleading Information (PHMI), also known as the integrity risk, and the computation of the Protection Levels (PL) based on SBAS or Galileo data. Galileo offers the following integrity information:

    1. **Single in Space Error (SISE)** describes the maximum standard deviation for the signal error in the range domain caused by satellite data. This cannot be measured directly and is obtained after providing an estimated SISE (SISEest).

    2. **Single in Space Accuracy (SISA)** is a method that provides with a prediction of the standard deviation for a Gaussian distribution that bounds the SISE distribution (the distribution of difference between SISE and SISEest). The system is considered sending hazardous misleading information to the user if SISE is greater than SISA.

- **The Integrity Flag (IF)**: the IF threshold is used to determine whether to use the corresponding satellite or not and is computed from the SISE distribution. For example, if SISE is larger than threshold, the integrity flag then indicates that it is not recommended to use the satellite.

6.4.2 Simulation Scenarios and Setup

To investigate the positioning performance achieved from a future Galileo navigation system together with the developed positioning model the use of the GSSF was considered. Only the Galileo Open Service (OS) was focused on, primarily because:

- The OS is planned to be free of charge and available to all types of users and applications, therefore it will be widely deployed in future navigation systems.

- The OS is the most applicable service to GPS standard positioning services.
- According to the current development challenges of the Galileo programme, the OS can be considered as the most possibly achievable Galileo positioning service (Fylor, 2009).

In order to benefit from its integrity advantage several satellite constellations were utilised, including Galileo and GPS, during the simulation study. By utilising Galileo OS single frequency within one of the frequency bands (E5a, E5b, E2-L1-E1, or E5-AltBoc), together with GPS CA signal within the L1 frequency band, a hybrid positioning service was made available. The simulation study was conducted in dynamic and static scenarios that only considered urban and rural environments as the GSSF only offers UERE budgets for these two environments.

For a dynamic scenario (mobile user), the system requires the route information for the aimed testing route. The *Define Trajectory* option available within GSSF can define this. This option allows entering a set of longitude, latitude and height coordinates which define the testing routes. The coordinates of the static points', applied in the experimental assessments routes, were entered into GSSF and these were used to identify the rural and urban trajectories in the simulation study. Conversely, the static scenarios were simulated at two different points using different UERE budgets that represented both rural and urban environments.

Both static and dynamic scenarios, defined by the simulation time intervals, follow the same intervals employed in the experimental work. During all simulation sessions, the position-sampling rate was set to 1 second. The SVS standard analysis functions analysed the data obtained from the static and dynamic simulation scenarios and this provided the mean, maximum and minimum values of the achieved positioning performance parameters. For further analysis, these parameters were exported into an Excel file. To quantify the positioning model's achievable performance with reference to future Galileo and GPS systems, the results from the simulation study were compared to the experimental measurements.

6.5 Summary

The chapter has described the evaluation methodology that has been employed to explore and assess the effectiveness of the positioning model concerning position sample accuracy, precision, NRTK service availability and number of GNSS satellites. The first part of the evaluation methodology focused on performing experimental measurement trails in order to observe and gather GPS and GLONASS data within a number of navigation environments (rural, suburban, and urban).

The second part of the methodology dealt with simulation of a hybrid positioning service offered by Galileo OS single frequency, alongside GPS standards frequency services. The simulation study utilized both dynamic and static scenarios by way of using points in both urban and rural settings.

The experimental results analysis and discussion of the assessment methodology of NRTK GNSS and GSSF are presented in next chapter (Chapter 7).

Chapter 7

7. Results Analysis and Discussion

7.1 Introduction

The evaluation methodology depicted in Chapter 6 was used in order to perform the following tasks:

- Evaluating the performance of the developed positioning model taken as a whole, presented in Chapter 5, in the course of the experimental measurements. This included the following:

    1. Evaluating the positioning performance attained from the developed positioning methods, augmented NRTK GNSS dual frequency service, proceeding at the MNU. This step entails the following constraints:

        - The positioning solutions determine the positioning performance, also described as position samples, accuracy and precision, number of GPS and GLONASS satellites, as well as the service availability.

    2. Quantifying the achieved positioning performance against the proposed minimum performance requirements level associated with pedestrian navigation application groups, as described in Chapter 6. In which, the identified maximum position error margin was 0.5-1 meter, and the maximum allowable DOP quantifiers were (HDOP ≤2.5 and PDOP ≤5).

    3. Determining the effect of the environment (rural, suburban and urban) on the obtained position accuracy.

- Examining the future Galileo Open Service (OS) positioning using GSSF and comparing its accomplished performance in opposition to the developed positioning model.

This chapter is split up into two key sections: Section 7.2 presents and discusses the outcome of the experimental measurements for the static and dynamic tests, which were employed to illustrate the performance achieved from the developed positioning model. Besides, Section 7.3 describes the results attained from the simulation examination, appraising the performance realised from future Galileo OS services.

7.2 Experimental Results

With the intention of evaluating the quality of the NRTK service, the assembled data were analysed with the subsequent assumptions: the navigation environments (urban, suburban and rural) and measurement scenarios (dynamic and static), the overall errors in GPS and GLONASS observation results from the total of different error components (for instance, the receiver clock offset, the satellite clock offset, the orbit error, the ionospheric and the tropospheric biases, etc.) and the amount of total errors have more or less a normal distribution, regardless of the component errors are distributed normally. Consequently, common formulae for normal distributed data were used in the analysis. The initial step was to filter outliers. The data was processed at a 95% confidence level to exclude all outliers.

The definition of the accuracy can be understood as how far the coordinates that are calculated during the testing are from the true values (Feng and Wang, 2007). For that reason, the accuracy for each coordinate component, East and North, was calculated. The entire accuracy of respective test was determined as the typical of the accuracy values at each epoch. In contrast, precision is a matter of degree of repeatability (or closeness) that repeated measurements display, and is therefore employed as a way to illustrate the quality of the data with regards to random errors (Rizos, 1999). It was represented by the standard deviation (SD) of the solutions (2-sigma, about 95% of solutions).

The real-time coordinate streams, produced by the rover receivers during the data collection utilising data sets that were concurrently gathered by the reference stations in the vicinity of these testing sections and the 3D coordinate times series in WGS84, a global reference system in which the locations that are determined with the GNSS positioning is displayed, are converted to the 3D coordinate time series referred to a local coordinate system such as OSGB36, the national datum of UK.

The positioning results, of the coordinate domain positioning methods, represent the core solution gained from the system model presented in this project. Referring to the measurements scenarios, the experimental outcome are explained in the following sub-sections.

7.2.1 Static Measurements Results

This section describes the results obtained from the experimental measurements conducted at the fixed observation sites OS1, OS2, OS3 and the benchmark points ST1-ST20. As explained in Section 6.3.4, these sites were located in urban, suburban, and rural area environments as shown in Figure 6.7 and 6.10. The results described in this section present only the performance during the testing trial conducted between 2:00pm to 3:00pm. This measurement period was chosen because it was more appropriate to conduct the dynamic experiments during that time and not for 24 hours due to practical reasons. The measurement period is in itself of no greater significance so long as the experiment is conducted at the same time throughout the trials in order to encompass the same satellite constellations. It may still be argued that longer measurement periods equal more accurate results. However, due to the impracticability of conducting 24 hour dynamic testing, the measurement period between 2:00pm and 3:00pm was chosen and followed. The overall results obtained from 24-hours of static measurements, including all testing trials are demonstrated in Appendix B.

7.2.1.1 Observation Sites

At the first observation site (OS1), the calculated accuracy for Easting position coordinates was 1.13 cm and for the Northing position coordinated was 1.47 cm at a 95% confidence level. The horizontal position errors for East coordinates are shown in Figure 7.1a. In addition, Figure 7.1b illustrates the North coordinates horizontal position errors. The NRTK availability experienced at this site was 98.43%. Moreover, Figure 7.1c illustrates the PDOP and the average number of tracked satellites, obtained during the same measurement period, the average of PDOP and tracked satellites was 2.12 and 11 respectively. The calculation and explanation of PDOP is described in Chapter 6 (Section 6.2.7). However, for the purpose of these results, it should be noted that the lower the PDOP, the better the accuracy. Likewise, the more tracked satellites, the better the accuracy. In figure 7.1c the PDOP is demonstrated on the y-axis on the left hand side of the graph, while the tracked satellites are demonstrated on the y-axis on the right hand side.

As described earlier, the precision level of each position solution can be described using the standard deviations. Therefore, for the same measurements conducted at OS1, the standard deviations for the errors in the Easting position coordinates were +/- 0.84 cm and for the Northing position coordinates were +/- 1.11 cm, for the NRTK observations.

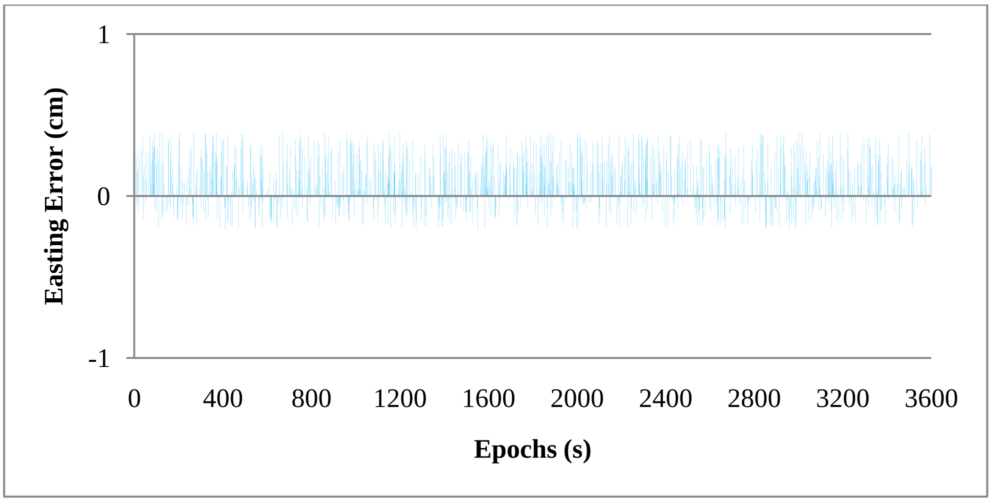


Figure 7.1a: Accuracy and Precision (Easting Error) for OS1.

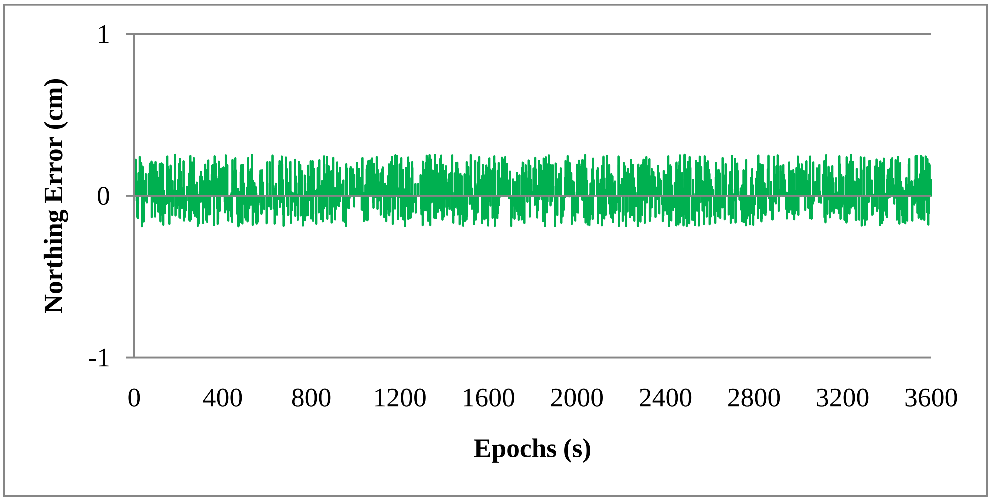


Figure 7.1b: Accuracy and Precision (Northing Error) for OS1.

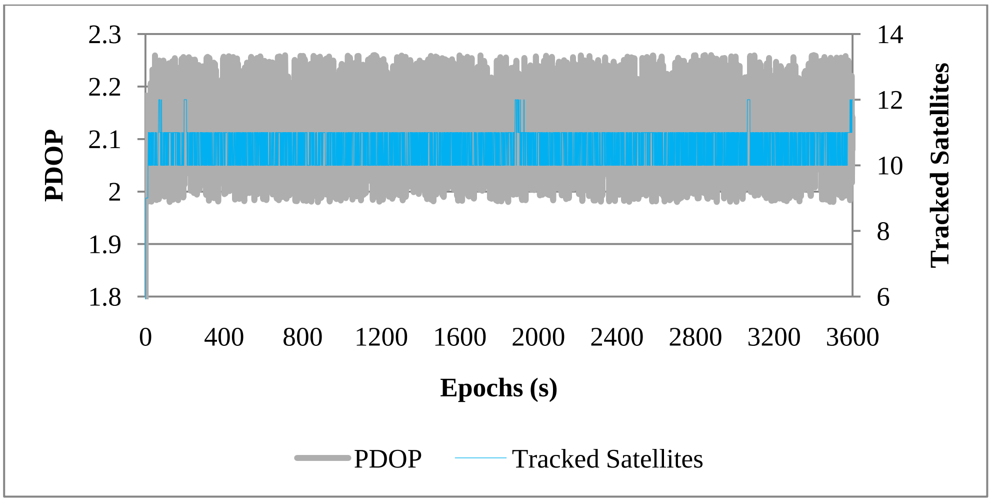


Figure 7.1c: PDOP and Tracked Satellites obtained during the static test OS1.

Below are the accuracy, precision, availability, tracked satellites and PDOP obtained during the test for OS1 and is summarised in Table 7.1. The computed measurements for accuracy and precision are described in Chapter 4 (Section 4.4.2) and Chapter 6 (Section 6.2.7). Furthermore, NRTK availability and PDOP calculations are described in Chapter 6 (Section 6.2.3).

Test	East – Accuracy Average (cm)	North – Accuracy Average (cm)	East – Precision SD (+/- cm)	North – Precision SD (+/- cm)	NRTK Availability (%)	Tracked Satellites Average	PDOP
OS1	1.13	1.47	0.84	1.11	98.43	11	2.12

Table 7.1: Measurements obtained during static tests for the OS1.

At same confidence levels, 95%, the position accuracy computed at site OS2 for the Easting coordinates was -21.32 cm and for the Northing coordinates was 33.13 cm. The Easting and Northing horizontal position errors are shown in Figure 7.2a and 7.2b In addition, Figure 7.2c illustrates the PDOP and the average number of tracked satellites, the average of PDOP was 2.44 and the average of tracked satellites was 9. The availability for OS2 was 86.51%.

The standard deviations for the errors in Easting and Northing position coordinates were summarised as +/- 2.32 cm and +/- 3.43 cm, for the samples obtained from NRTK positioning methods. Table 7.2 summaries all obtained measurements obtained at OS2.

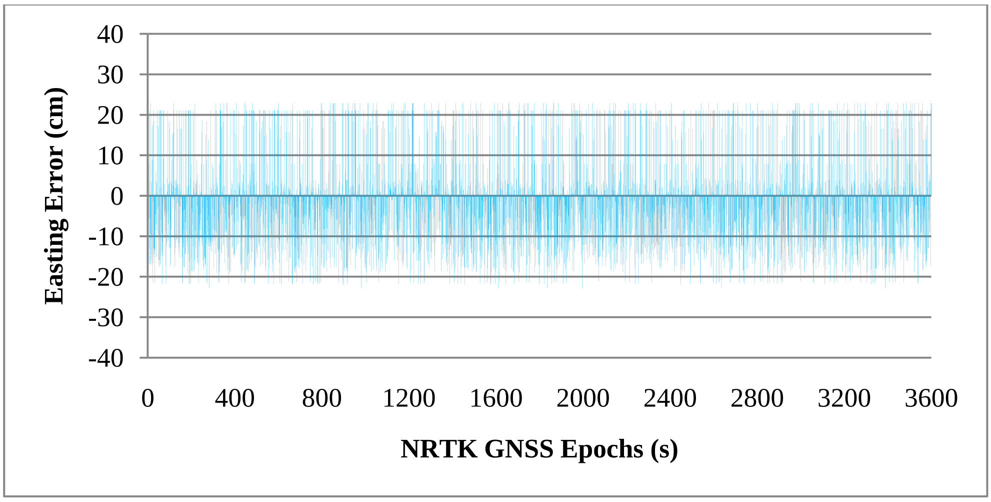


Figure 7.2a: Accuracy and Precision (Easting Error) for OS2.

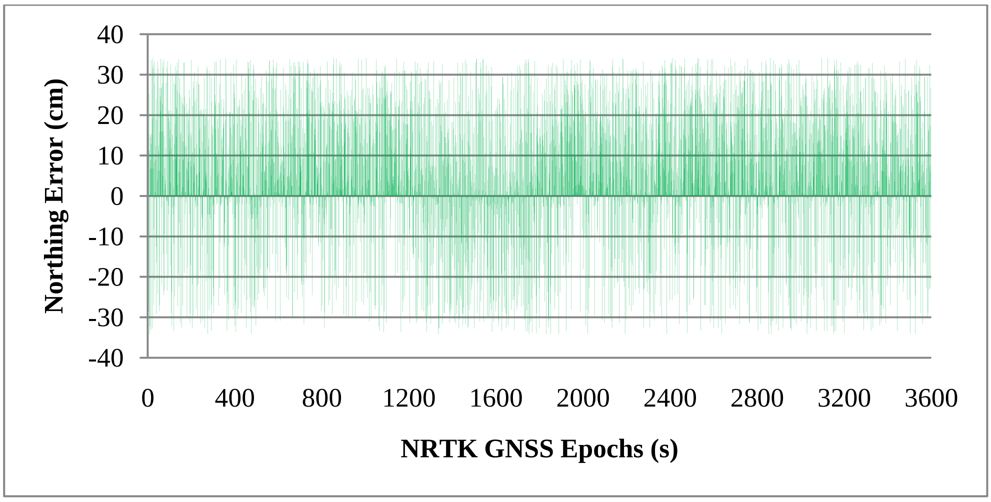


Figure 7.2b: Accuracy and Precision (Northing Error) for OS2.

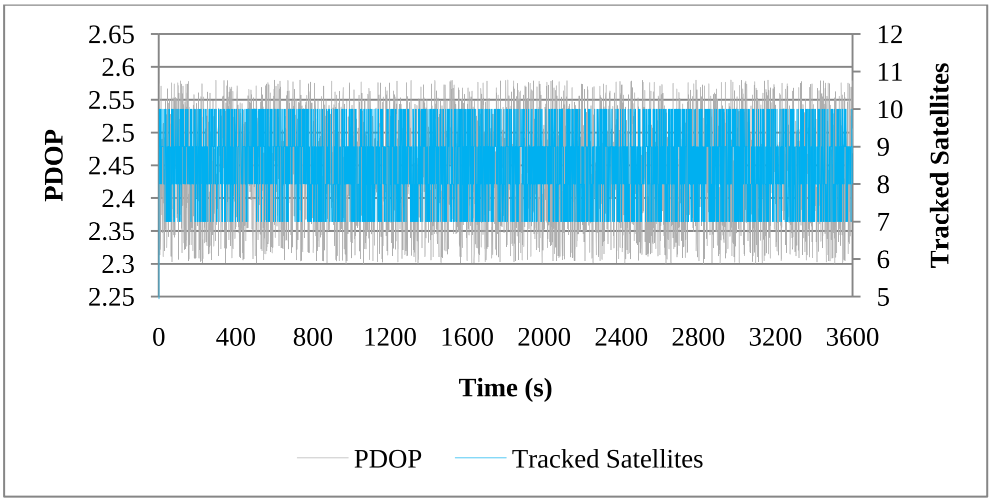


Figure 7.2c: PDOP and Tracked Satellites obtained during the static test OS2.

Test	East – Accuracy Average (cm)	North – Accuracy Average (cm)	East – Precision SD (+/- cm)	North – Precision SD (+/- cm)	NRTK Availability (%)	Tracked Satellites Average	PDOP
OS2	-21.32	33.13	2.32	3.43	86.51	9	2.44

Table 7.2: Measurements obtained during static tests for the OS2 between 2pm-3pm.

At OS3 the test was conducted in urban environment. The accuracy for East and North coordinates were 44.4 cm and 77.7 cm respectively. The availability was 68.87%. Therefore, by reason of the environmental effects, such as high multipath and constrained augmentation services accessibility, the worst position was achieved at OS3.

At OS3 the PDOP was 4.70, this verifies that the positioning data, which is measured at OS3, was achieved from satellites with poorer geometry in comparison to OS1 and OS2. Besides, because of the surrounding obstructions, the typical value for the number of tracked satellites at OS3 was 7, compared to 11 and 9 satellites at OS1 and OS2 respectively.

The precision at OS3 were summarised as +/- 4.62 cm and +/- 6.22 cm. The measurement obtained for the observation sites OS3, are summarised in Figures 7.3a, 7.3b and 7.3c. A summary of acquired measurements at OS3 are shown in Table 7.3

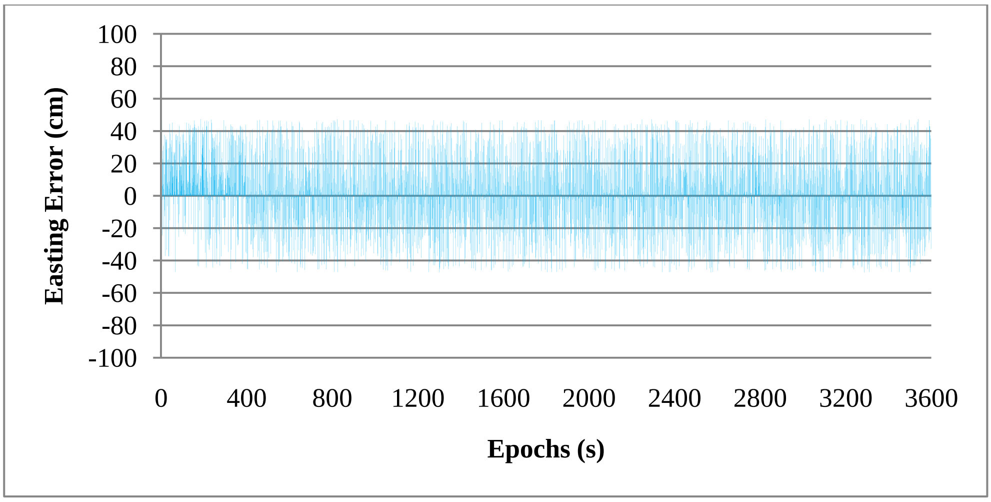


Figure 7.3a: Accuracy and Precision (Easting Error) for OS3.

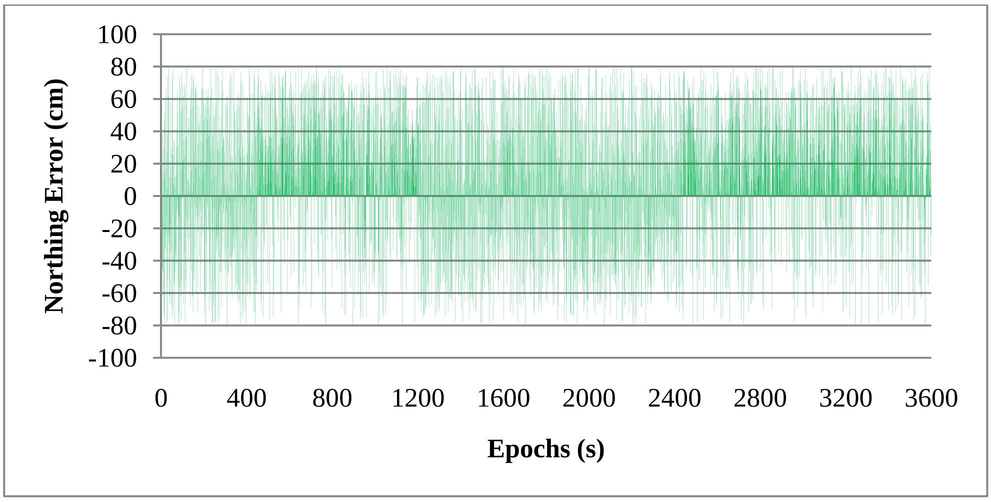


Figure 7.3b: Accuracy and Precision (Northing Error) for OS3.

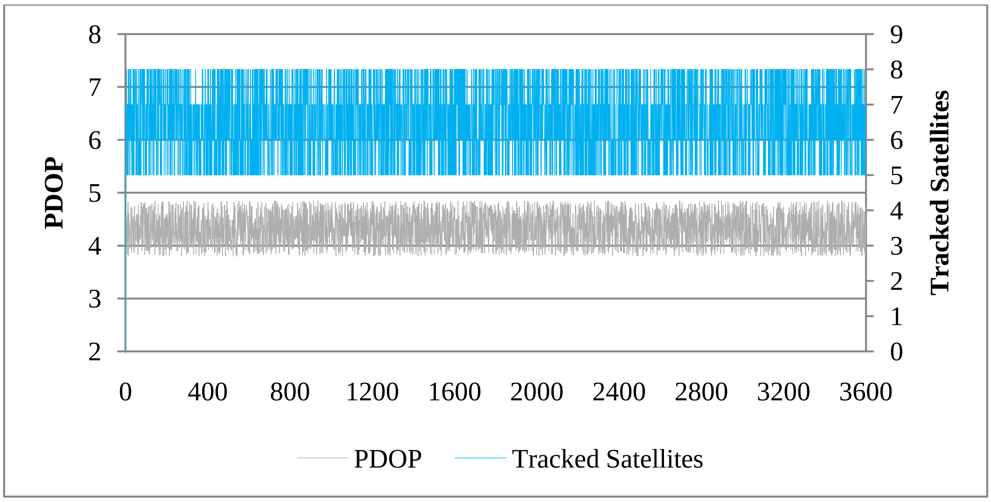


Figure 7.3c: PDOP and Tracked Satellites obtained during the static test OS3.

Test	East – Accuracy Average (cm)	North – Accuracy Average (cm)	East – Precision SD (+/- cm)	North – Precision SD (+/- cm)	NRTK Availability (%)	Tracked Satellites Average	PDOP
OS3	44.40	77.70	4.62	6.22	68.87	7	4.70

Table 7.3: Measurements obtained during static tests for the OS3.

Tables and summarised outcomes explained in this section are based on epochs with legitimate positioning observations, in accordance with the illustrated figures. As shown, OS1 had the highest accuracy, precision and more trustworthy levels compared to OS2 and OS3. The enhanced positioning performance at the OS1 can be understood as a result of the open space with no obstacles and certain availability of the correction messages and the efficiency of the generated integrated carrier phase corrections employed to correct and compute the user's position.

The NRTK positioning method at the MNU faced several disadvantages at OS3, for instance the blockage of signal, multipath, unavailability and delays of the information for correction. The position accuracy against the delay in the correction messages reception, also described as Age of Correction (AoC). Usually, the delays are because of the vulnerability of the medium that is being used to bring the messages of correction to the experimental place. The experiment showed how the accuracy became noisier when the AoC went over one second, although the impact of the AoC on the accuracy of the solutions is not palpable as the factors above, i.e. the amount of satellites in sight and PDOP.

The availability of the augmentation services from TopNET+ at the MNU was more than 99% of the measurement periods, because of the devoted good link between the MNU and TopNET+ data server.

A summary of the accuracy, precision, availability and the PDOP obtained during the tests for OS1, OS2 and OS3 are summarised in Table 7.1. The results in this table are based on epochs with valid NRTK observations.

Test	**East – Accuracy Average (cm)**	**North – Accuracy Average (cm)**	**East – Precision SD (+/- cm)**	**North – Precision SD (+/- cm)**	**NRTK Availability (%)**	**Tracked Satellites Average (Mean)**	**PDOP (Mean)**
OS1	1.13	1.47	0.84	1.11	98.43	11	2.12
OS2	-21.32	33.13	2.32	3.43	86.51	9	2.44
OS3	44.40	77.70	4.62	6.22	68.87	7	4.70

Table 7.4: Accuracy and precision in centimetres obtained during static tests, for the East and North coordinate components.

7.2.1.2 Benchmark Points

The benchmark points, ST1-ST20, were situated in different navigational environments with a choice of different conditions, from rural area to densely built-up areas, shown in Figure 6.6. The static measurements spanned over several days. During each day twelve testing trials in different time periods were conducted. Each static trial lasted for one hour.

The accuracy and precision acquired at a 95% confidence level during the test for the benchmark points ST1-ST20 is summarised in Table 7.5. In addition, the tracked satellites, availability and PDOP are also shown in Table 7.5. The calculated accuracy was at different levels for the benchmark points. As can be seen, ST1-ST2, ST3, ST10-ST12 and ST20 had the best accuracy and precision of all the tests, with most values below 10 cm.

Test	**East – Accuracy Average (cm))**	**North – Accuracy Average (cm)**	**East – Precision SD (+/- cm)**	**North – Precision SD (+/- cm)**	**NRTK Availability (%)**	**Tracked Satellites Average (Mean)**	**PDOP (Mean)**
ST1	-1.3	1.77	1.3	0.79	97.89	10	2.52
ST2	1.7	-3.1	1	1.3	97.49	9	2.84
ST3	1.97	1.1	0.87	1.62	97.63	10	2.89
ST4	-23.72	-17.1	3.57	2.65	89.76	8	2.98
ST5	30.83	-21.87	4.13	3.37	78.68	7	3.67
ST6	-37.17	44.37	5.11	6.22	69.28	7	4.57
ST7	27.19	-16.94	3.97	2.89	72.18	6	4.20
ST8	13.47	8.26	2.69	2.17	93.32	9	3.01
ST9	-17.13	-11.43	3.77	2.03	92.46	8	3.13
ST10	1.66	1.11	0.83	1.44	98.13	11	2.36
ST11	-6.9	11.76	1.74	2.26	94.16	8	3.18
ST12	2.31	6.81	1.68	2.78	96.68	9	2.94
ST13	-51.18	47.63	6.18	5.47	65.74	5	5.42
ST14	47.23	66.11	5.89	6.79	68.67	5	4.97
ST15	66.91	73.54	6.23	6.93	59.39	5	5.41
ST16	78.23	-43.81	7.67	5.11	63.85	6	5.03
ST17	46.21	17.94	5.23	3.13	74.41	6	4.72
ST18	-6.3	-3.1	1.54	1.27	96.11	9	2.51
ST19	8.73	4.90	3.84	3.05	95.21	8	3.09
ST20	-1.23	1.76	1.13	1.66	97.13	10	1.99

Table 7.5: A summaries of accuracy, precision, tracked satellites and PDOP obtained during static tests for benchmark points ST1-ST20.

The accuracy obtained from each test for the East coordinate component can be seen in Figure 7.4a. During NRTK static tests the East accuracy was better than 40 cm for an average of 62% of the NRTK GNSS epochs.

The same pattern could also be also perceived in the North coordinate component results as presented in Figure 7.4b. Generally, NRTK GNSS results were more correct in rural and suburban areas than urban areas.

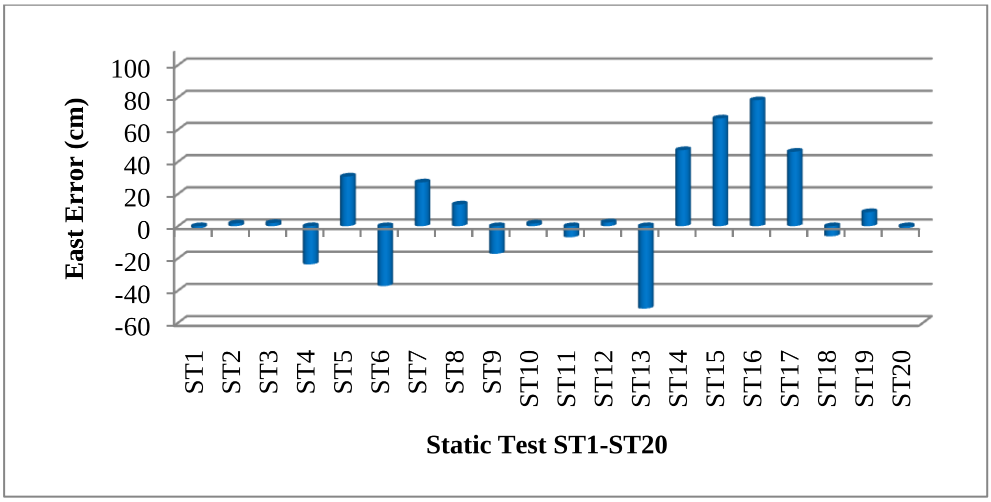


Figure 7.4a: Accuracy of solutions from each static test (ST1-ST20) for the East coordinate component (cm).

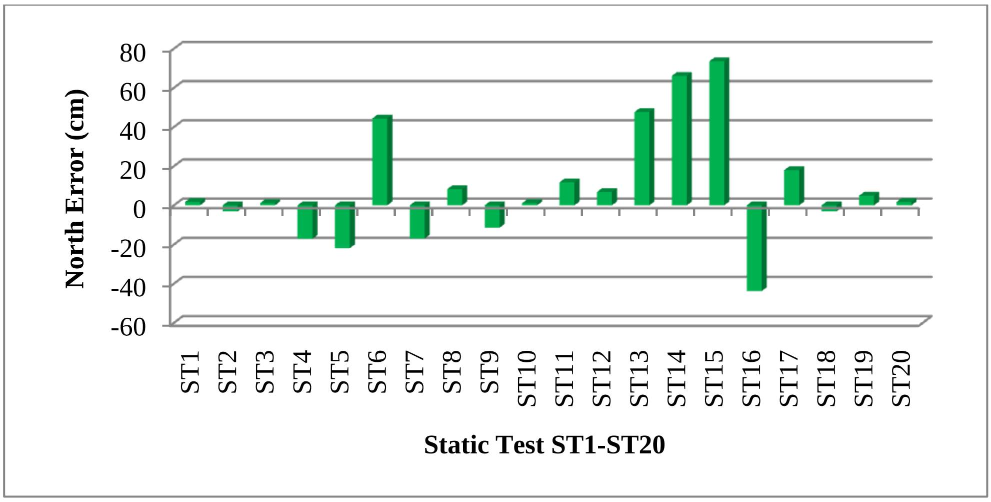


Figure 7.4b: Accuracy of solutions from each static test (ST1-ST20) for the East coordinate component (cm).

The availability was determined as the percentage of observations from which a NRTK GPS solutions (integer ambiguities resolved) was gained during a test (Brown et al. 2005a). This is an important index for the high-quality performance of the TopNET+ service.

The NRTK service availability during static tests was 84.91% on average for all tests ST1-ST20 as can be seen in Table 7.5. The availability with the lowest levels for static tests was detected during ST15 (59.39%). All results for all benchmark point are shown in Figure 7.5. All these tests were performed by using the CORS configuration, which may point to the additional problems that NRTK meets when resolving opacities at the rover side (MNU) for CORS configurations (Chapter 2, Section 2.2.3).

Figure 7.5: NRTK GNSS availability results of observation for ST1-ST20.

A distinct feature of the TopNET+ service is that of when a NRTK solution is not possible because of the uncertainties not being attended to, the solution switches to DGPS; of course, only if the corrections continue to be received. It can be inferred that problems with the GPRS data link did not cause the availability to drop during ST1-ST20.

Nevertheless, DGPS solutions and its presence are not indicating whether all necessary corrections messages are received or not. In GSM/GPRS (TCP), communication data is Cyclic Redundancy Check (CRC) checked, it is not error checked. Thus, the data can still be received; however, it might be incorrect or incomplete. The pseudo-ranges and phases can form the correction messages. At times when pseudo-ranges are utilised, every epoch provides a solution independently of pre- or post-observations. Phase solutions require more observation data to resolve integer uncertainties. Hence, this will have a bigger impact on integer fixing if some phase data of satellites are absent because of communication link.

The ambiguity resolution process could have been affected by aspects, such as few satellites in sight, constellation geometry, and undependable observations, during these tests.

7.3.1 Dynamic Measurement Results

The results that are attained from the measurements conducted at the dynamic routes 1 (DT1) and 2 (DT2), are presented in this section. These were located in urban, suburban, and rural area environments respectively (see Chapter 6, Section 6.3.3). The dynamic measurements were conducted during several days. Twelve testing trials in different time periods took place each day, and the duration was approximately one hour for each trial. For the purpose of quantifying the positioning performance gained at each dynamic route, the collected GPS and GLONASS data were processed and analysed concerning the horizontal position accuracy, precision and the experienced service availability.

The results described in this section, alike the results obtained from static measurements, present the performance attained while one testing trials that took place during the measurement period (2:00pm to 3:00pm), at a number of selected benchmark points identifying every path. These benchmark points were selected when showing diverse levels of positioning performance at each one testing route. The performance results are summarised in Table 7.5 in section 7.2.1.2 (Benchmark Points), and illustrated in Figures 7.4 and 7.5. With reference to benchmark points noticed in each route, also described in Section 6.3.3, the subsequent points were selected:

- Benchmark Points ST3 → ST4 → ST5 → ST6 → ST8 → ST9 → ST10 on route 1 (DT1).
- Benchmark Points ST13 → ST15 → ST17 → ST19 on route 2 (DT2).

7.3.1.1 Dynamic Test 1 (DT1): Rural and Suburban Environment

This section presents the positioning performance achieved at different locations (benchmark points ST3, ST4, ST5, ST6, ST8, ST9 and ST10) on route 1. As shown in Figure 6.5 (Chapter 6), this route simulated a combine of rural and suburban navigation area, in which GPS and GLONASS signals were occasionally blocked by an adjacent building at benchmark points, ST4 (Sports Hall), ST8 and ST9 (Howell Building), from one side during the measurements. At benchmark point ST5 the signals were blocked from three sides, Art Centre, John Crank and Lecture Centre building. In addition, point ST6 was blocked from two sides, Gordon Hall and Lecture Centre. The testing areas at Brunel University contain excellent mobile communication coverage.

The accuracy and precision were computed in 95% confidence level, and the NRTK GNSS availability for the position samples in DT1 obtained are shown in Table 7.5 (Section 7.2.1.2). Furthermore, the East and North position errors for benchmark points ST3-ST6 and ST8-ST10 are shown in Figure 7.6a and 7.6b.

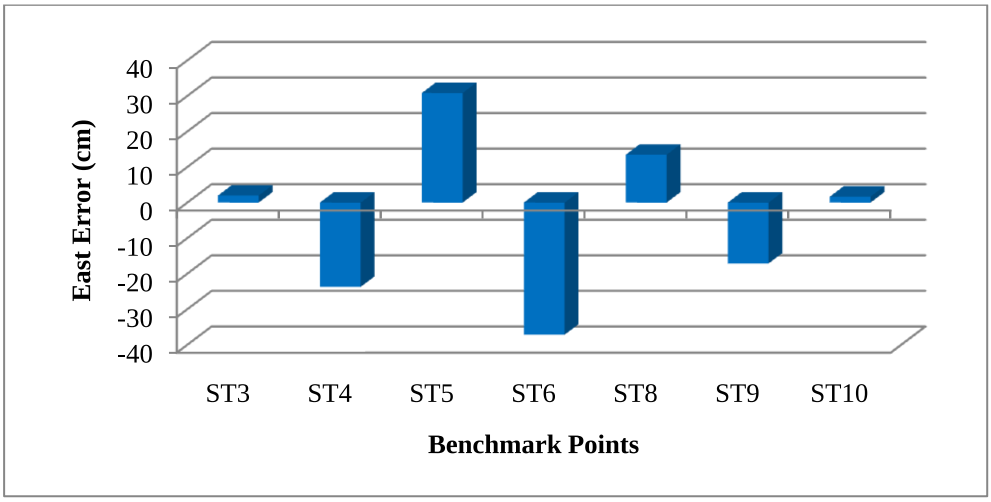


Figure 7.6a: The East coordinate errors for benchmark points ST3-ST6 and ST8-ST10.

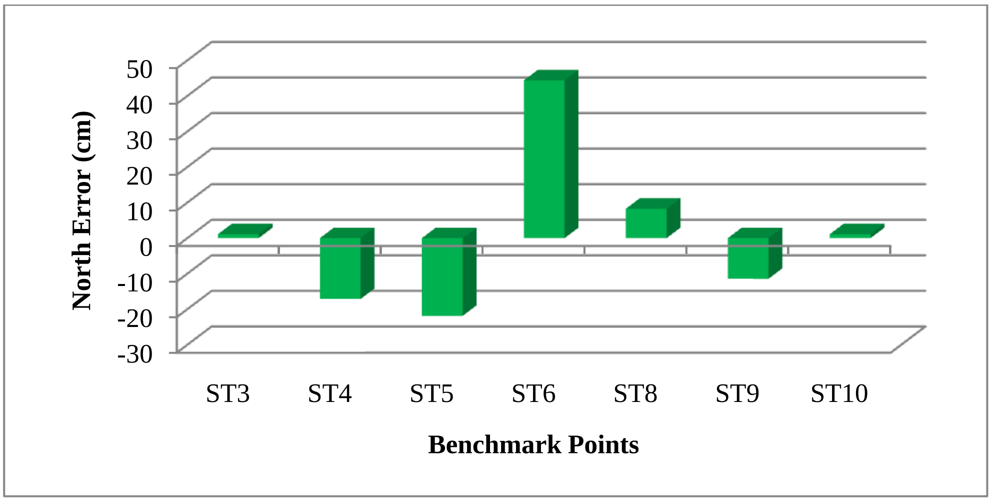


Figure 7.6b: The East coordinate errors for benchmark points ST3-ST6 and ST8-ST10.

The worst data measurements were, at DT1, notable when passing through benchmark points ST5, ST6 and ST9. These marker points were placed between several buildings as presented in Figure 6.7. The horizontal accuracy computed at point ST5, ST6 and ST9 were 30.83 cm, -37.17 cm and -17.13 cm respectively for East coordinate errors. The North coordinate errors were -21.87 cm, 44.37 cm and -11.43 cm respectively.

As shown in Table 7.5, the availability of the NRTK GNSS service during DT1 for benchmark points (ST3-ST6 and ST8-ST10) had numerous number of NRTK availability levels due to the environment. While the availability level with the highest outcome was obtained during ST10 (98.13%), the lowest was ST6 (69.28%). The location of the start and end points ST3 and ST10 could take place at a clear view location in comparison to the rest of the benchmark points during this route. The PDOP values computed at point ST3 were somewhat higher, even though the number of tracked satellites at both ST3 and ST10 were high (10 and 11). This increased the position errors at ST3 compared to ST10.

The benchmark points ST4, ST5, ST6, ST8 and ST9 identify the middle/end of dynamic test 1 (DT1). These points were located at a built-up area compared to the rest of the marker points at this route. The route for DT1 is shown in Figure 6.7 (Chapter 6). The average numbers of tracked satellites were 7 and 8. The highest average of PDOP values was at ST6, 4.57. The lowest average of PDOP was at ST4 2.98. These values decreased compared to points ST3 and ST10. The tracked satellites and PDOP for DT1 are shown in Figure 7.7.

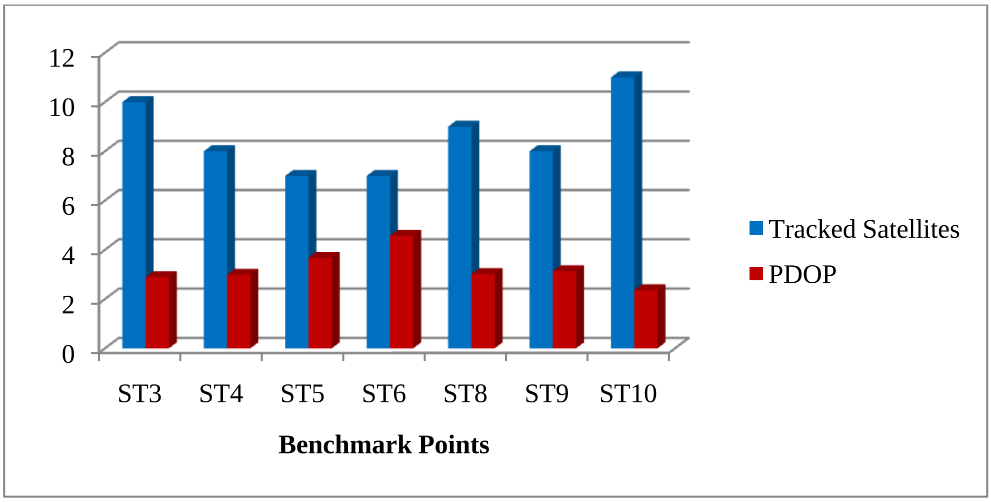


Figure 7.7: Tracked satellites and PDOP obtained during DT1.

The performance that was attained at points ST3 and ST10 were best compared to benchmark points (ST4, ST5, ST6, ST8 and ST9) along DT1.

The 2D Root Mean Square Error (RMSE) that was observed during DT1 is presented in Figure 7.8. The measured path, which depicts the DT1, was determined from the traces of the position samples, computed at all benchmark points by means of the coordinate domain and the NRTK GNSS augmentation service.

The horizontal accuracy along each measured path achieved from the coordinate domain was better than 20 cm, with reference to the surveyed path. The gaps were apparent when a NRTK solution was not available, which can be seen in Figure 7.8. Aspects such as low amount of satellites in view, constellation geometry, and no reliable observations, could have influenced on the ambiguity resolutions process throughout these tests. Especially, the availability in the built-up area is far lower than for the rest of the route.

On average, NRTK solutions were obtained only about 88.44% of the time, which are lower than that which was achieved during static test for OS1 (98.43%).

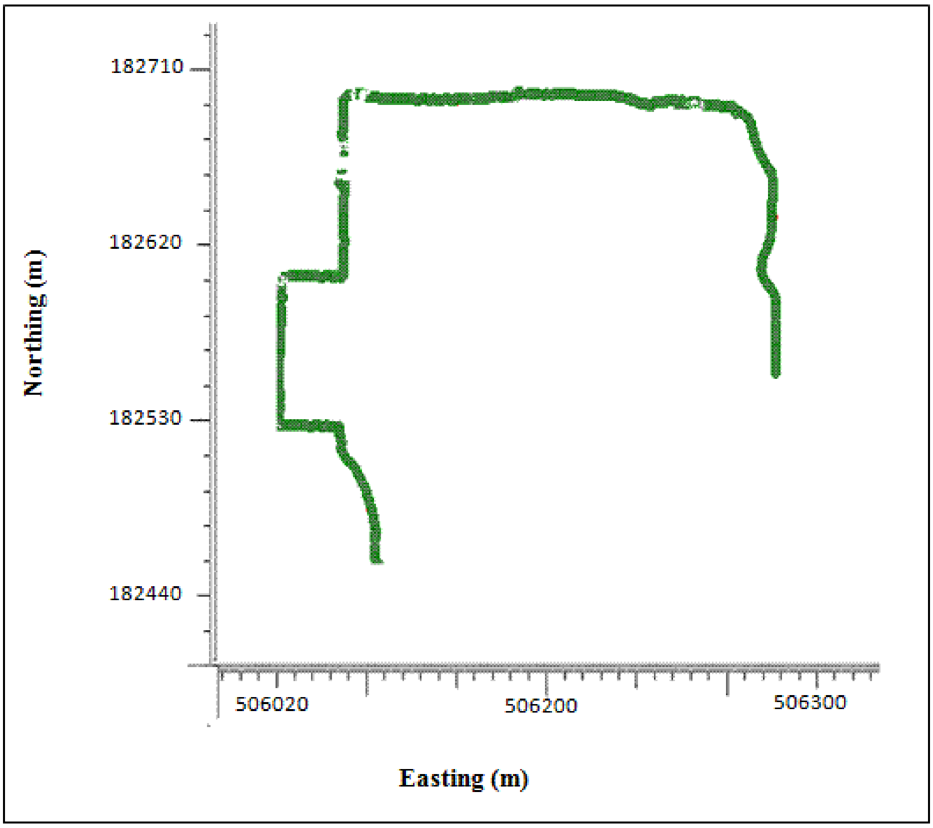


Figure 7.8: 2D RMSE errors observed during DT1, represented over the route during the test.

7.3.1.2 Dynamic Test 2 (DT2): Urban Environment

In this section the positioning performance that is achieved at different locations (benchmark points ST13, ST15, ST17 and ST19) on route 2, throughout the measurement period (2:00pm to 3:00pm), is presented. As already explained in Section 6.3.3, this route was selected at indeed the densest and built up area around Brunel University campus, in which signals from satellites were expected to be blocked by surrounding buildings. Some of these routes were chosen in-between eight-storey accommodation buildings (Bishop Complex). The summary of the positioning performance results gained at benchmark points for dynamic tests can be seen in Table 7.5 in Section 7.2.1.2. The testing areas held exceptional mobile communication coverage at Brunel University.

The satellite availability of GPS and GLONASS signals were limited for ST13 and ST15, in which the average value of the number of tracked satellites were 5 for both ST13 and ST15. The PDOP values for ST15 decreased compared to ST13 due to the poor line-of-sight to the satellites, blockage and high multipath. Additionally, the benchmark points ST17 had a better accuracy and availability than S13 and ST15. In addition, benchmark point ST19 had the best accuracy and precision of all the benchmark points in DT2. All the performance results are summaries in Table 7.5 in Section 7.2.1.2.

Furthermore, the East and North position errors for benchmark points ST3-ST6 and ST8-ST10 are shown in Figure 7.9a and 7.9b.

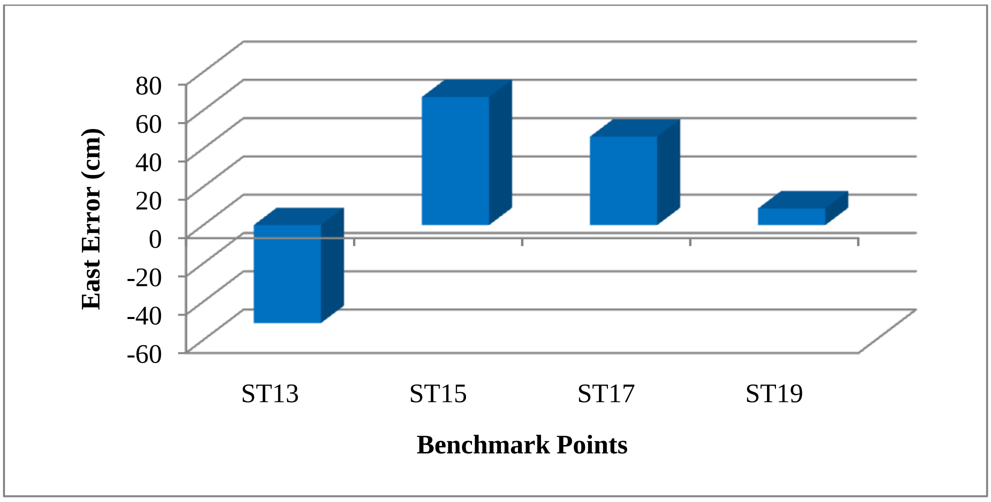


Figure 7.9a: The East coordinate errors for benchmark points ST13, ST15, ST17 and ST19.

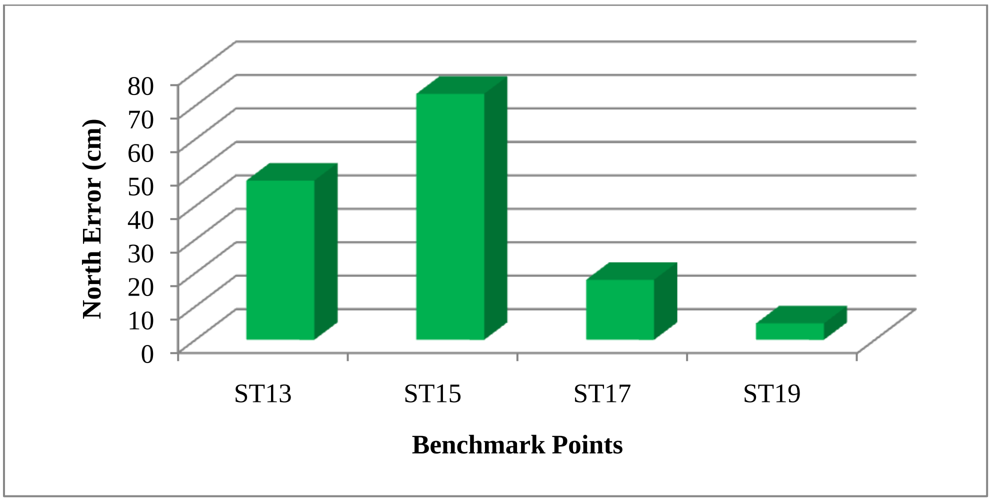


Figure 7.9b: The North coordinate errors for benchmark points ST13, ST15, ST17 and ST19.

As explained earlier in Figure 7.7, benchmark points ST13 and ST15 were encircled by buildings. Hence, the availability of GPS and GLONASS signals were restricted at these points, and a large interference to the received signals could be observed.

The unavailability of GPS and GLONASS satellites at benchmark points ST13 and ST15 degraded the accuracy achieved from NRTK positioning service, in which, the accuracy reached below 80 centimetres.

With regards to the amount of visible satellites tracked, the variation of PDOP was examined. The DOP is a measure of the quality of the GPS and GLONASS data that is being received from the satellites and is a mathematical representation for the quality of the navigation positioning solution, described in Chapter 6, Section 6.2.7. A number tracked satellites and where these satellites are located in the sky, are the main factors affecting DOP.

The highest average of PDOP values was 5.42 for benchmark point ST13 and for ST15 it was 5.41. The best PDOP value was at ST19 (3.09). The tracked satellites and PDOP for DT2 are illustrated in Figure 7.10.

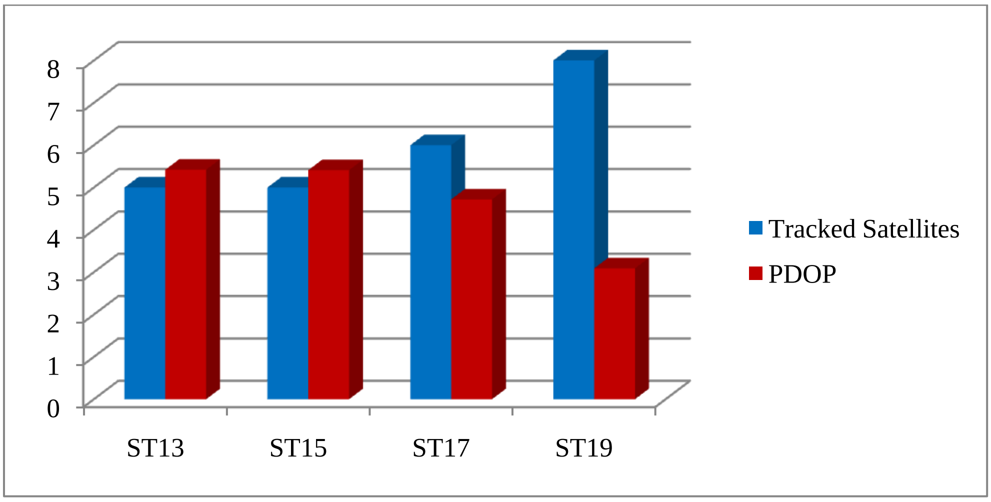


Figure 7.10: Tracked satellites and PDOP obtained during DT1.

Like DT1, the measured path was decided by way of using the traces of the position data, computed from the dynamic measurements that were conducted at DT2, during the period (2:00 to 3:00pm). The paths that were measured, along with the surveyed measured one, are demonstrated in Figure 6.9 (Chapter 6). The horizontal accuracy average for every measured path attained from the NRTK GNSS, with reference to the surveyed path, was below 85 cm.

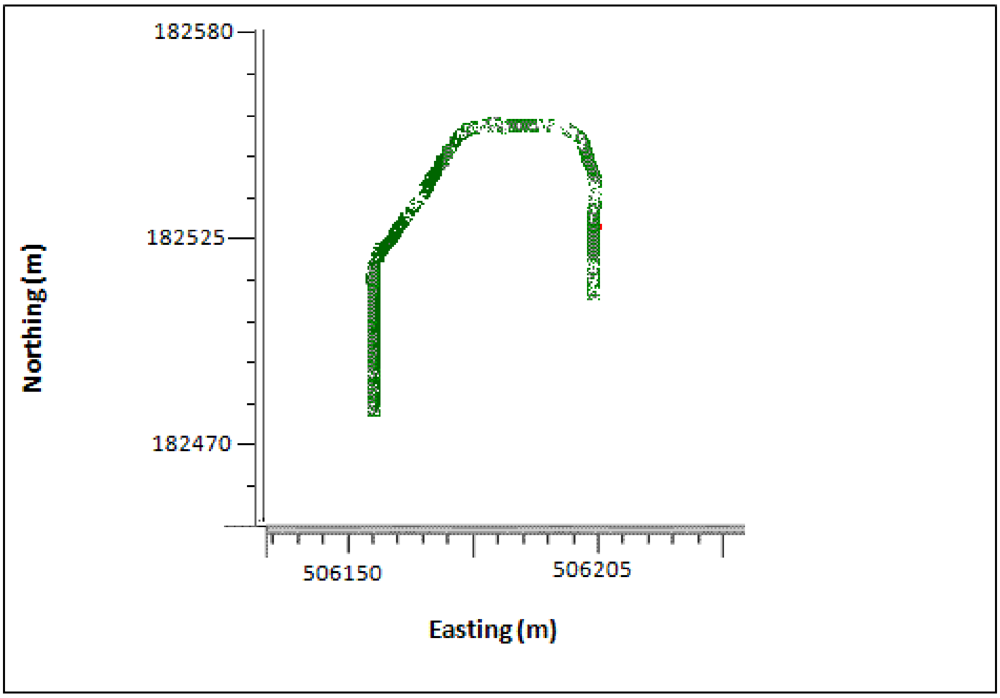


Figure 7.11: 2D RMSE errors observed during DT2, represented over the route during the test.

It is rather obvious that gaps appear when a NRTK solution is not available, which can be discerned in Figure 7.11. Low numbers of satellites in line-of-sight, no dependable observations, constellation geometry and other factors could have had influence on the ambiguity resolution when these tests took place. The availability in built-up area in particular is lower than for the remaining route.

In general, NRTK solutions for the dynamic test DT2 were gained about no more than 73.68% of the time, and this is lower than the one achieved during static test for DT1 (88.44%). The standard accuracy in the most compactly built-up area during DT2 for benchmark points ST13, ST15 and ST17 were 66.51% of the time. And that is to some extent below the static observation site OS1 (68.87%).

Various aspects could be seen to cause the lack of availability in the course of the dynamic test for DT1 as well as DT2.

The satellite signals (GPS and GLONASS) blockage and multipath when passing densely built-up areas, which were very common along the route 1 (DT1) and route 2 (DT2), as shown in Figures 6.5 and 6.6. The signal blockage and multipath caused the ambiguity fix to be lost and therefore the NRTK solution could not be obtained.

7.4 Discussion

As described in Section 7.2, the experimental results have explored the achieved positioning performance during the testing trial (2:00pm to 3:00pm). From the end user's point of view, the performance analysis of TopNET+ NRTK GNSS service was concerning the positioning samples accuracy, precision, number of GPS and GLONASS satellites and PDOP and the service availability. The discussion in this section includes the main conclusions achieved from the results presented in Section 7.2. The results depict the performance on the whole, achieved from the 24-hours measurements at each observation site, OS1-OS3. The assessments, for the static measurements ST1-ST20, took place during several days. Twelve testing trials in different time periods were conducted during each day. Each and every static trial took one hour. Additionally, concerning the dynamic tests, DT1 and DT2, the measurements that took place spanned over several days. Every day twelve testing trials were conducted in different time periods.

The main contributor to the measurement errors was the navigation environment. It caused the increasing of the Dilution of Precision (DOP) values and was also responsible for degrading the availability of GPS and GLONASS satellites. Simultaneously, this factor in this context was also responsible for inducing multipath and atmospheric delays on measurements of GPS and GLONASS, thus, in turn, increasing the magnitude of the position error. It could be observed from the results that the positioning performance in built-up areas (urban environments), was the lowest in comparison to the other environments, suburban and rural areas. This was noticeable clearly when using the existing NRTK GNSS positioning method at the MNU. In the built-up area environment in which the experimental tests DT2 and DT1 where taking place, the availability was really affected by the typical factors found in an urban canyon environment when using GNSS. Tall buildings, narrow roads and tree canopies caused signal blockage, shadowing and multipath. The NRTK solution could not be obtained as the signal blockade and multipath were responsible for the loss of NRTK solution.

The effect of the number of GPS and GLONASS satellites in view on the NRTK GNSS solutions, clearly display the relationship between the numbers of satellites employed in the solution and the accuracy of the positioning solutions. That is, the solutions were less noisy when the number of satellites increased, and the accuracy decreased when the number of satellites was ≤6. For example, at OS1, the number of satellites was 11 and the solutions were evidently more accurate, and at ST13-ST15 the numbers of satellites were 5. Nevertheless, the NRTK dual frequency receiver (rover) at the MNU has been affected (low NRTK availability) from the real-time GPS and GLONASS augmentation data and AoC. This happened because of the efficiency of the receiver, which secured the availability of real-time GNSS augmentation data at the MNU. Hence, it provided an effective integrated carrier phase correction components in real-time, employed in the error correction process. Consequently, the rover combined its local carrier phase observations with the real-time corrections from the reference stations to output position solutions at the centimetre-level for positioning service provision when having the dedicated remote positioning component at MNU. The system presented the following advantages:

- The influence of the AoC on the final position solution accuracy was considerably reduced or removed.

- The opportunity of receiving and processing GPS and GLONASS navigation and augmentation data was made available.

- The roving receiver location and its correlation with the correction information, which was used to augment the user’s position.

- In all environments and measurement scenarios, the establishment of reliable and highly accurate position solutions, satisfying the associated application requirements, was ensured.

The second main proper aspect that influenced the achieved positioning performance was the capability of the dual frequency receiver, the wireless transmission channel and the supported output data formats. The standard solution outputs that were provided in NMEA formats made the foundation for the coordinate domain method. An advanced performance was demonstrated by the positioning method. This is used to derive from the ability to realise the corrections directly on the positioning data, gaining a highly accurate position solution, even if the amount of tracked satellites at the rover side (MNU) are not enough. The wireless transmission channel is an important component of the application of NRTK. The data server, in an NRTK GNSS facility, assembles the raw observations from a number of reference stations and then sends corrections wirelessly to a rover positioning terminal, after it has carried out an integrated processing. The rover at MNU combines the local navigation positioning (carrier phase) observations with the real-time corrections from the reference stations to yield position solutions. There are a number of possible transmission methods that can be employed for NRTK GNSS positioning. Along with the different mobile networks in today’s market, the GPRS (EDGE) or HSDPA mobile networks are the best alternatives and the latter has additional advantages in the bandwidth and service trustworthiness.

Viewing the experimental results, the greatest performance attained from the static measurements, was at OS1 because of the clear line-of-sight to the satellites that was experienced at this position. The overall position accuracy average was 1.13 cm in East coordinate component and 1.47 cm in North coordinate component for the position samples obtained from the NRTK GNSS positioning methods. Subsequently, irrelevant dissimilarities between the accuracy and NRTK availability levels were seen between different times of observations, and all average values were under the maximum error threshold 0.5-1 m, as shown in Table 7.1.

The lowest positioning accuracy derived from the static measurements was observed at site 3 (OS3), due to blockage of signals and interference triggered by surrounding environment. Therefore, throughout the 24-hours measurements at this site, the GPS and GLONASS NRTK availability at the MNU was 68.87% of the measurement time. The average of the overall accuracy during the 24-hours of measurements at OS3 was 44.40 cm for the East coordinate component and 77.70 cm for North coordinate component for the position samples obtained from the NRTK GNSS positioning methods. In addition, the average of PDOP values and tracked satellites corresponding to the position solutions computed at the MNU was 4.70 and 7 respectively. The NRTK is sensitive to interference caused by surrounding obstacles in a suburban environment (buildings, trees, bridges etc.). Consequently, the NRTK availability decreases. This creates complications as regards to the accuracy, thus, making it problematic for the user at MNU to obtain an accurate position.

The best positioning performance gained from the dynamic measurements was at part of DT1 (ST3 and ST10), where clear GPS and GLONASS satellites' views were somewhat affected from the immediate environment. Satellites could be tracked with good geometry, in which the general average of PDOP during the 12 testing trials for ST3 and ST10 were 2.89 and 2.36 respectively. These two averages were below the availability threshold values (PDOP ≤5) identified earlier in Table 6.1. Moreover, not more than a minor difference between corresponding accuracy levels were computed at all benchmark points during the 12 testing trials at DT1. The accuracy on the whole was below 20 cm for the samples obtained from the NRTK GNSS positioning methods. The availability of NRTK solutions were available for about 88.44% of the experimental time between 2:00pm to 3:00pm, and this is lower than the one which was achieved during the static test for OS1 (98.43%).

Correspondingly, when looking at the experimental results obtained from the 12 trials of dynamic measurements, the worst positioning accuracy was at DT2, which was situated within an urban area. A substantial difference between the positioning accuracy and availability values was obtained at the benchmark points, identifying this route 2. The accuracy ranged from 8.73 cm (East coordinate error) and 4.90 cm (North coordinate error) at benchmark point ST19 to 66.91 cm (East coordinate error) and 83.54 cm (North coordinate error) at benchmark point ST15. The overall position accuracy average for all marker points at DT2 was below 85 cm. Thus, accurate position data (below the threshold), at this route, were computed by way of only using the advanced positioning methods developed and implemented at the MNU. Based on the results and discussion provided in the above sections, the following main points are summarised below:

- The great precision positioning method at the MNU was possible to bring highly accurate position solutions with improved accuracy, throughout all testing trials and measurement periods in all navigation environments considered in this study. This was due to two principal reasons; the availability of valid correction information with very low delay, as well as, the effectiveness of the rovers (NRTK receiver) functional approaches in perceiving and correcting the measurement errors and computing the position solution.

- The NRTK GNSS positioning method has achieved the performance requirements identified for applications demanding high accuracy, such as a navigation system for visually impaired people.

- Discarding the urban environment, improved positioning performance was attained from the static measurements in contrast to dynamic measurements; this was because the multipath effects and lack of visibility of the satellites.

- When the dynamic measurements were conducted, a variation in the computed accuracy and availability was noticeable between the benchmark points that identified each testing route based on the GPS and GLONASS service availability restrictions.

- The positioning performance can be best achieved in the open space environments, either in dynamic or static measurement scenarios. Nonetheless, the NRTK GNSS positioning methods at MNU were affected significantly by the environmental conditions.

- As explained in Chapters 3, 4, and 5, the background elements, more specifically the navigation environment, the measurement scenario, receiver output capability, and the entitled positioning requirements constituted indeed the main factors affecting the positioning performance. Taking these factors into account, the advanced positioning methods (NRTK GNSS) were developed, in which every positioning method worked based on diverse data formats, and supplied different performance levels, which were either considered sufficient or insufficient on the basis of the performance requirements.

- NRTK GNSS service depends strongly on the type of environment in which the system is used. Although NRTK provides excellent performance characteristics (rural area) and can be easily accessible by unlimited users, service availability analysis in urban canyon areas have shown that the availability requirement is not met for visually impaired people navigation system services. The satisfactory accuracy levels were achieved if the NRTK GNSS service proved to be available more than 90% of the measurement time for the dynamic test in suburban/urban environments. This then confirms the idea of having NRTK GNSS availability limitations as the main trigger to establish the communication session between the MNU and NSC, as explained in Chapter 4. Therefore, the video and voice access would enable visually impaired people to start utilising the remote sighted guidance service immediately whenever the NRTK is unavailable and when they need it and benefit from guidance by a remote sighted guide at NSC and for however long it is required.

7.5 Simulation Results

The simulation scenarios were conducted in similar scenarios as the “real test” (NRTK) environments using Galileo System Simulation Facility (GSSF). It offers several UERE error budgets for different environments (rural, suburban and urban). The benchmark points that were recognised in the experimental testing were used in the simulation facility in order to depict static and dynamic environments. In addition, hybrid satellite constellations were employed in the simulation scenarios, comprising Galileo and GPS constellations. The aim with the simulation study was to explore the positioning performance achievement from the future Galileo OS dual frequency service (E5a-E1, E5b-E1, or E5-AltBoc-E1), described in Section 2.2.5 (Chapter 2), and joined by the present GPS standard L1 signal, described in Section 2.2.1 (Chapter 2).

The results presented in this section constitute the outcome of 24-hours of simulation runtime for static scenarios and one hour runtime repeated in 12 varying periods for dynamic scenarios. The positioning sampling rate that was used was 1 second. The positioning performance achieved in the rural reference environment during static test (OS1, OS2 and OS3) are depicted in Tables 7.6a-c.

Frequency Band	Accuracy Average (95%) (m)	Precision SD (+/- m)	Availability (%)	Tracked Satellites Average (Mean)	PDOP (Mean)
E5a-E1/L1	3.95	0.33	100	17	1.67
E5b-E1/L1	3.94	0.33	100	17	1.67
E5-AltBoc-E1/L1	3.80	0.21	100	17	1.67

Table 7.6a: Positioning performance simulating observation site 1 (OS1) in the rural environment.

Frequency Band	Accuracy Average (95%) (m)	Precision SD (+/- m)	Availability (%)	Tracked Satellites Average (Mean)	PDOP (Mean)
E5a-E1/L1	4.34	0.36	98.78	16	1.87
E5b-E1/L1	4.31	0.36	98.78	16	1.87
E5-AltBoc-E1/L1	4.17	0.26	98.78	16	1.87

Table 7.6b: Positioning performance simulating observation site 2 (OS2) in the suburban environment.

Frequency Band	Accuracy Average (95%) (m)	Precision SD (+/- m)	Availability (%)	Tracked Satellites Average (Mean)	PDOP (Mean)
E5a-E1/L1	5.17	0..43	96.25	12	2.14
E5b-E1/L1	5.13	0.43	96.25	12	2.14
E5-AltBoc-E1/L1	4.86	0.37	96.25	12	2.14

Table 7.6c: Positioning performance simulating observation site 3 (OS3) in the urban environment.

As can be seen in the tables above (7.6a-c), the total average of the position samples accuracy from all frequency bands for OS1, OS2 and OS3 were 3.89 m, 4.27 m and 5.05 m respectively. The average of PDOP was between 1.67 to 2.14 for static scenarios (OS1, OS2 and OS3).

The positioning performance achieved in the suburban/urban environment during dynamic simulation scenarios (DT1 and DT2) is summarised in Tables 7.7a and 7.7b.

Frequency Band	**Accuracy Average (95%) (m)**	**Precision SD (+/- m)**	**Availability (%)**	**Tracked Satellites Average (Mean)**	**PDOP (Mean)**
E5a-E1/L1	4.12	0.34	98.76	16	1.83
E5b-E1/L1	4.10	0.34	98.76	16	1.83
E5-AltBoc-E1/L1	3.88	0.27	98.76	16	1.83

Table 7.7a: Positioning performance simulating dynamic route 1 (DT1) in the rural/suburban environment.

Frequency Band	**Accuracy Average (95%) (m)**	**Precision SD (+/- m)**	**Availability (%)**	**Tracked Satellites Average (Mean)**	**PDOP (Mean)**
E5a-E1/L1	4.27	0.43	97.25	12	2.13
E5b-E1/L1	4.23	0.43	97.25	12	2.13
E5-AltBoc-E1/L1	4.16	0.37	97.25	12	2.13

Table 7.7b: Positioning performance simulating dynamic route 2 (DT2) in the urban environment.

The total average of the position accuracy achieved for DT1 and DT2 using all frequency bands was 4.03 m and 4.22 m for dynamic scenarios, respectively. For the same position samples, the corresponding average of all PDOP values was 1.83 and 2.13. The availability of satellites was slightly limited in this environment for DT2 (97.25%). The number of tracked satellites was reduced to 12 satellites for DT2 compared to the 16 satellites for DT1 during all simulation trials. Hence, the positioning performance from GPS and Galileo service was likewise gained in the simulated urban environment with a minor degradation in comparison to the rural environment.

As described in the tables above, the total average of the position samples accuracy from all frequency bands was between 3.80 m to 5.15 m for static and dynamic scenarios. For that reason, accurate and dependable position solutions can be gained from the future hybrid system (GPS and Galileo) compared to the standalone GPS (8-10 m), because of the total experienced service availability within the simulated reference rural environment, as described in Figure 7.12.

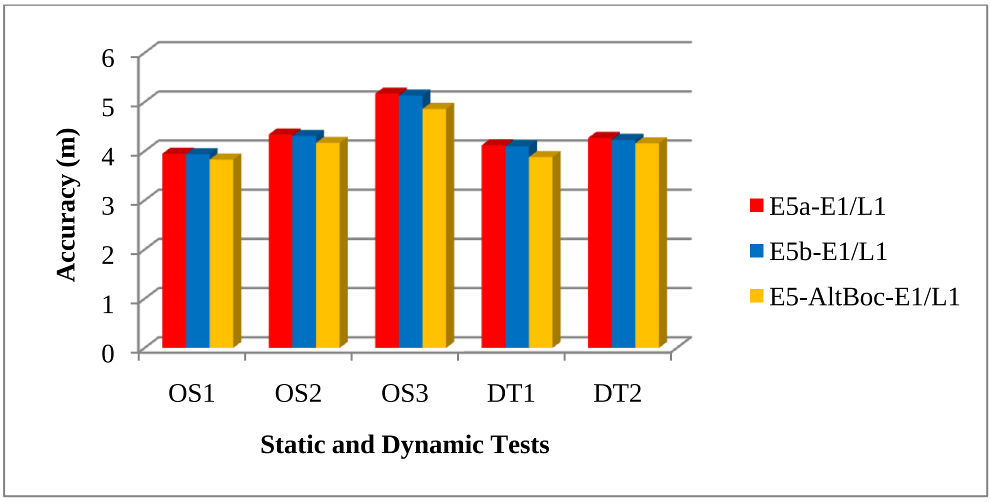


Figure 7.12: Accuracy performance of the Static and Dynamic test obtained from GSSF.

The average PDOP for dynamic scenarios, DT1 and DT2 was 1.83 and 2.13 respectively. The number of satellites that were tracked was around 17, together with GPS and Galileo during the static simulation trials within the rural environment, OS1. Nevertheless, the maximum amount of tracked GPS and Galileo satellites in dynamic scenarios (DT2) was 12. Moreover, the average of the availability for all simulation trials was 98.21%. This outlines the advantage of availability from having multiple systems working jointly. However, the performance measurements achieved with NRTK GNSS during the static and dynamic test are considerably better then the hybrid system of Galileo and GPS. The results obtained in the simulation studies for the hybrid system of GPS and Galileo are not satisfactory and were below the accuracy threshold values 0-1 m, identified in Chapter 6 (Table 6.1). Nonetheless, the availability, reliability and the PDOP are within the threshold values.

The finding from this section are summarised as follows:

- A hybrid system, combining future Galileo OS along with GPS standard positioning are more precise, accurate and dependable than standalone GPS. This is because of the utilisation of multiple satellite constellations and numerous frequencies in the positioning fixing process.

- A basic positioning performance is obtainable from all Galileo signals that are identified with diverse frequency bands. A small performance difference was observed between the signals though. This is accounted in GSSF, using different UERE budgets allotted for every frequency band.

- The NRTK GNSS outperforms the hybrid standard services offered by future Galileo OS and GPS. The hybrid system using the pseudo-range of the signals compared to NRTK using both carrier-phase and pseudo-range. However, the availability and reliability of the hybrid positioning services are significantly better than the NRTK GNSS positioning model in suburban and urban scenarios and environments. Therefore, this recognises areas of compatibility and integration between the NRTK GNSS positioning model and future systems.

7.4 Summary

In this chapter, the results obtained from the overall evaluation process conducted to quantify the performance of the developed positioning model, has been described. Different related factors have been taken into account in the description. The positioning performance obtained from the advanced methods NRTK GNSS was measured and contrasted concerning the positioning solutions accuracy and precision, laterally with augmentation data availability. From the NRTK GNSS positioning method, the best performance was achieved while having clear satellite view and high augmentation data availability. However, the

NRTK GNSS positioning methods had service availability difficulties in urban environments.

Furthermore, this chapter also explored the positioning performance that was attained from simulating a future hybrid system comprising of Galileo OS and GPS, in varied scenarios and environments. Comparisons were made between the performances obtained from the hybrid services, along with the performance that was attained from the developed positioning model by way of using the NRTK GNSS method. It was concluded that the NRTK GNSS positioning method was able to provide a significantly higher accuracy levels. However the availability was lower than the hybrid system (GPS and Galileo).

Simulation scenarios of the Galileo system were carried out. However, due to the unavailability of the Galileo system these scenarios were not experimentally validated.

Chapter 8

Conclusions and Suggestions for Future Work

In this thesis a presentation of the research work, which has been conducted in enhancing the performance of the positioning technology utilised within visually impaired people navigation application, has been offered. A new and precise positioning model was proposed. The adaptive framework is understood as approaching an integration of the available positioning technology into the context of surrounding wireless communication for a maintainable performance. The positioning model has the capability of delivering indeed accurate, precise and consistent position solutions, and thus is fulfilling the requirements of visually impaired people navigation application, as identified in the adaptive framework.

The conclusions of the key tasks that were undertaken are presented in this chapter, which furthermore presents the identified main outcomes of this research work. The conclusions made from the literature review and initial investigations of EOA, GNSS and NRTK positioning performance are summarised below. Additionally, the adaptive framework’s main features are presented, along with the positioning model. The central findings gained from the extensive evaluation of the positioning model are described with several related aspects as a reference point. Finally, this chapter concludes with some suggestions for future work in order to develop and enhance the positioning model that provides further accurate positioning services and extend its capability for in-door environments.

8.1 Conclusions

The central points of conclusion drawn from the literature review and the initial research investigation can be summarised as follows:

- ➢ The most crucial component in the navigation system for visually impaired people is the positioning technology. Important information about when and where the services are delivered is derived from the positioning technology. GPS is the most commonly deployed positioning technology.

Nevertheless, the performance is influenced by numerous error sources that is degrading the accuracy of the position solutions accuracy, and also restraining its service integrity and availability. Even though several GPS augmentation techniques have been presented and employed in different applications, yet, the attained positioning performance was based on the availability of up-to-date and dependable correction information. This is affected by the data transmission means, measurement scenarios and navigation environments. Moreover, a deep deliberation of visually impaired people navigation system applications architecture and positioning needs is required when utilising NRTK GNSS and its augmentation systems.

- A set of preliminary performance experiments of different mobile wireless technologies were conducted, such as UMTS and HSDPA, for utilisation in the system. The performance assessment was focused on the following link features: delay, jitter and packet loss of the GPS data and the live voice and video streaming. These features were chosen to be assessed because they have a significant impact on the overall performance of the navigation system. The outcome of these preliminary experimental studies have confirmed that the HSDPA is the only technology that matches the ITU standards in navigation environments, such as urban, suburban, rural and indoor. Therefore, these contextual factors were considered in the developed positioning model for sustainable and efficient performance.

The applied strategy to address the conclusions above and enhance the positioning performance of GPS for visually impaired people navigation system applications, was presented in this thesis in two different steps as explained below:

1. A new precise positioning model that raises the positioning accuracy and service reliability of the applications for visually impaired people was suggested and developed. The establishment of an efficient positioning model that incorporates NRTK GNSS and its augmentation position

solutions. The positioning model was applied as client-server architecture comprising two main components, the Navigation Service Centre (NSC) and the Mobile Navigation Unit (MNU). The new model has incorporated both components for the purpose of switching the MNU from position determination to server-based positioning mode grounded on the NSC, in case of positioning and augmentation data unavailability. The MNU utilises WADGNSS sources supplying networked-DGNSS correction data with the aim of efficiently augmenting the GPS and GLONASS measurements accumulated at the MNU, and compute an advanced position solution.

In order to explore the positioning model performance in terms of the achieved position solutions accuracy, precision, and service availability and reliability, a comprehensive evaluation methodology was illustrated and utilised. The evaluation process entailed experimental and simulation studies which were carried out while taking into account several contextual aspects identified within the adaptive framework. This embraces the navigation environment, measurements scenarios and available position sensing resources. The central conclusions drawn from the evaluation process are summarised as follows:

- The results from the experiments have shown and thus confirmed that the positioning model's position computation methods NRTK GNSS, applied at the MNU, were capable of delivering position solutions with enhanced accuracy levels in contrast to the existing GPS positioning service, throughout all navigation environments and measurement scenarios. The NRTK positioning method has satisfied the performance requirements for high accuracy demanding applications. Therefore, the positioning model is capable of delivering precise positioning in real-time using GPS-RTK Signal for visually impaired people.

- The average of position accuracy achieved from NRTK GNSS within the urban environment and during a dynamic measurement scenario was below 85 cm. In the same concern, the corresponding NRTK availability values computed using NRTK GNSS data at the MNU was 73.68% comparing to 88.44% computed at the rural/suburban environment. During the best measurement conditions in rural area, the average of the position accuracy achieved from NRTK GNSS was below 2 cm for the static measurement, in comparison to below 35 cm and below 80 cm achieved using static measurements in suburban and urban areas respectively. Hence, the NRTK GNSS positioning methods at MNU have outperformed the existing GPS services in worst and best conditions for accuracy measurements. This can be explained due to the high precision dual frequency receiver and the assured high availability of up-to-date and reliable augmentation data at the MNU alongside with the effectiveness of the functional lines in processing and correcting navigation data.

- The conclusions from the simulation results showed that appropriately accurate and reliable position samples can be obtained from the combination of future Galileo OS with GPS standard positioning services. The hybrid positioning service outperformed by the NRTK GNSS positioning model at MNU in terms of the positions service accuracy in all scenario and navigation environments. Furthermore, the hybrid system of Galileo and GPS could not be verified in a “real” experimentation because Galileo system is yet not fully functional, therefore a simulation study was conducted. However, the satellite availability in all scenarios and navigation environments was higher than the positioning model at MNU using NRTK GNSS. This recognises the need for further work on development of the positioning model and the exploration of the possibility of incorporating the future services within the same platform including the positioning model.

- In this research the experiments of NRTK GNSS at MNU and the quality of service (QoS) of the transmission of video, voice and positioning data over various wireless mobile networks (Chapter 5, Section 5.3.1) were not conducted in a combined system. As it is outside the scope of this thesis. However, HSDPA technology is sufficient to transmit video streams of micro environment of the visually impaired person with sufficient resolution to the NSC. With improved accuracy with NRTK, the system will be able to guide the blind to avoid obstacles with better accuracy.

8.2 Future Work

With regard to the conclusions of this research project, an advanced performance was attained from the developed positioning model. On the other hand, this achievement might be perceived as insufficient for applications demanding high availability of GPS and GLONASS satellites. Additionally, the indoor environment was not considered within the navigation environments during the system evaluation. This platform can be employed for further research activities in order to guarantee the best use of the system in providing help for visually impaired people, as well as aging population with some disability. The subsequent steps are proposed:

- Follow the development of GPS, GLONASS and Galileo systems enabling to incorporate future broadcasted navigation signals, correction messages and integrity information within the positioning model. This will in turn permit the provision of more reliable and accurate positioning services in all navigation environments.

- Investigate the possibility of using NRTK GNSS and EGNOS/SISNET (Signal in Space through the Internet) data for correction at the MNU, as described in Chapter 5, Section 5.6.1 and shown in Figure 8.1. The accuracy that can be obtained would in a combined system of applying GPS augmentation techniques, such as NRTK and EGNOS/SISNET improve significantly with the already established *Adaptive, Reliable, and Accurate Positioning Model for Location-Based Services* model, by Al

Nabhan (2009). These data are included within RTCM v3 messages and can be received from networked-based DGPS systems using the Ntrip communication protocol.

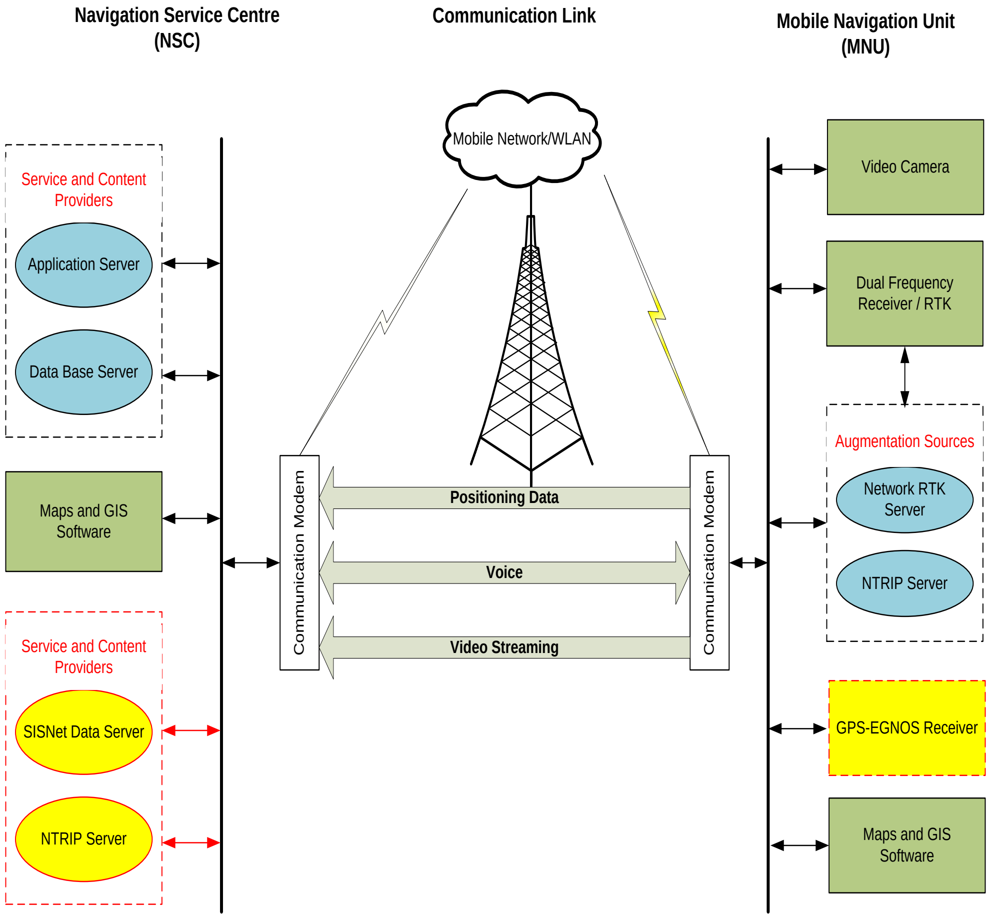


Figure 8.1: Future system model operational architecture including EGNOS/SISNET.

- Utilise additional navigation information built on a pedestrian Dead Reckoning (DR) model as a means to extend the positioning model's capability for indoor environments. This step involves the implementation of the integrated domain positioning method at the MNU, using an Extended Kalman Filtering (EKF) approach, or any effective algorithm for navigation data fusion.

- Since the system only tested as a prototype, a fully functional system prototype needs to be constructed, based on the previous research outcomes in order to perform further testing of the system under the best degree of achievement that satisfies both the technical and user requirements. This requires the establishment of the system using the proposed design of the communication link, MNU and NSC as proposed in the mentioned Chapters 3 to 7.

- Further future work can be accomplished by modifying the system to be used in other applications, such as unmanned vehicles, military applications, police, etc.

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Appendix A: Experimental Testing Locations

Appendix B: Overall Experimental Results

Overall positioning performance at all benchmark points on static testing routes OS1, OS2 and OS3:

Test	East – Accuracy Average (cm)	North – Accuracy Average (cm)	East – Precision SD (+/- cm)	North – Precision SD (+/- cm)	NRTK Availability (%)	Tracked Satellites Average (Mean)	PDOP (Mean)
OS1	1.09	1.42	0.78	1.04	98.68	11	2.10
OS2	-21.28	33.05	2.28	3.38	88.12	9	2.39
OS3	39.65	75.89	3.76	5.89	69.69	7	4.38

Overall positioning performance at all benchmark points on dynamic testing DT1, and DT2 (averages of 12 dynamic testing trials):

Test	East – Accuracy Average (cm))	North – Accuracy Average (cm)	East – Precision SD (+/- cm)	North – Precision SD (+/- cm)	NRTK Availability (%)	Tracked Satellites Average (Mean)	PDOP (Mean)
ST1	-1.3	1.77	1.3	0.79	97.89	10	2.52
ST2	1.7	-3.1	1	1.3	97.49	9	2.84
ST3	1.97	1.1	0.87	1.62	97.63	10	2.89
ST4	-23.72	-17.1	3.57	2.65	89.76	8	2.98
ST5	30.83	-21.87	4.13	3.37	78.68	7	3.67
ST6	-37.17	44.37	5.11	6.22	69.28	7	4.57
ST7	27.19	-16.94	3.97	2.89	72.18	6	4.20
ST8	13.47	8.26	2.69	2.17	93.32	9	3.01
ST9	-17.13	-11.43	3.77	2.03	92.46	8	3.13
ST10	1.66	1.11	0.83	1.44	98.13	11	2.36
ST11	-6.9	11.76	1.74	2.26	94.16	8	3.18
ST12	2.31	6.81	1.68	2.78	96.68	9	2.94
ST13	-51.18	47.63	6.18	5.47	65.74	5	5.42
ST14	47.23	66.11	5.89	6.79	68.67	5	4.97
ST15	66.91	73.54	6.23	6.93	59.39	5	5.41
ST16	78.23	-43.81	7.67	5.11	63.85	6	5.03
ST17	46.21	17.94	5.23	3.13	74.41	6	4.72
ST18	-6.3	-3.1	1.54	1.27	96.11	9	2.51
ST19	8.73	4.90	3.84	3.05	95.21	8	3.09
ST20	-1.23	1.76	1.13	1.66	97.13	10	1.99

Appendix C: List of Publications

Nawzad Al-Salihi, Khalid Alhajri, Vanja Garaj, and Wamadeva Balachandran, *‘The performance comparison of 3G and WLAN network for application in a navigation system for visually impaired people’*, The Navigation Conference & Exhibition – Are We There Now, (NAV 07), London, UK, Oct 2007.

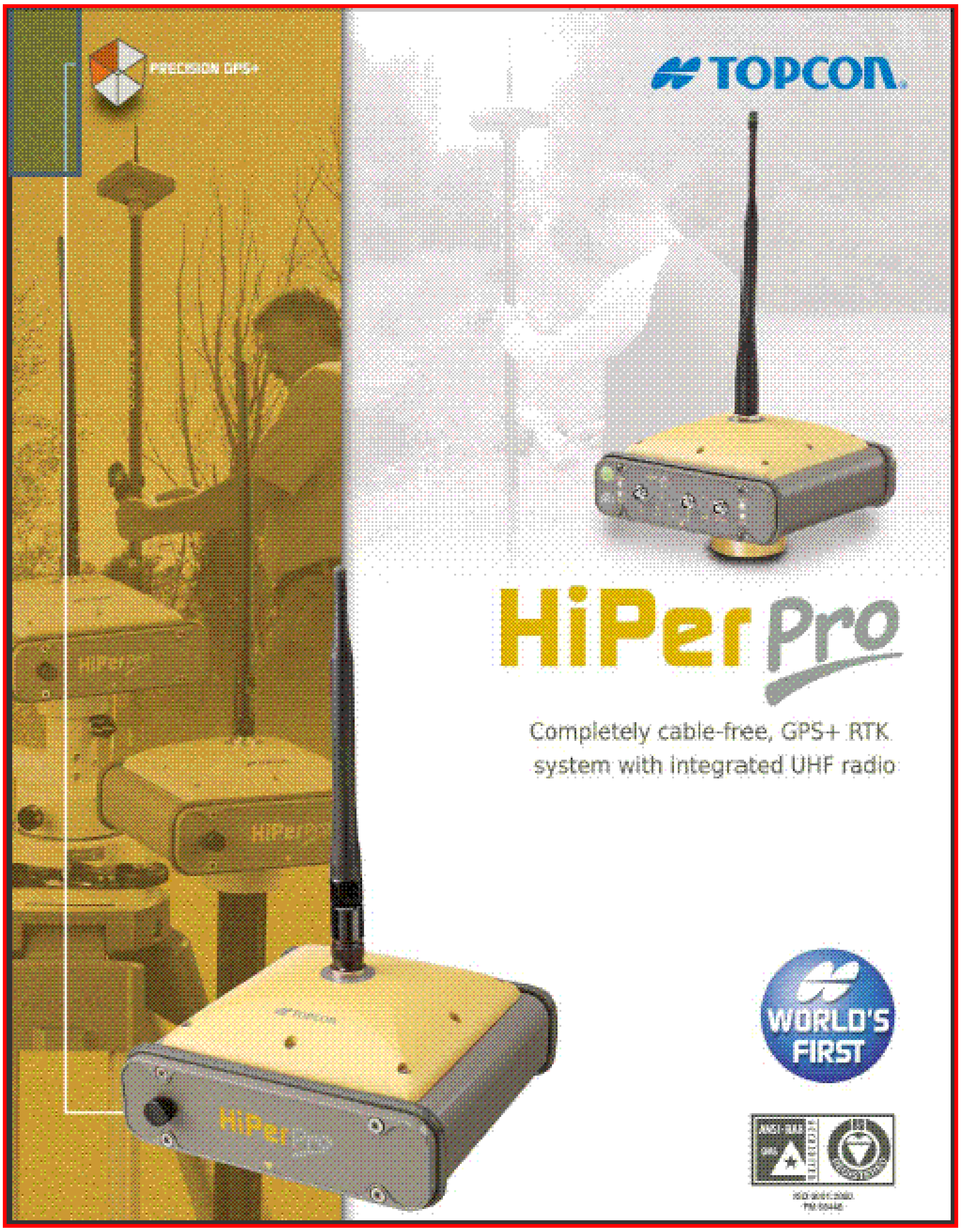
Khalid Alhajri, **Nawzad Al-Salihi**, Vanja Garaj, Ziad Hunaiti and Wamadeva Balachandran *‘The performance of HSDPA (3.5 G) network for application in a navigation system for visually impaired people,,* Sixth Annual Conference on Communication Networks and Services Research (CNSR 2008), 5-8 May 2008, Halifax, Nova Scotia, Canada. IEEE Computer Society 2008.

Khalid Alhajri, **Nawzad Al-Salihi**, Vanja Garaj and Wamadeva Balachandran, *‘The performance of WiFi network for application in a navigation system for visually impaired people’*, The 7th Annual Wireless Telecommunications Symposium, April 24-26 2008, Pomona, California, USA. IEEE Communications Society 2008.

Nawzad Al-Salihi and Wamadeva Balachandran, ‘*A Comparison of GPS and Galileo Signals for Application in a Navigation System for Visually Impaired People’*, The Navigation Conference & Exhibition – We Are Here! (NAV 08), London, UK, Oct 2008.

Appendix D: Topcon Hiper Pro Receiver and FC-200 Controller

Topcon Hiper Pro:



Topcon is proud to introduce the next addition to the popular HiPer family of GPS+ receivers, the new HiPer Pro!

This revolutionary receiver is truly worthy to join this extremely successful lineup of precision GPS+ products. The HiPer Pro also is consistent with Topcon's tradition of innovation not imitation; by being the World's First completely cable free base and rover RTK system with an integrated UHF radio system.

Just as the Topcon HiPer Lite and HiPer Lite+ revolutionized the design of modern GPS receiver technology, the HiPer Pro offers the same completely cable free system design and operational advantages. With the added extended range performance of a UHF style radio system.

Topcon engineers and scientists have once again developed a revolutionary, integrated design that incorporates a transmitting UHF radio in the base receiver, eliminating the need for external radios and batteries. The new HiPer Pro will provide up to 4 miles of coverage with the internal radio, a 1 watt transceiver working in the 380 – 470 MHz range. Topcon also offers a simple, but powerful repeater system to extend your range as your needs change.

In order to eliminate the radio interference hassles of traditional UHF radio designs, the Topcon Hiper Pro incorporates advanced radio technology called "Free Channel Scan", which automatically detects disruptive radio interference and changes channels to compensate.

The new HiPer pro offers you a complete RTK GPS system that leaves behind the mess of complicated, tangled cables we have come to expect at the typical RTK base station. Compare HiPer Pro to the competition. You will find that although they have tried to make efforts to improve the rover end of the RTK system, the base station still includes a complex design with a slew of cables and modular components!

That's right, no more hassles of an RTK Base Station with it's convoluted mess of external batteries, antennas, and RTK radios that are all connected with fragile cables. Topcon has designed a complete, integrated RTK Base & Rover system that is completely cable free. No more cables to break, and no more wasted time of a complicated base receiver setup.

At Topcon, we strive to produce advanced product designs that make your life easier by solving the everyday problems you encounter on the job site such as broken cables and complicated systems setups. The new HiPer Pro offers the advantages of less equipment to carry into the field, and less to forget back at the office!

The Topcon HiPer Pro also incorporates Topcon's industry leading GPS+GLONASS satellite tracking technology. The added advantage of dual constellation tracking provides more satellite coverage, increased performance, and improved precision over GPS only systems. Topcon leads all others in the GPS industry as the only dual-frequency, dual-constellation system manufacturer.

Topcon is proud to be leading the precision GPS industry with the most advanced technology, the most innovative system designs, and the most complete and diverse precision product lineup available. Contact your local dealer to find out why more professionals are choosing Topcon GPS+ solutions over all the rest!

TOPCON
Phone: (800) 443-4567
Specifications subject to change without notice
Patents Pending
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P/N: 7010-0675 Rev. A Printed in U.S.A. 5/04

Description	40 channel integrated GPS+ receiver/antenna with MINTER interface.
Tracking Specifications	
Tracking Channels, standard	40 L1 GPS (20 GPS L1+L2 on Cinderella[2] days)
Tracking Channels, optional	20 GPS L1+L2 (GD), GPS L1 + GLONASS (GG), 20 GPS L1+L2+GLONASS (GGD)
Signals Tracked	L1/L2 C/A and P Code & Carrier and GLONASS
Performance Specifications	
Static, Rapid Static	H: 3mm + 0.5ppm V: 5mm + 0.5ppm
RTK	H: 10mm + 1ppm V: 15mm + 1ppm
Power Specifications	
Battery	Internal Lithium-Ion batteries for up to 14+ hours of operation (10 hrs TX)
External power input	6 to 28 volts DC
Power consumption	Less than 4.2 watts
GPS+ Antenna Specifications	
GPS / GLONASS Antenna	Integrated
Ground Plane	Integrated flat ground plane
Radio Antenna	Center-mount UHF Antenna
Radio Specifications	
Radio Type	Internal Tx/Rx UHF (Selectable frequency range)
Power Output	1.0W/0.25W (selectable)
Wireless communication*	
Communication	Bluetooth™ version 1.1 comp.
I/O	
Communication Ports	2x serial (RS232)
Other I/O Signals	1pps, Event Marker
Status Indicator	4x3-color LED's, two-function keys (MINTER)
Control & Display Unit	External Field Controller
Memory & Recording	
Internal Memory	Up to 1 GB
Data Update Rate	Up to 20 times per second (20Hz)
Data Type	Code and Carrier from L1 and L2, GPS and GLONASS
Data Input/Output	
Real time data outputs	RTCM SC104 version 2.1, 2.2, 2.3, CMR, CMR+
ASCII Output	NMEA 0183 version 3.0
Other Outputs	TPS format
Output Rate	Up to 20 times per second (20Hz)
Environmental Specifications	
Enclosure	Aluminum extrusion, waterproof
Operating Temperature	-30°C to 55°C
Dimensions	W: 159 x H: 172 x D: 88 mm / 6.25 x 6.75 x 3.5 In
Weight	1.65 kg / 3.64 lbs

*Bluetooth™ type approvals are country specific. Please contact your Topcon representative for more information.

[1] [illegible]

[2] [illegible]

FC-100
Rugged Windows CE™
Field Computer

GB-1000
Modular GPS+
Base Receiver

Topcon FC-200 Controller:

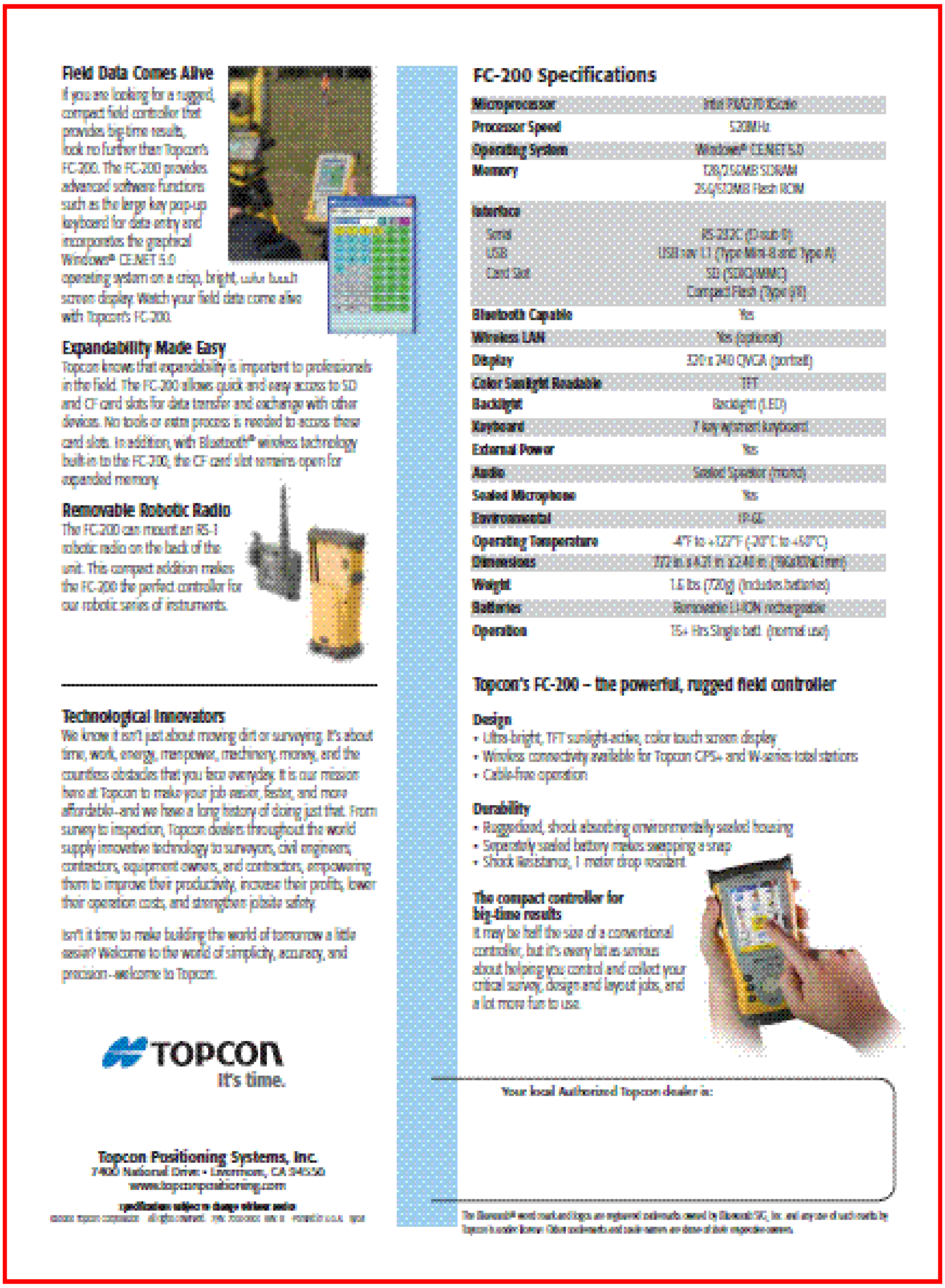
TOPCON

FC-200

Windows® Field Controller

Topcon's powerful, rugged, handheld field controller

- Built-in Bluetooth® wireless technology
- Ultra-bright, TFT, color touch screen display
- Windows® CE.NET 5.0 operating system
- Internal WiFi Optional
- Easy access Compact Flash and SD Media card slots deliver memory expansion and connectivity options
- 520MHz XScale processor
- Removable, Robotic Radio
- 128/256MB SDRAM, 256/512MB Flash ROM



Field Data Comes Alive

If you are looking for a rugged, compact field controller that provides big-time results, look no further than Topcon's FC-200. The FC-200 provides advanced software functions such as the large key pop-up keyboard for data entry and incorporates the graphical Windows® CE.NET 5.0 operating system on a crisp, bright, color touch screen display. Watch your field data come alive with Topcon's FC-200.

Expandability Made Easy

Topcon knows that expandability is important to professionals in the field. The FC-200 allows quick and easy access to SD and CF card slots for data transfer and exchange with other devices. No tools or extra process is needed to access these card slots. In addition, with Bluetooth® wireless technology built-in to the FC-200, the CF card slot remains open for expanded memory.

Removable Robotic Radio

The FC-200 can mount an RS-1 robotic radio on the back of the unit. This compact addition makes the FC-200 the perfect controller for our robotic series of instruments.

Technological Innovators

We know it isn't just about moving dirt or surveying. It's about time, work, energy, manpower, machinery, money, and the countless obstacles that you face everyday. It is our mission here at Topcon to make your job easier, faster, and more affordable--and we have a long history of doing just that. From survey to inspection, Topcon dealers throughout the world supply innovative technology to surveyors, civil engineers, contractors, equipment owners, and contractors, empowering them to improve their productivity, increase their profits, lower their operation costs, and strengthen jobsite safety.

Isn't it time to make building the world of tomorrow a little easier? Welcome to the world of simplicity, accuracy, and precision--welcome to Topcon.

TOPCON
It's time.

Topcon Positioning Systems, Inc.
7400 National Drive • Livermore, CA 94550
www.topconpositioning.com

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FC-200 Specifications

Microprocessor	Intel PXA270 XScale
Processor Speed	520MHz
Operating System	Windows® CE.NET 5.0
Memory	128/256MB SDRAM 256/512MB Flash ROM
Interface	
Serial	RS-232C (D-sub 9)
USB	USB rev 1.1 (Type Mini-B and Type A)
Card Slot	SD (SDIO/MMC) Compact Flash (Type I/II)
Bluetooth Capable	Yes
Wireless LAN	Yes (optional)
Display	320 x 240 QVGA (portrait)
Color Sunlight Readable	TFT
Backlight	Backlight (LED)
Keyboard	7 key w/smart keyboard
External Power	Yes
Audio	Sealed Speaker (mono)
Sealed Microphone	Yes
Environmental	IP-66
Operating Temperature	-4°F to +122°F (-20°C to +50°C)
Dimensions	7.72 in x 4.21 in x 2.40 in (196x107x61mm)
Weight	1.6 lbs (720g) (includes batteries)
Batteries	Removable Li-ION rechargeable
Operation	15+ Hrs Single batt. (normal use)

Topcon's FC-200 – the powerful, rugged field controller

Design
- Ultra-bright, TFT sunlight-active, color touch screen display
- Wireless connectivity available for Topcon GPS+ and W-series total stations
- Cable-free operation

Durability
- Ruggedized, shock absorbing environmentally sealed housing
- Separately sealed battery makes swapping a snap
- Shock Resistance, 1 meter drop resistant

The compact controller for big-time results
It may be half the size of a conventional controller, but it's every bit as serious about helping you control and collect your critical survey, design and layout jobs, and a lot more fun to use.

Your local Authorized Topcon dealer is:

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