Nottingham Geospatial Institute

Automotive Applications of High Precision GNSS

By

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Abstract

This thesis aims to show that Global Navigation Satellite Systems (GNSS) positioning can play a significant role in the positioning systems of future automotive applications. This is through the adoption of state-of-the-art GNSS positioning technology and techniques, and the exploitation of the rapidly developing vehicle-to-vehicle concept. The merging together of these two developments creates greater performance than can be achieved separately. The original contribution of this thesis comes from this combination: Through the introduction of the Pseudo-VRS concept. Pseudo-VRS uses the princples of Network Real Time Kinematic (N-RTK) positioning to share GNSS information between vehicles, which enables absolute vehicle positioning. Pseudo-VRS is shown to improve the performance of high precision GNSS positioning for road vehicles, through the increased availability of GNSS correction messages and the rapid resolution of the N-RTK fixed solution.

Positioning systems in the automotive sector are dominated by satellite-based solutions provided by GNSS. This has been the case since May 2001, when the United States Department of Defense switched off Selective Availability, enabling significantly improved positioning performance for civilian users.

The average person most frequently encounters GNSS when using electronic personal navigation devices. The *Sat Nav* or *GPS Navigator* is ubiquitous in modern societies, where versions can be found on nomadic devices such as smartphones and dedicated personal navigation devices, or built in to the dashboards of vehicles. Such devices have been hugely successful due to their intrinsic ability to provide position information anywhere in the world with an accuracy of approximately 10 metres, which has proved ideal for general navigation applications.

There are a few well known limitations of GNSS positioning, including anecdotal evidence of incorrect navigation advice for personal navigation devices, but these are minor compared to the overall positioning performance. Through steady development of GNSS positioning devices, including the integration of other low cost sensors (for instance, wheel speed or odometer sensors in vehicles), and the development of robust map matching algorithms, the performance of these devices for navigation applications is truly incredible.

However, when tested for advanced automotive applications, the performance of GNSS positioning devices is found to be inadequate. In particular, in the most advanced fields of research such as autonomous vehicle technology, GNSS positioning devices are relegated to a secondary role, or often not used at all. They are replaced by terrestrial sensors that provide greater situational awareness, such as radar and lidar. This is due to the high performance demand of such applications, including high positioning accuracy (sub-decimetre), high availability and continuity of solutions (100%), and high integrity of the position information. Low-cost GNSS receivers generally do not meet such requirements.

This could be considered an enormous oversight, as modern GNSS positioning technology and techniques have significantly improved satellite-based positioning performance. Other non-GNSS techniques also have their limitations that GNSS devices can minimise or eliminate. For instance, systems that rely on situational awareness require accurate digital maps of their surroundings as a reference. GNSS positioning can help to gather this data, provide an input, and act as a fail-safe in the event of digital map errors. It is apparent that in order to deliver advanced automotive applications - such as semi- or fully-autonomous vehicles - there must be an element of absolute positioning capability. Positioning systems will work alongside situational awareness systems to

enable the autonomous vehicles to navigate through the real world. A strong candidate for the positioning system is GNSS positioning.

This thesis builds on work already started by researchers at the University of Nottingham, to show that N-RTK positioning is one such technique. N-RTK can provide sub-decimetre accuracy absolute positioning solutions, with high availability, continuity, and integrity.

A key component of N-RTK is the availability of real-time GNSS correction data. This is typically delivered to the GNSS receiver via mobile internet (for a roving receiver). This can be a significant limitation, as it relies on the performance of the mobile communications network, which can suffer from performance degradation during dynamic operation. Mobile communications systems are expected to improve significantly over the next few years, as consumers demand faster download speeds and wider availability. Mobile communications coverage already covers a high percentage of the population, but this does not translate into a high percentage of a country's geography. Pockets of poor coverage, often referred to as *notspots*, are widespread. Many of these notspots include the transportation infrastructure.

The vehicle-to-vehicle concept has made significant forward steps in the last few years. Traditionally promoted as a key component of future automotive safety applications, it is now driven primarily by increased demand for in-vehicle infotainment. The concept, which shares similarities with the Internet of Things and Mobile Ad-hoc Networks, relies on communication between road vehicles and other road agents (such as pedestrians and road infrastructure). N-RTK positioning can take advantage of this communication link to minimise its own communications-related limitations. Sharing GNSS information between local GNSS receivers enables better performance of GNSS positioning, based on the principles of differential GNSS and N-RTK positioning techniques. This advanced concept is introduced and tested in this thesis.

The Pseudo VRS concept follows the protocols and format of sharing GNSS data used in N-RTK positioning. The technique utilises the latest GNSS receiver design, including multiple frequency measurements and high quality antennas.

Acknowledgements

This thesis, and the research that has been carried out to produce it, was made possible through an Engineering and Physical Sciences Research Council (EPSRC) Cooperative Awards in Science and Technology (CASE) studentship, with the invaluable support of the industrial partner MIRA Ltd. This PhD training method has brought great benefits to me through the excellent access to facilities, expertise, and training that are available at both the industrial partner MIRA Ltd and the academic partner the University of Nottingham.

This research gained greatly from the availability of world class testing facilities and the ready access to automotive research experts. In particular, Dr Anthony Baxendale as industrial supervisor provided valuable guidance and positive encouragement to explore new avenues of research, and together with Mr Tim Edwards helped to define the nature of the PhD study. It was the early experiments with various GNSS receivers on the MIRA test circuits that outlined the very limited capability of GNSS positioning technology available in the vehicle testing environment.

It was during my honeymoon in April 2010 that I had my initial telephone conversation about further study at the University of Nottingham. My soon-to-be secondary supervisor probably had no clue about my present circumstances, but Professor Terry Moore was full of encouragement and ideas. Perhaps it was the euphoria of making one life changing decision that gave me the confidence to leave the comfortable world of land and building surveying to re-join the student collective. Professor Moore's calm and incisive observations have been extremely valuable throughout the PhD project, including memorable advice following a conference presentation in Nashville in 2012.

On the first day of the PhD project, there was a blanket of snow between me in Yorkshire, and my destination in Nottingham. With the greatest of intentions, I made a valiant attempt to make it through the blizzards. My trusty Peugeot 306 estate made rather unexpected progress, but alas I had to retreat home as I approached Sheffield and encountered some expensive looking rear-wheel-drive executive saloons floundering helplessly on the nearside of the motorway. Although I wanted the subject of the first email to my primary supervisor to be something more poignant, the reply highlighted the complete understanding and flexibility that Dr Xiaolin Meng would provide for the next four years of study. Dr Meng showed great patience and support from the outset, allowed the freedom to explore the thesis topics broadly, encouraged collaboration with colleagues, and instilled the importance of attending conferences, seminars, lectures, and other academic and industrial events.

I was fortunate to have the Nottingham Geospatial Institute as my home for the duration of the PhD project. The facilities and equipment available to students are excellent, and the support from technical staff is a real asset to the Institute. From the very start of the project, Mr Sean Ince, Mr Joseph Ryding, and Dr Lukasz Bonenberg all took great time to support my early research training, allowing me to have hands-on experience with the latest GNSS positioning technology available.

A PhD project can be a solitary experience. This is not always a negative aspect, but it is important to have friends in similar circumstances to share any frustrations and concerns. I was lucky within the Nottingham Geospatial Institute to have many fellow students to offer such support. Principle among them is Mrs Jessica Shi, who has become a great friend and deserves great credit for persevering with the wayward approach to our collaborative experiments during the early days of the PhD project. Jessica had a great influence on my confidence during my study, and for that I will be externally grateful.

I found great pleasure in working with other students and academics at the Nottingham Geospatial Institute. I am appreciative of the kindness and humour of my fellow student Mr Yang Gao, and wish him every success in his further study. The welcoming nature of Dr Craig Hancock and our common connection to the University of Newcastle Upon Tyne, gave me great opportunity to hone my own teaching and demonstrating skills through the surveying lectures and field courses.

Many of the strengths I have that allowed me to complete a PhD project have been inherited from my parents, Neil and Janet. They manage to blend that perfect balance of encouragement and expectation, that as a child allowed me to leap into the unknown whilst not being afraid of failure. I believe I have patience and perseverance, and I can demonstrate humility whilst having confidence in my own abilities - all thanks to my parents. I offer special thanks to my father for his particular contributions to this thesis during proofreading, although I can only apologise for my continued use of the Oxford comma.

Finally, my most sincere thanks are to my wife, Kathryn. My life will be defined by the events of 2010, but none more so than when I married Kathryn. Returning to university is not an option open to many, but Kathryn never questioned the decision and supported me through the entire project with unending love and encouragement. It is a testament to Kathryn's patience that she quietly accepted my tardy progress with household diy, and demonstrated no concerns about my student lifestyle when in July 2014 she gave birth to our son Benjamin. And even after such a life changing event, she found the time to further contribute to this thesis through a most thorough proofreading. Kathryn is an inspiration and it is a joy to be her husband. It is now my life's ambition to repay that love and support.

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List of Abbreviations

2G	Second generation
3G	Third generation
4G	Fourth generation
5G	Fifth generation
A-GNSS	Assisted-GNSS
ABS	Anti-lock Braking System
ACC	Adaptive Cruise Control
ADAS	Advanced Driver Assistance System
AEB	Autonomous Emergency Braking
AHS	Automated Highway System
AoC	Age of Correction
ARF	Ambiguity Resolution Function
ARW	Angle Random Walk
AV	Autonomous Vehicle
AVLS	Automatic Vehicle Location System
BASt	Bundesanstalt für Straßenwesen (German Federal Highway Research Institute)
BKG	Bundesamt für Kartographie und Geodäsie (German Federal Agency for Cartography and Geodesy)
BPSK	Binary Phase Shift Keying
C-ITS	Cooperative ITS
C/A	Coarse Aquisition
C2C	Car-to-Car
CAN	Controller Area Network
CCW	Cooperative Collision Warning
CDMA	Code Division Multiple Access
CEA	Consumer Electronics Association
CEN	Comité Européen de Normalisation (European Committee for Normalisation)

CEP	Circular Error Probable
CORS	Continuously Operating Reference Station
DAB	Digital Audio Broadcasting
DARPA	Defense Advanced Research Projects Agency
DGNSS	Differential GNSS
DGPS	Differential GPS
DOP	Dilution of Precision
DSRC	Dedicated Short Range Communication
ECDIS	Electronic Chart Display and Information System
ECEF	Earth Centred Earth Fixed
ECI	Earth Centred Inertial
EDGE	Enhanced Data rates for GSM Evolution
EGNOS	European Geostationary Navigation Overlay Service
EKF	Extended Kalman Filter
EPS	Electronic Payment System
ERP	Electronic Road Pricing
ETSI	European Telecommunications Standards Institute
EU	European Union
EUPOS	EUropean POSition determination system
FDMA	Frequency Division Multiple Access
FOC	Full Operational Capability
FVD	Floating Vehicle Data
GBAS	Ground-Based Augmentation System
GEO	Geostationary Earth Orbit
GIOVE	Galileo In-Orbit Validation Element
GIS	Geographic Information System
GLONASS	GLObalnaya NAvigatsionnaya Sputnikovaya Sistema (Global Navigation Satellite System)
GMSK	Gaussian Minimum Shift Keying
GNSS	Global Navigation Satellite System
GPRS	General Packet Radio Service
GPS	Global Positioning System
GRAS	Ground-based Regional Augmentation System
GSA	European Global Navigation Satellite Systems Agency

GSM	Groupe Special Mobile
HGV	Heavy Goods Vehicle
HSDPA	High-Speed Download Packet Access
HTTP	Hypertext Transfer Protocol
I/O	Input/Output
ICD	Interface Control Document
ICT	Information and Communication Technology
IEEE	Institute of Electrical and Electronics Engineers
IGS	International GNSS Service
IGSO	Inclined Geosynchronous Orbit
IMU	Inertial Measurement Unit
INS	Inertial Navigation System
IOC	Initial Operational Capability
IoT	Internet of Things
IOV	In-Orbit Validation
IoV	Internet of Vehicles
IP	Internet Protocol
IRNSS	Indian Regional Navigation Satellite System
ISA	Intelligent Speed Adaptation
ISO	International Organisation for Standardisation
ITS	Intelligent Transport System
JIT	Just-in-time
LAAS	Local-Area Augmentation System
LAMBDA	Least squares AMbiguity Decorrelation Algorithm
LBS	Location-Based Service
LDW	Lane Departure Warning
LEO	Low Earth Orbit
LoS	Line of Sight
LSVA	Leistungsabhängige Schwerverkehrsabgabe (Performance-related Heavy Vehicles Fee (Switzerland))
LTA	Land Transport Authority
LTE	Long Term Evolution
MAC	Master Auxiliary Concept
MANET	Mobile Ad-hoc NETwork

MEMS	Micro-Electro-Mechanical System
MEO	Medium Earth Orbit
MIMO	Massive-Input Massive-Output
MIRA	Motor Industry Research Association
mmWave	millimeter Wave
N-RTK	Network Real-Time Kinematic
NAVSTAR	NAVigation System using Timing And Ranging
NGB	Nottingham Geospatial Building
NGI	Nottingham Geospatial Institute
NMEA	National Marine Electronics Association
NMR	Nuclear Magnetic Resonance
NNSS	Navy Navigation Satellite System
NTRIP	Networked Transport of RTCM via Internet Protocol
OBD	On-Board Diagnostics
OBU	On-board unit
OEM	Original Equipment Manufacturer
OGC	Open Geospatial Consortium
OS	Ordnance Survey
OTF	On-the-fly
PIARC	Permanent International Association of Road Congresses
PND	Personal Navigation Device
POI	Point Of Interest
PPP	Precise Point Positioning
PRN	Pseudo-Random Noise
QZSS	Quasi-Zenith Satellite System
RADP	Required Autonomous Driving Performance
RF	Radio Frequency
RFID	Radio-Frequency IDentification
RINEX	Receiver INdependent EXchange (format)
RMS	Root Mean Squared
RNP	Required Navigation Performance
RNSS	Regional Navigation Satellite System
RPM	Revolutions Per Minute

RSSI	Received Signal Strength Indicator
RT-PPP	Real-Time Precise Point Positioning
RTCM	Radio Technical Commission for Maritime serivces
RTK	Real-Time Kinematic
SAE	Society of Automotive Engineers
SBAS	Satellite-Based Augmentation System
SD	Standard Deviation
SEP	Spherical Error Probable
SIM	Subscriber Identity Module
SLAM	Simultaneous Location And Mapping
SoL	Safety of Life
SoOP	Signals of OPportunity
SSR	State Space Representation
SVN	Satellite Vehicle Number
TDMA	Time Division Multiple Access
TTE	Time-to-event
TTFF	Time-To-First-Fix
UGV	Unmanned Ground Vehicle
UHF	Ultra-High Frequency
UK	United Kingdom
US	United States
UTSP	Unshielded Twisted Single Pair
UWB	Ultra Wideband
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
V2X	Cummulative term for V2V, V2I, V2P, etc.
VANET	Vehicular Ad-hoc NETwork
VBLR	Vision-Based Lane Recognition
VHF	Very-High Frequency
VRS	Virtual Reference Station
WA-RTK	Wide Area RTK
WAAS	Wide Area Augmentation System
WAVE	Wireless Access in Vehicular Environments
WGS84	World Geodetic System 1984

Chapter 1

Introduction

1.1 Overview

The phenomenal growth and success of Global Navigation Satellite System (GNSS) positioning for road vehicles since the millennium has made the technology ubiquitous in the automotive sector. However, the performance of GNSS positioning for advanced automotive applications has proven to be limited; this is particularly evident from the lack of GNSS positioning technology in widely publicised autonomous vehicle developments.

This is despite the development and increased availability of new GNSS positioning techniques, such as Network Real Time Kinematic (N-RTK) positioning, which can deliver high precision positioning solutions. There is an opportunity for mass market applications of high precision GNSS positioning, including the establishment of as-yet unknown downstream applications.

This chapter outlines the background and motivation for this thesis, including the outline of the research problem, the aims and objectives, and the contribution to knowledge that is made. Then follows several examples of GNSS positioning of road vehicles, captured during real-world trials at the University of Nottingham, and an introduction to the automotive applications of GNSS positioning, with relevance to the Intelligent Transport Systems (ITS) market.

A recent development in ITS may help to resolve or lessen the inherent positioning performance issues of GNSS positioning for road vehicles. Research into Vehicle-to-Vehicle (V2V) communication shows that by sharing information between vehicles, this can help to fill in the knowledge gaps that exist in current positioning solutions[1]. The original driver for such research was to improve the route navigation performance of vehicles by notifying drivers of congestion, or warning of other difficult driving conditions ahead (such as hazards or poor weather). But the technology can offer much more, and this thesis aims to show that this information sharing platform can be used to improve GNSS positioning performance. These concepts are explored further in Chapter 2.

GNSS positioning for road vehicles is introduced, which is explored in greater detail in Chapter 4 and Chapter 5, followed by a description of the testing facilities available at the Nottingham Geospatial Institute.

Finally, the thesis organisation is outlined.

1.2 Thesis research problem

This thesis addresses automotive applications of high precision GNSS positioning. Generally, high precision GNSS positioning techniques are not widely used in the automotive sector. This is due to a combination of several factors, such as high cost, the limits of positioning robustness, competition

[1] The V2V concept is part of the wider V2X concept, where X stands for many other transportation methods, transport infrastructure, and other road agents. The most common are vehicles (V), pedestrians (P), and infrastructure (I). The concept shares similarities with the Internet of Things (IoT), and has a provenance in Mobile ad hoc Networks (MANET). Other terms for this field include Car-to-Car communications (C2C), Connected Vehicles and Cooperative ITS (C-ITS).

from other positioning sensors, public awareness, and a lack of demand from ITS applications. This is despite the acknowledgment that accurate positioning is a key enabling technique for many advanced ITS applications.

High precision GNSS positioning is not a panacea for vehicle positioning in all ITS applications. In fact, high precision GNSS positioning suffers from several major limitations. This thesis will address the following problems with high precision GNSS positioning for automotive applications:

- GNSS signal outages;
- GNSS correction message outages;
- The speed of integer ambiguity resolution; and
- The high cost of GNSS hardware (through the use of single frequency RTK).

The eradication or minimisation of these GNSS positioning limitations could have a significant impact on the future development of ITS applications. The future of driving is expected to progress through increasing levels of automation, towards a vehicle that can be considered driverless. An accurate absolute position could be a vital tool in this implementation.

This thesis addresses these problems through the research aims and objectives given in Section 1.2.1. The contribution to knowledge of this thesis is outlined in Section 1.2.2.

1.2.1 Thesis aims and objectives

The measurable aims and objectives of this thesis are listed below. The aims of the thesis are to:

- Occupy the gap between GNSS and ITS development;
- Understand the ITS application requirements and related barriers to market;
- Evaluate the available positioning technologies, and their application advantages and limitations;
- Exploit the latest GNSS developments for ITS applications;
    - Maximise the performance of high precision and robust GNSS;
    - Identify alternative and innovative uses of GNSS for automotive applications (which may include non-positioning uses); and
- Attain a ground truth solution for ITS testing applications, and benchmarking hardware;
    - Determine the real time positioning accuracy requirement.

To achieve the aims, the following objectives were determined:

- Evaluate the role of GNSS positioning in future ITS applications;
- Comparison study of the available GNSS positioning technologies for ITS;
    - GNSS receivers, GNSS positioning techniques, integration of other sensors;
- Determine the Required Navigation Performance (RNP) for ITS applications;
    - Accuracy, Integrity, Continuity, Availability;
    - But also considering mobility and cost effectiveness;
- Evaluate N-RTK positioning for road vehicle positioning applications; and
- Exploit V2X communications to develop a new and innovative GNSS positioning solution.

1.2.2 Contribution to knowledge

This thesis makes a contribution to knowledge in the area of GNSS positioning for road vehicles. This is demonstrated by the publication of several journal, conference, and magazine papers, which are listed in the Appendices. The contribution is made in three steps:

1. The evaluation of N-RTK positioning for road vehicle positioning;
2. The connection between the vehicle-to-vehicle (V2V) concept and GNSS positioning; and finally
3. The development, testing, and assessment of the Pseudo-VRS cooperative vehicle positioning technique.

The evaluation of N-RTK positioning for road vehicle positioning starts with a detailed understanding of the RNP of positioning systems for ITS applications. There is no RNP standard for road vehicles, hence the information is gathered primarily from literature and research studies. The work carried out by previous authors into N-RTK positioning showed that the major limitation of this technique for vehicle positioning is the low availability of a position solution. Original tests and exhaustive evaluation in this thesis contribute to the quantification of this limitation, supporting the previous analysis from other authors.

Of specific note, this thesis provides evidence that the the performance of N-RTK positioning for road vehicles is directly related to the received strength of the incoming cellular signals. This evidence was invited for publication in GPS World in 2013.

GNSS vehicle positioning and the V2X concept are independent from one another. Each have existed for a long period of time, although GNSS positioning is established as a technology in automotive sectors whereas V2X remains a research concept (for the most part). This thesis helps to bring the two techniques together, through the acquisition of a substantial body of knowledge regarding cooperative vehicle positioning - in particular, this thesis provides a comparison of available techniques and outlines their characteristics. Real-world tests are designed and implemented to test hypotheses regarding cooperative vehicle positioning, and to determine an objective assessment.

This thesis also provides a thorough analysis of the positioning requirements of a number of specific ITS and ADAS applications. In particular, Table 3.5 outlines the technical requirements of ITS and ADAS applications, and Table 3.6 and Table 3.7 include the required navigation parameters for various current and future ADAS applications.

Through this assessment, a new technique is developed called Pseudo-VRS. This is a cooperative vehicle positioning technique based on relative GNSS positioning, but results in an high-accuracy absolute position solution. It takes one of the principles of N-RTK positioning and amends it to suit the automotive scenario and V2X communication standards. This results in a technique that can deliver significantly greater GNSS positioning performance, when compared to traditional high precision GNSS positioning techniques. The Pseudo-VRS technique was invited for publication in the Innovation section of GPS World in 2014.

1.3 GNSS positioning of vehicles

The majority of vehicle positioning research over the past two decades has focused attention on GNSS centred systems. This is emphasised by the abundant use of Sat Nav devices to assist in-car navigation. Despite its apparent monopoly over vehicle positioning in the commercial sector, the most successful systems developed to guide autonomous vehicles either relegate GNSS to one of a suite of sensors (Brown, 2010; Murray, 2007; Naranjo et al., 2009), or almost disregard it altogether (Urmson, 2012; Mobile Robotics Group (MRG), 2012). This is often due to its apparent lack of positioning accuracy or availability (Kane, 2011). Popular terrestrial positioning sensors are used in its place, including: Lidar, radar, image-based cameras, UWB, and signals of opportunity (Haigh, 2012). Clearly the combination of different complimentary sensors is important, but it would be a mistake to discount the more advanced GNSS positioning techniques. This is particularly evident with the expansion and modernisation of the four GNSS services.

GNSS has been widely adopted for vehicle navigation because it offers absolute positioning with global coverage (Wang et al., 2005), the receiver chips are now relatively inexpensive (van Diggelen, 2010), and comprehensive digital maps are also available. Vehicle navigation is also a non-safety critical activity, so if the navigation device makes a mistake, it is generally nothing more than an inconvenience. The algorithms used to determine the best navigation route and to calculate which road the vehicle is on are quite robust and mature.

GNSS positioning lends itself to vehicle navigation as the velocity and heading accuracies both increase as the vehicle speed increases (Bevly and Cobb, 2010), which are used to determine the appropriate navigation message. It is also possible to navigate with only three satellites, as the height component is less important for vehicle navigation, and can be assumed from the digital map database (road vehicles tend not to leave the ground) (Bevly and Cobb, 2010).

Due to the proliferation of GPS chips in mobile phones and PND's, 99% of receivers manufactured each year are classified as L1 C/A code (van Diggelen, 2010). As an example chip, the Broadcom BCM 4751 designed for mobile phones is compact, at 2.9 by 3.1 millimetres. Twenty years ago this would have been one thousand times bigger, although it never existed because this chip is vastly more complex. TTFF is now as good as a second, when assisted or if geographically unchanged since the last fix. Sensitivity is one thousand times better than in the early 1990s.

Tested in an urban environment, the Broadcom chip using a PND antenna tracked a path through the streets with a median horizontal error of 4.4 metres (van Diggelen, 2010). Using a survey grade receiver with the same antenna, it does not manage to even produce a position for large patches of the journey, and when stationary, the position appears to be highly unstable. Because mobile phone GPS receivers are designed to be highly sensitive, they out-perform survey grade receivers in the urban environment.

Figure 1.1 shows the positioning solutions obtained from a typical Sat Nav device. The green dots signify positions output from a Samsung Galaxy S2 smartphone (with a SiRF StarIV GPS chipset), showing that the solution is adequate for navigation purposes. Note that in the figure the vehicle was driving in the left hand lane, from the right hand side of the image to the left, The error in the position is a combination of the accuracy of the GPS chip and the orthoimage provided by Google.

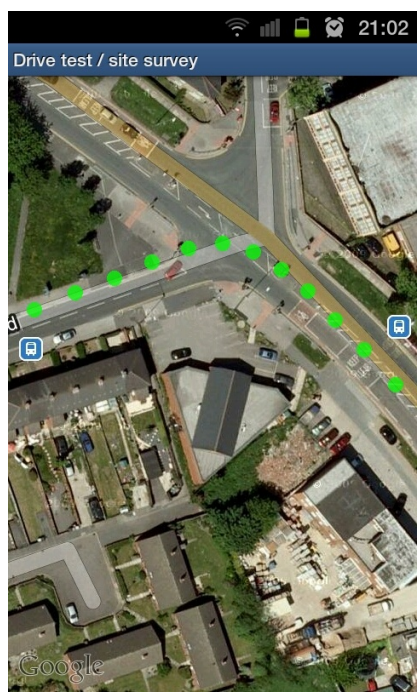


Figure 1.1 – Positioning solutions from a Samsung Galaxy S2 smartphone on board a road vehicle.

Although the positioning technique is fundamentally the same, inexpensive L1 GPS chips utilise additional techniques to assist the positioning algorithms. For instance, modern GNSS receivers can distinguish between signals of the same frequency from different satellites partly due to the signal strength (as the relative satellite-receiver distance changes very slowly this strength also changes slowly) (Bevly and Cobb, 2010). However, such techniques are less successful when trying to achieve centimetre-accuracy from dual frequency receivers.

Due to the relatively slow development and replacement of the GNSS satellite hardware, manufacturers of GNSS positioning devices have turned to alternative methods to improve their positioning performance. These methods include A-GNSS, the use of map-matching algorithms, movement constraints in the positioning model, and using SoOP such as Wi-Fi. A-GNSS is widely used for mobile phone positioning. By providing the device with an initial position calculated through triangulation from cell towers and additional GNSS ephemeris information, the position calculation is similar to that of a hot-fix.

The following Sections demonstrate the achievable positioning solutions from the four main techniques of GNSS positioning: Stand-alone; DGNSS; PPP; and RTK. The example results are taken from a best case scenario, using the NGI's electric locomotive as a test vehicle. The locomotive runs on a track approximately 120 metres in length in a pinched obround shape, located on the roof of the NGI. This location benefits from an almost clear sky view, although there are sources of multipath.

1.3.1 Stand-alone positioning

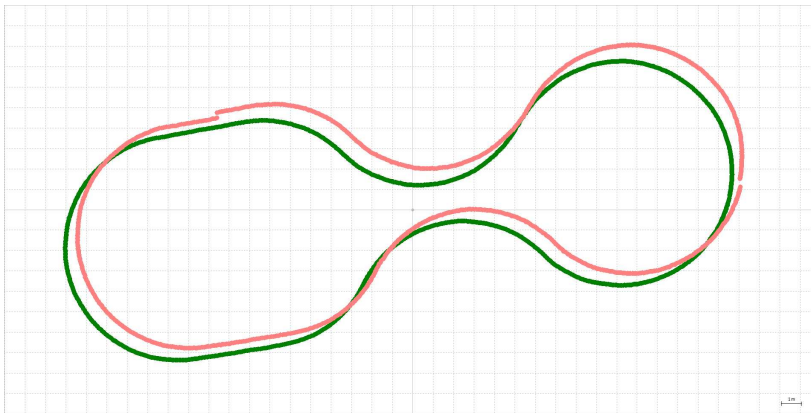
A comprehensive overview of stand-alone GNSS positioning is given in Section 4.3.3. Stand-alone GNSS positioning is expected to provide an accuracy of 5 to 13 metres, primarily depending on the number of visible satellites and the hardware - in particular the GNSS antenna and its view of the sky. This type of GNSS positioning is used in the majority of hand held mass-consumer devices, such as PNDs, Sat Navs, and smartphones. As with these devices, stand-alone positioning has a wide availability. This is mostly due to the configuration of the GNSS receiver positioning engine, as it is set to allow weak and reflected signals in the solution.

To demonstrate the extreme difference that GNSS hardware and software has on the performance of stand-alone positioning, two experiments were carried out. The first used a survey-grade GNSS receiver and antenna, and the second used an off-the-shelf smartphone. The results are shown in Figure 1.2. The GNSS receivers were located on the NGI's electric locomotive, which moved along the track for one lap.

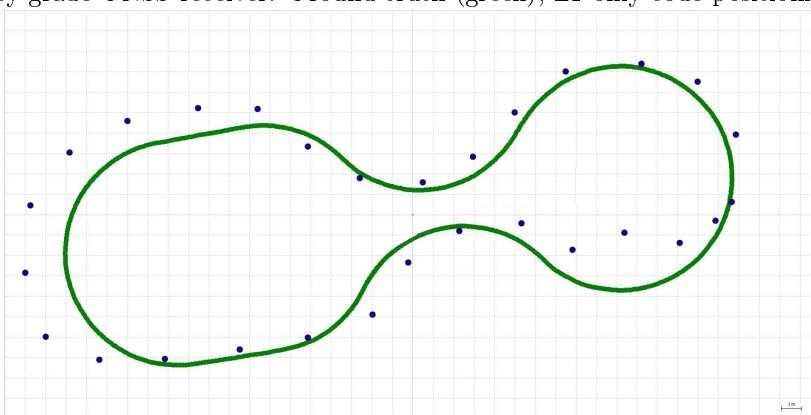
Stand-alone positioning with survey-grade GNSS receiver.
Figure 1.2a demonstrates the typical performance from stand-alone positioning using a Leica GS10 receiver and Leica AS10 antenna, with a good sky view. In this case, the solutions from stand-alone positioning are shown in pink, and the control solution is shown in green. The stand-alone positioning solution is consistently providing a solution to the North-East of the control solution, but is otherwise reasonably accurate - the mean error was only 1.108 metres.

Stand-alone positioning with an off-the-shelf smartphone.
Figure 1.2b demonstrates the typical performance from stand-alone positioning using a Motorola G smartphone with built-in GNSS antenna, and a good sky view. By default, many smartphones use multiple systems to determine their position (commonly known as "Fused" on Android devices), so for this experiment the GPS Benchmark application was used to generate the GNSS-only position. In this case, the solutions from the stand-alone positioning are shown in blue and the control solution is again shown in green. The results here are worse with the smartphone than with the first solution using the survey-grade GNSS receiver, with much greater deviation from the truth. However, the solutions do follow the general path of the control solution. The mean error of the observations was 3.110 metres.

The performance of the smartphone compares well in this experiment, but the conditions are favourable. There is a near-perfect sky view, and little interference. The performance of this type



a). Survey-grade GNSS receiver: Ground truth (green); L1-only code positioning (pink).



b). Off-the-shelf smartphone.Ground truth (green); smartphone positioning (blue).

Figure 1.2 – Stand-alone positioning example.

of GNSS receiver needs to be enhanced or augmented with further information to be useful for navigation. Map matching and GNSS velocity measurements, built-in IMU's, and A-GNSS can all help to constrain the movement of the smartphone GNSS receiver solution.

1.3.2 Differential GNSS positioning

A comprehensive overview of DGNSS is given in Section 4.3.4. DGNSS positioning is expected to provide a positioning accuracy from approximately 2 metres down to 0.1 metres. This is based on the source of the differential corrections, which commonly varies depending on the application (for example, marine, aviation, surveying, and mobile phone applications). Code-based DGNSS positioning typically provides an accuracy of 1 to 2 metres, whereas carrier-phase-based DGNSS techniques can provide an accuracy of 0.1 metres.

Figure 1.3 demonstrates the typical performance of single-frequency, carrier-phase-based DGNSS positioning using a Leica GS10 receiver and Leica AS10 antenna. In this diagram, the DGNSS solution is shown in blue and the control solution is green. The mean error was 0.969 metres.

1.3.3 Precise Point Positioning

PPP is fundamentally limited at the current time due to long ambiguity resolution times. From initialisation the process can take several minutes, and must be re-started each time the GNSS receiver loses lock of the satellites causing an unknown jump in the integer number of cycles. Once the ambiguity is resolved, the solution is typically on a par with that from RTK positioning, demonstrated in Section 1.3.4. PPP positioning is commonly used in marine applications - where

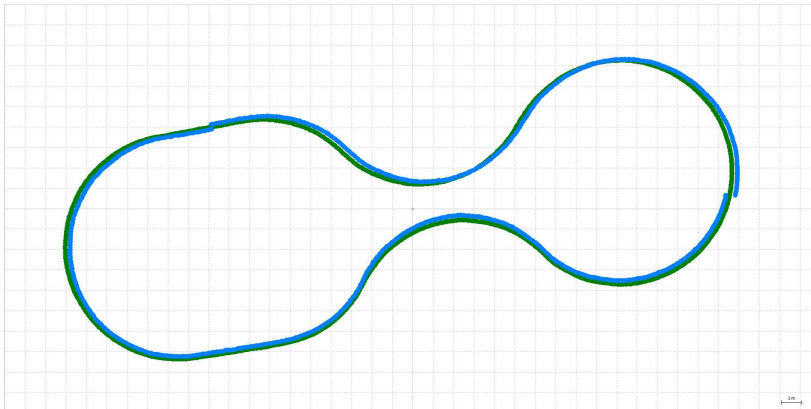


Figure 1.3 – Differential GNSS positioning example. Ground truth (green); L1-only DGNSS positioning (blue).

RTK positioning is not available - due to the continuous visibility of satellites and low demand for rapid integer ambiguity resolution. The International GNSS Service (IGS) provides various products to enable PPP, with near-real time solutions available through commercial partners.

1.3.4 Real Time Kinematic positioning

A comprehensive overview of RTK positioning is given in Section 4.3.5. RTK positioning can provide a positioning accuracy of 5 centimetres form a single epoch solution (given a fixed integer ambiguity), but sub-centimetre positioning accuracy is achievable by processing data from a static observation period of 10 minutes - something that is unlikely in a driving application. Several services exist to provide RTK corrections to the end-user, depending on the application, the desired positioning accuracy, and the user's geographical location. For instance, land-based applications can make use of CORS networks of GNSS base station receivers, whereas close to shore marine applications utilise local base station services provided by commercial organisations. Off-shore RTK is restricted by the limited range in which RTK corrections remain valid (approximately 10 to 20 kilometres).

Figure 1.4 demonstrates the typical performance of dual-frequency RTK positioning, using a Leica GS10 receiver and Leica AS10 antenna. The blue dots represent an RTK solution, and the green dots represent the ground truth. In this case the mean standard deviation is 0.013 metres.

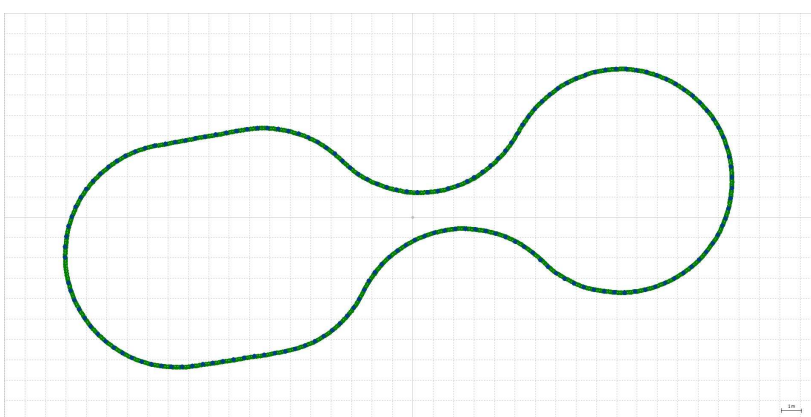


Figure 1.4 – RTK positioning example. Ground truth (green); RTK (dual frequency) positioning (blue).

RTK positioning can provide a high accuracy, high precision solution as demonstrated in Figure 1.4, although this is not always the case. The solution accuracy depends heavily on the rapid delivery of the RTK correction information, the baseline length between the base and rover GNSS receivers, and the number of visible satellite vehicles. RTK positioning techniques used for static applications (such as surveying) are not appropriate for driving applications, due mainly to the dynamic nature of the environment. This is expanded further in Section 4.4.

1.3.5 Heading and velocity measurement with GNSS

GNSS heading measurement.

In Caporali (2001), it was shown that two GNSS antennas with a baseline of 0.6 metres, can deliver 0.1 degrees horizontal and 0.4 degrees vertical accuracy (root mean squared (RMS)). This was done using the Ambiguity Resolution Function (ARF) and refined with least squares. The ARF method is an ambiguity-independent algorithm that was developed in 1981. The algorithm can be constrained by using a variance-covariance matrix that strongly weights the baseline length (which is accurately known) (Hofmann-Wellenhof et al., 2008).

The extremely short baseline cancels the atmospheric effects, so there is no contribution to the single difference. The direction of each satellite is also the same for each antenna given the geometry of the satellites-receiver configuration, and the enormous distance travelled by the signal. The clock terms can be removed through double differencing.

Using GNSS positioning for heading determination (or other attitude determination) has several benefits. Namely, there are no moving parts in the hardware so the vehicle can undergo large mechanical and thermal inertial change. The heading observation is referenced to true geographic North (or any other absolute reference system), and is unaffected by local magnetic influence (unlike a traditional compass). The system is also initialised extremely quickly compared to traditional methods such as using a gyroscope.

GNSS velocity measurement.

Velocity calculation from GNSS observations is conveniently more accurate than absolute positioning. Fundamentally, GNSS positioning systems provide useful characteristics for velocity determination, including Doppler measurement, accurate relative positioning, and continuously available signals.

Even the most basic and low-cost GNSS receivers can deliver velocity measurements to an accuracy of 5 cm/s. More complex and higher cost GNSS receivers will improve the accuracy slightly, to approximately 1 cm/s, but perhaps more significantly they can also provide an update rate of up to and over 100 Hertz (Bevly and Cobb, 2010).

1.3.6 GNSS receiver comparison trials

To determine the positioning performance of off-the-shelf GNSS receivers for road vehicle positioning, a data collection exercise was carried out at the proving ground at MIRA. Three GNSS receivers were used to capture GNSS positioning solutions, listed as follows:

- Garmin Oregon handheld GPS;
- NovAtel SPAN CPT; and
- OXTS RT3100.

The Garmin Oregon is an all-in-one device, and as such was placed on the vehicle dashboard. It is a high-sensitivity GPS-only receiver, which also includes a barometric altimeter and a 3-axis electronic compass. The solution is calculated in real time and captured in a text file.

The NovAtel and OXTS devices required connection to an external GNSS receiver, placed on the roof of the test vehicle. The NovAtel SPAN CPT device is a dual frequency GNSS receiver and includes an INS (fiber optic gyroscopes and MEMS accelerometers) that can output at 100 Hertz. The device supports RTK and PPP, but in this test the data was post-processed.

The OXTS RT3100 is a similar device to the NovAtel device, but includes a single frequency GNSS receiver and does not support RTK-based positioning. In this test the solution was post-processed.

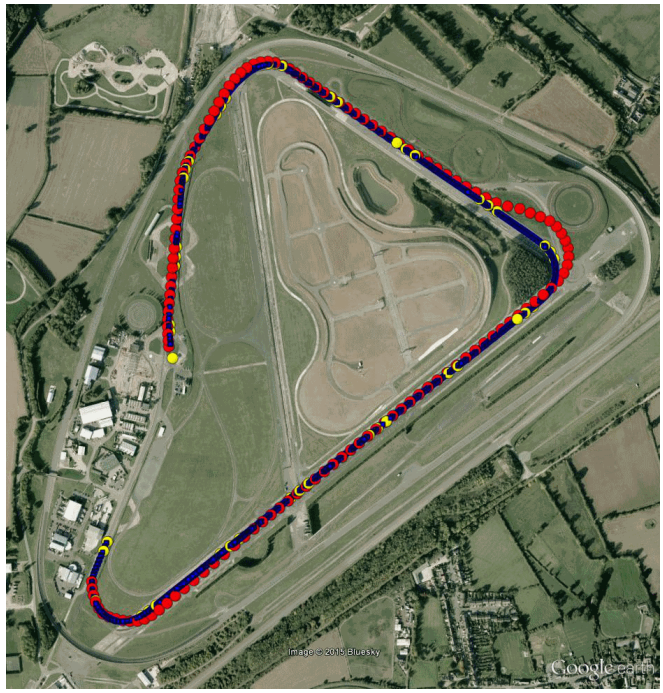


Figure 1.5 – GNSS receiver trials at MIRA proving ground - overview of No.1 circuit.

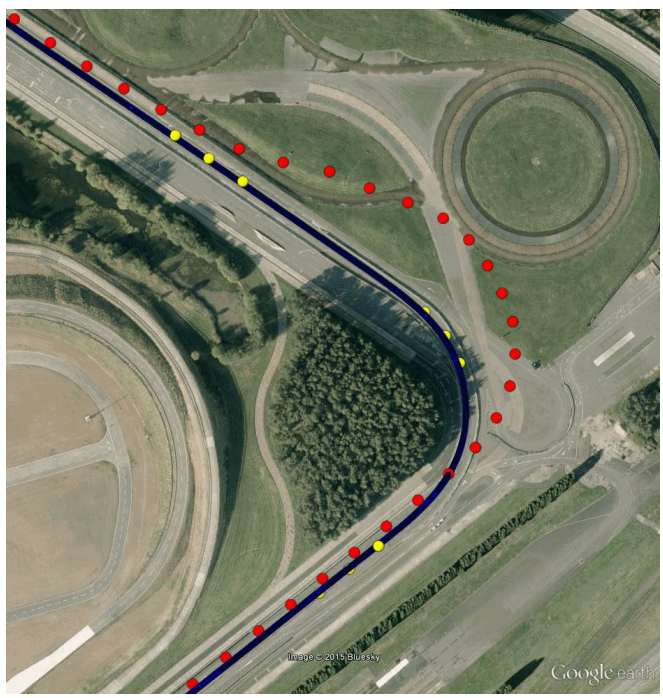


Figure 1.6 – GNSS receiver trials at MIRA proving ground - North East corner.

The results of a driving test are shown in Figure 1.5. The red dots represent the Garmin Oregon solution; the yellow dots represent the NovAtel solution; and the smaller blue dots represent the OXTS solution. It is clear that the Garmin solution provides a reasonable solution for general navigation, although the device does not perform well when the vehicle is cornering (as can be seen more clearly in Figure 1.6). This is the nature of a device designed for hiking, and the slow update rate of the other built-in sensors. In particular, it highlights the limitation of GNSS devices without MEMS assistance for dynamic applications where there is also the likelihood of signal obscuration - in this case dense tree coverage. This would make GNSS-only devices a poor option for ITS applications such as motorcycle lane positioning.

The performances of the NovAtel and OXTS devices are very similar, which demonstrates the influence and benefit of inertial navigation sensors for vehicle navigation. The OXTS device is an L1-only GNSS receiver, yet appeared to perform as well as the dual frequency NovAtel device.

1.4 Automotive applications of GNSS

1.4.1 GNSS receiver market

The use of satellite-based positioning is extremely prevalent in the automotive environment, predominantly using the Global Positioning System (GPS) service. Given the very low cost of positioning chipsets, and the global coverage and availability of positioning solutions, its exploitation for automotive applications has been prolific. *Satellite Navigation* or *Sat Nav* devices saw an explosion of popularity at the beginning of the twenty first century, primarily for route guidance applications for the drivers of road vehicles[2]. This has led many vehicle manufacturers to offer Sat Nav devices that are integrated into vehicle dashboards - at first in high-end vehicles for a significant premium, and now available in most new passenger vehicles for a modest fee or as standard. The devices are also integrated into the general infotainment system of the vehicle.

Together with the increased use of navigation applications on personal smartphones, this has led to a reduction in the number of after-market units sold in the last few years (European Global Navigation Satellite Systems Agency, 2015). Such device manufacturers now focus on offering enhanced services related to route guidance, such as real time traffic updates and dynamic mapping. This challenge is also likely to effect embedded navigation devices.

The market for GNSS receivers is now dominated by mobile phones in terms of numbers of units sold (Betz et al., 2013), as shown in Figure 1.7. In 2012, 900 million GNSS chips were manufactured for use in mobile phones. This compares to approximately 58 million for tablets and mobile computing, and 45 million for automotive devices (embedded and aftermarket devices). These numbers dwarf the traditional users of GNSS systems: Only 300,000 units were manufactured for military users, and 4.4 million for industrial users (for example, surveyors, machine control, aviation, and marine).

However, this domination is not economic. Mobile phone GNSS chips typically cost approximately US$1 to US$3, whereas military grade GNSS receivers can cost tens of thousands of dollars. GNSS positioning is a secondary feature for the mobile phone, whereas it is the key technology in other markets.

The European Global Navigation Satellite Systems Agency (GSA) published a report in March 2015 that estimates the cumulative core value of GNSS technology between 2013 and 2023 (European Global Navigation Satellite Systems Agency, 2015). An important conclusion from this report was that Location-Based Services (LBS) and Road industries account for 91.2% of the cumulative core value of GNSS technology, as shown in Figure 1.8. The positioning of road vehicles is an important aspect in each of these industries.

[2]The term *Sat Nav* is a malapropism, as it is not the navigation of satellites, but the use of satellite-based technology by user devices to enable positioning and navigation - generally with the assistance of digital maps. The term is most prevalent in the UK, whereas the most common phrase in other English speaking countries is either *GPS Navigator* or simply *GPS*. In non-English speaking countries, the term is either *GPS* or some variation of *GPS navigator*, *GPS navigation device*, *auto GPS*, or *auto-navigation*, in the native language.

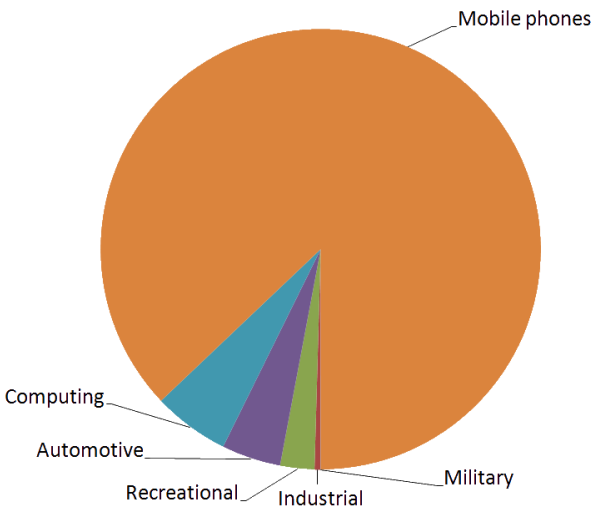


Figure 1.7 – GNSS market 2012: Number of GNSS receivers sold by type.

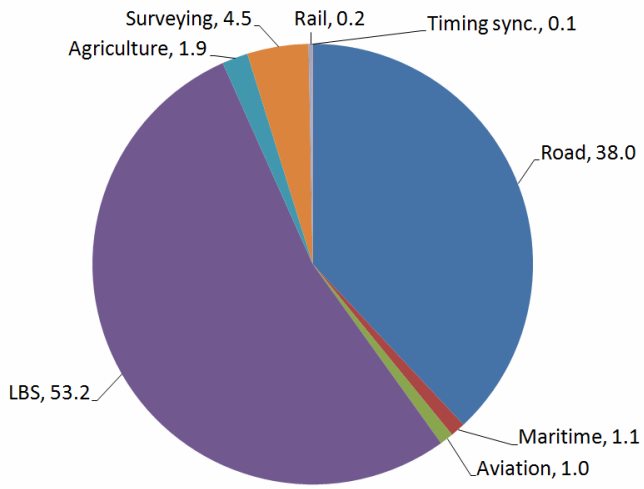


Figure 1.8 – The estimated cumulative core value 2013-2023 of GNSS technology by industry (%). From the ESA GNSS Market Report, 2015.

The application of GNSS technology is widespread in the automotive environment - and for uses beyond Sat Nav devices. GNSS receivers are increasingly used for timing, tracking, enforcement, and mapping purposes in the transport sector. The technology is now considered part of the critical infrastructure of a country (Lorimer, 2010), and vital for the development of innovative new transport technologies.

1.4.2 Positioning systems for automotive applications

GNSS is not a vital prerequisite for vehicle positioning. This is evident from the widely discussed examples of successful vehicle positioning or navigation solutions, such as those autonomous vehicles generously publicised by various media outlets in recent years (discussed in more detail in Section 2.3) or current Advanced Driver Assistance Systems (ADAS). This is because positioning systems based on GNSS-only cannot meet the typical required navigation performance (RNP) of

many current and future ITS applications. However, GNSS signals are widely available in general, with global coverage, and often provide an inexpensive solution for basic navigation tasks. GNSS receivers are commonly paired with other positioning sensors to provide a continuous positioning system. These include inertial sensors, terrestrial ranging sensors, and vehicle borne sensors (wheel odometers and steering angle encoders).

A large body of vehicle positioning research either side of the millennium focused attention on GNSS-centred systems. This is emphasised by the abundant use of Sat Nav devices to assist in-car navigation. These devices continue to use L1-only code-based GNSS positioning, albeit now supplemented with various performance improvements such as map matching algorithms, vehicle odometer integration (for embedded devices), and Assisted-GNSS (A-GNSS).

Despite its apparent monopoly of vehicle positioning in the commercial sector, the most successful systems developed to guide autonomous vehicles either relegate GNSS to one of a suite of sensors (Brown, 2010; Murray, 2007; Naranjo et al., 2009), or almost disregard it altogether (Urmson, 2012; Mobile Robotics Group (MRG), 2012). This is often due to its apparent lack of positioning accuracy or availability (Kane, 2011). Popular terrestrial positioning sensors include lidar, radar, image-based cameras, Ultra Wideband (UWB), and signals of opportunity (Haigh, 2012). Clearly the combination of different complimentary sensors is important, but it would be a mistake to discount the more advanced GNSS positioning techniques that are available, and the enhancements available due to the expansion of the four global GNSS services.

1.4.3 Intelligent Transport Systems

Intelligent Transport Systems (ITS) merge transport with information and communication technology (ICT) (Miles and Chen, 2004). As described in Section 2.2, this usually involves transport vehicles, drivers, and the operating infrastructure. The term is very broad, and this makes the ITS economic market value surprisingly large.

GNSS technology is an increasingly important constituent of many ITS applications. The World Road Association rates GNSS location systems as a key enabling technology for ITS (Miles and Chen, 2004). Any ITS that involves some form of positioning or navigation, or requires accurate timing, may use GNSS receivers as a primary or secondary source. However, where GNSS technology has enabled many ITS applications, certain fundamental aspects of GNSS positioning have created a development ceiling, restricting the exploitation of more advanced ITS applications.

Unlike other candidate ITS technologies, GNSS positioning does not require any significant modifications to transport infrastructure (Miles and Chen, 2004). This is in contrast to technologies that rely on the identification of surrounding features, such as lane markings, prominent features, or other vehicles. A GNSS positioning system is inherently an off-the-shelf positioning solution.

1.4.4 MIRA proving ground positioning

The Motor Industry Research Association (MIRA) based in the UK near to Coventry, who sponsored this project through an industrial CASE Studentship, use GNSS technology during testing and validation. However, the use is limited by fundamental flaws in GNSS positioning such as limited availability or accuracy, or the lack of availability of reliable receivers. The MIRA proving ground, shown in Figure 1.9, includes several outdoor vehicle testing circuits. Yet even in this open-sky environment, GNSS positioning is known to perform unreliably.

In 2011, the innovITS ADVANCE testing facility was officially opened (Wilson, 2011), as shown in Figure 1.10. The facility, based at MIRA, is a comprehensive cityscape consisting of a network of roads with junctions and roundabouts, traffic signals and signs, and changes in elevation. There are also several communication systems including mobile communications (GSM and 3G), Wi-Fi, and a wireless MESH network. It is also possible to program a GNSS denial situation. All of these systems are configurable and controllable on-site, allowing an unlimited number of controlled test conditions to be set.

Figure 1.9 – Aerial photo of the MIRA proving ground.

Figure 1.10 – The official opening of the innovITS ADVANCE testing facility at MIRA near Coventry.

1.4.5 V2X and connected cars

Collaboration or cooperation is a popular topic in research. From the Internet of Things (IoT) to V2V technology, agents that can communicate directly with one another can generate large benefits. This is loosely based on the holistic idea, first attributed to the Greek philosopher and scientist Aristotle (Aristotle and McMahon, 2008), which is most commonly phrased as:

> the whole is greater than the sum of its parts.

This is also known as synergy, and explains why road agents working together can perform better. On top of this clear advantage, the complex systems theory of emergence suggests that novel strategies will develop from the as-yet undefined patterns and structures (Kiel, 2002). It is clear however, that in order to facilitate this development, certain technological advances need to be achieved. In this case, individual road agents need to accurately identify their locations, and

communicate easily and safely with other agents. This is a shift away from protective and passive road safety systems of the past, towards preventative and active transport safety.

The term connected car is used to describe a road vehicle (typically a passenger vehicle) that is connected to the internet, and often acts as a wireless access point to allow nearby devices to utilise its internet connection. Several vehicle manufacturers and technology companies are currently developing platforms that allow devices to connect to the vehicle's infotainment system. These include MirrorLink from the Car Connectivity Consortium, Android Auto from Google, and CarPlay from Apple Inc. The connected car is part of the V2X concept, although it is not generally a platform that allows nearby vehicles to communicate

This thesis demonstrates the benefit of the V2X concept, through the development of an innovative GNSS cooperative positioning technique known as Pseudo-VRS.

1.5 High precision GNSS

GNSS positioning can play an important role in future high accuracy and high precision vehicle positioning solutions. Although the technology dominates the consumer personal navigation device market, and is embedded in billions of electronic devices for various applications, it is generally considered a poor choice for high accuracy vehicle positioning. For instance, the most advanced examples of autonomous vehicles do not use GNSS receivers as a primary device for positioning during autonomous control. Examples include the Google autonomous vehicle and the Robotcar from the Oxford Mobile Robotics Group at the University of Oxford in the UK, which both rely on terrestrial systems that sense the local environment.

The majority of vehicle positioning research over the past two decades - in academia and industry - has focused attention on GNSS centred systems. This is emphasised by the abundant use of Sat Nav devices to assist in-car navigation. However, these low-cost, consumer-grade devices offer relatively poor positioning accuracy. Theoretically, a Sat Nav device will provide positioning accuracy that is at best 13 metres, although several simple and conveniently low-cost techniques can improve this to around 5-10 metres.

GNSS positioning is considered to have a poor performance for high accuracy applications. Low-cost GNSS receivers can achieve positioning accuracy of approximately 10 metres, and the solution degrades quickly if the GNSS antenna cannot receive unreflected signals directly from the satellites[3]. GNSS positioning accuracy, however, can be improved dramatically using additional GNSS signals and modern geodetic techniques. For instance, RTK GNSS positioning can provide better than 5 centimetre accuracy positioning during dynamic use. This is also an absolute positioning accuracy that could be achieved on any road in the world (given the correct GNSS infrastructure), which is an important consideration when using positioning information in future ITS and V2X applications.

Significant investment into new GNSS constellations (Galileo and BeiDou), and modernised signals in existing GNSS constellations (GPS and GLONASS), will in the future provide much greater satellite visibility and availability, protection from multipath and signal interference, and high accuracy dual-frequency positioning at a much lower end-user cost.

Section 1.5.2 introduces the three main GNSS techniques available for road vehicle positioning. High accuracy GNSS positioning techniques suffer from staggering limitations when employed for vehicle positioning. The rapidly changing number of visible satellites, GNSS signal cycle slips, and dynamic multipath, each causes chaos with ambiguity resolution algorithms. The accuracy of a GNSS receiver can vary from a few centimetres to several metres within a few epochs, and dual frequency GNSS receiver technology is typically fifty times more expensive than an off-the-shelf Sat Nav device (although this may change with the future development of the GNSS constellations and signals, as discussed in Section 4.5).

[3]The later issue is fundamentally difficult to solve, as the GNSS signal power is extremely low - the transmit power from the satellite is equivalent to a 40 Watt light bulb, and the satellite is at least 20,000 kilometres above the Earth's surface (Hofmann-Wellenhof et al., 2008). Together with the physical characteristics of electromagnetic waves, this means that signals cannot pass through solid objects and are subject to various forms of very significant signal noise.

1.5.1 The ubiquitous Sat Nav

The relatively low-cost Sat Nav devices primarily use L1-only code-based positioning from inexpensive GNSS chips, although they increasingly use additional inertial, dead-reckoning, or map matching systems to increase positioning performance. Figure 1.11 shows the performance of a Sat Nav device (white dots) and the performance of a high precision GNSS receiver (a Leica Geosystems GS10 with AS10 antenna, shown as green dots). Although the underlying Google image is of unknown accuracy, it is clear that the positioning performance of the Sat Nav device is suitable for navigation applications but not for more complex applications that demand high accuracy. The driver remained on the correct side of the road (left-hand) and did not mount the footpath or leave the road as suggested by the Sat Nav device.

Figure 1.11 – The positioning performance of a Sat Nav device (white) compared to a high precision GNSS receiver (green).

Sat Nav devices are renowned for occasional direction errors. Most people have anecdotal evidence of a Sat Nav device leading them to the wrong location, down the wrong road, or trying to direct the driver in a manner that would be against the highway code. Most of these occurrences are due to operator error (incorrect input of destination address) or out of date digital mapping, but the device can suffer from errors due to poor location. The screenshot in the left of Figure 1.12 shows a Sat Nav device performing navigation. The blue arrow shows the position the device believes the vehicle is located, whereas the vehicle is actually positioned at the yellow circle. The Google StreetView image in the right of Figure 1.12 shows the situation the driver is encountering. The parallel roads are running close to one another, and due to the limited positioning accuracy of the Sat Nav device, and the assumptions it makes about the intentions of the driver (based on the proposed route choice), the device does not accurately determine that the vehicle has joined the left-hand exit slip road.

However, Sat Nav devices perform relatively well in terms of availability and continuity. A solution is provided rapidly once satellites are visible, and often when some signals are only available as non-direct line of sight. This has led to the prolific spread of GNSS positioning capability throughout Personal Navigation Devices (PND) such as smartphones, tablets, and of course Sat Nav devices.

Figure 1.12 – Example of a Sat Nav device identifying the wrong vehicle location during navigation.

1.5.2 High precision GNSS positioning techniques

The following is a breakdown of the three main available GNSS positioning techniques for ITS, and the emerging techniques called Network Real Time Kinematic (N-RTK) and Real Time Precise Point Positioning (RT-PPP). All values are horizontal accuracy (the height accuracy is worse by a factor of 1.5 to 2 (Hofmann-Wellenhof et al., 2008)), because for current ITS applications vertical accuracy may not be as important as the horizontal accuracy.

***Stand-alone*: 13 metres.**

GPS single point positioning using the coarse acquisition (C/A) code will deliver a position accuracy of 13 metres (2-SD), with GLONASS[4] providing a slightly worse accuracy. The GNSS receiver estimates the position by comparing the broadcast navigation message with a known copy, measuring the range between each satellite and the receiver, and then solving for the three unknown coordinates of the receiver (XYZ) and an unknown time correction.

Using the modern navigation signals or multiple GNSS constellations can deliver accuracy better than 5 metres. These figures can be improved by smoothing, for instance by using the phase ranges, or by adopting a Kalman filter (good for dynamic applications) (Hofmann-Wellenhof et al., 2008; Kaplan and Hegarty, 2009).

This technique is primarily limited by the availability of GNSS satellite signals (for example, in tunnels, dense urban areas, or areas of vegetation cover).

***DGNSS*: 1.5 metres.**

Differential GNSS (DGNSS) incorporates many different techniques, with various sources of differential corrections (for example, using Satellite-Based Augmentation Systems (SBAS)). Typical position accuracy of code-based differential GNSS is 1 to 2 metres. This has to be taken with caution as there are many sources of error that differential services deal with in separate ways, and according to particular applications (for example, marine, aviation, surveying, and mobile phone applications). It is possible to get an accuracy of 0.1 metres by measuring carrier-phases and utilising a short baseline to the reference station (Hofmann-Wellenhof et al., 2008; Kaplan and Hegarty, 2009).

The simplest methods provide code-based range corrections to improve the stand-alone position solution. DGNSS positioning has the additional limitation of the availability of the correction messages. For example, delivery of the messages over a GSM/GPRS data link is limited by cellular coverage.

[4]GLONASS is the acronym for GLObal'naya NAvigatsionnaya Sputnikovaya Sistema, which translates into English as Global Navigation Satellite System.

***RTK*: 0.05 metres.**

RTK positioning[5] uses advanced phase measurements of the GNSS carrier signal, and estimation of the number of complete carrier signal cycles between the satellite and receiver. Resolving the integer number of cycles between each satellite and the receiver is computationally intensive (although differential services can increase the successfulness and reduce initialisation times). Typically, dual frequency observations are used to remove ionospheric effects and reduce the number of calculations by combining the two different signal wavelengths

Assuming the RTK positioning is to provide a solution based on a single epoch, the typical accuracy would be around 5 centimetres (given a short baseline of less than 20 kilometres between the base and rover receivers). The drawback of this technique is that it relies on the continuous lock of satellites to hold the phase ambiguity, otherwise the system needs to be re-initialised (this can take 1-2 minutes). However, if the integer ambiguity is lost, the system can revert to a differential position, and given the receiver is measuring carrier-phases, this could provide a decimetre-level position accuracy. In non-navigation scenarios, making static observations for 10 minutes plus 1 minute per kilometre (of baseline length) would provide sub-centimetre accuracy (Hofmann-Wellenhof et al., 2008; Kaplan and Hegarty, 2009).

RTK positioning is mainly limited by GNSS cycle slips or outages that require re-initialisation of the integer ambiguity resolution. Differential RTK services can be expensive and rely on the delivery of information via communications medium.

***N-RTK and RT-PPP*: 0.05 metres.**

Work carried out by Aponte et al. (2008) showed that N-RTK positioning can deliver high accuracy positioning solutions in a dynamic transport environment. The system is based on an expanded RTK principle, using multiple reference stations spread over a wide area, allowing greater vehicle mobility.

RT-PPP is a rapidly emerging technology that uses precise satellite clock and ephemeris information - traditionally only available for post processed solutions - in a real time technique. These are some of the most significant sources of error in GNSS positioning, and the Precise Point Positioning (PPP) technique has been shown to deliver better than decimetre accuracy (Lachapelle and Petovello, 2006). RT-PPP is not explored in this thesis as the integer ambiguity resolution time is a significant limiting factor for high precision vehicle positioning.

Further information about the achievable positioning accuracies of different GNSS positioning techniques can be found in Section 4.3.

As highlighted in previous research, the adoption of these advanced GNSS positioning techniques for vehicle positioning continues to have limitations. In particular, the vehicle-borne GNSS receiver requires correction information in order to quickly and accurately calculate its position, and frequent signal cycle slips caused by signal obstruction requires the re-initialisation of this calculation. This thesis outlines measures to minimise these limitations by utilising the communication options provided by the emerging V2X technologies and cooperative GNSS positioning techniques. Specifically the subjects of this thesis include:

- Utilising advanced geodetic or survey grade GNSS positioning techniques for vehicle positioning;
- Significantly increasing the availability of high accuracy GNSS positioning for road vehicles; and
- Demonstrating the benefit of V2X communication for cooperative GNSS positioning.

1.5.3 Non-GNSS positioning systems

GNSS receivers are the overwhelming positioning sensor choice for vehicle navigation and positioning. GNSS receiver chips are now very low-cost, and the civil service from GNSS providers is

[5] RTK positioning is also considered a form of differential GNSS positioning, although it is distinguished from DGNSS by the use of the carrier phase measurements.

free to the end-user. The coverage is global, and for the desired applications, the availability is generally very good. However, GNSS positioning does have limitations, and for certain applications alternative positioning systems and devices exist and are in use. Alternatives include technologies that utilise the electromagnetic spectrum, inertial and dead reckoning measurements, and less commonly, magnetism.

Electromagnetic sensors mostly operate in the visible and radio wavelengths. Visible light is used passively through cameras, and actively by laser scanners (lidar). Amongst other techniques, radio waves are used in radar, Loran, and UWB. More information about these techniques can be found in Section 4.6.1. As is the case with GNSS positioning, the use of electromagnetic waves is hindered by signal obstruction, attenuation, reflection, and jamming or interference (Groves et al., 2014).

Radio waves used for non-positioning purposes can be exploited. These are referred to as Signals of Opportunity (SoOP), and include Bluetooth, Wi-Fi, FM radio, and Digital Audio Broadcasting (DAB). Cellular communications have long been used for positioning, relying on the proximity of the device to the transmitting tower and triangulation.

Inertial sensors measure a combination of acceleration, rotation, and occasionally magnetism. This allows the determination of velocity and orientation. The best performing inertial sensors are mechanical, although they can be bulky and expensive. Low-cost Micro-Electro-Mechanical Systems (MEMS) sensors offer a low-cost inertial solution, and typically offer good navigation performance when combined with other sensors. Promising current research is exploring the use of cold-atom technology and de Broglie wave interference, which appears to enable low-cost, robust, and high accuracy inertial navigation (Kasevich, 2007).

Simple dead reckoning sensors on a vehicle include a wheel odometer and steering angle sensor, to crudely determine velocity and direction of travel. Other less traditional sensors used for positioning include magnetic and barometric sensors, nuclear magnetic resonance gyroscopes, Doppler measurements from the Iridium satellite, and pseudolites (Groves et al., 2014). The positioning performance of these sensors is not explored in this thesis, but their relationship in a combined positioning solution is considered.

1.5.4 Absolute positioning requirement

The application of simultaneous location and mapping (SLAM) technology for vehicle navigation has been successfully implemented in many well-publicised semi- and fully-autonomous vehicle projects. These include Google's autonomous vehicle (Kane, 2011) and Oxford Mobile Robotics Group's Bowler Wildcat (Mobile Robotics Group (MRG), 2012). It is also apparent that many of these projects do not have GNSS sensors as a primary positioning sensor, and some do not utilise GNSS sensors at all. Although the vehicles navigate through their environment successfully, this can leave the positioning system with a poor absolute positioning performance.

This is important for several reasons. Most importantly for this thesis, it may significantly reduce the benefits of V2X applications, or increase the complexity of their implementation. Absolute vehicle positioning based on a common reference system and a common reference frame allows the direct sharing of position-based information, which is inherently independent from the sensor technology used to create the positioning information.

Absolute positioning is also a critical component of digital map production. This has been deemed a key enabling technology for V2X (Meng et al., 2008). The generation and continuous revision of high resolution digital maps is important for up-to-date information. Clearly, based on established navigation conventions, it is important to know the geographic start and end point of a journey, and this is easily achieved through the use of an absolute positioning sensor.

Finally, GNSS positioning sensors have been shown to be excellent complimentary sensors in the integrated sensor approach to positioning. For instance, GNSS sensors and inertial measurement units have strengths that out-weigh the limitations of the other. GNSS sensors can also provide valuable information for SLAM, as purely relying on situational awareness for navigation has limitations. More detail about this subject is provided in Section 4.6. An important aspect of

this integration is that GNSS sensors provide a useful service for on-the-fly calibration of low-cost positioning sensors, such as dead reckoning and terrestrial ranging sensors.

GNSS positioning is the only absolute positioning system that can offer a high accuracy and high accuracy position with globally availability.

1.5.5 Positioning standards

There are no international agreements for positioning accuracy standards for ITS technology. There are specific standards held by the International Organisation for Standardisation (ISO) relating to data quality and the transmission of information (such as ISO/TR 21707:2008). Other organisations such as the European Committee for Normalisation (CEN) and the Open Geospatial Consortium (OGC), work toward voluntary technical agreements and implementation standards.

The definitive guide to ITS applications and systems is the PIARC (Permanent International Association of Road Congresses) ITS Handbook (Miles and Chen, 2004). Also known as the World Road Association, they have created a detailed guide to the history of ITS, including the development of ITS applications, technology, and infrastructure.

There are various ITS organisations around the world, such as ITS America, ITS-UK, ERTICO-ITS Europe and ITS Australia. They bring together academia, companies, government departments, and individuals in the ITS industry. They work together on local and global agreements for good working practices, lobbying of government, and promoting ITS technology.

Where positioning or navigation is required in the transport domain, and standards or requirements are used, the whole performance of the positioning system is typically addressed. This is the case in aviation and the RNP, which is a type of performance-based navigation (PBN). The RNP is used to define the radius with which an aircraft can determine its own position (within 95% total system error), whilst adhering to strict limits on position availability, continuity, and integrity. The performance is well defined, but the highest accuracy required in aviation is 0.1 nautical miles (185.2 metres), which is rather lax compared to some ITS application requirements. RNP values of 4 or 10 nautical miles are typical in aviation (International Civil Aviation Organization, 1999).

1.6 Testing facilities and previous research at the Nottingham Geospatial Institute

1.6.1 NGI testing facilities

The initial research in this thesis was carried out at the Nottingham Geospatial Institute (NGI) using state-of-the-art testing facilities. These bespoke in-house facilities allow repeated controlled experiments, and are a useful tool in the development of ITS and V2X technology.

The roof of the Nottingham Geospatial Building (NGB, the home of the NGI) is the location of a remotely operated electric locomotive running on a 186 millimetre gauge railway track. A photograph of the locomotive and plan of the track are shown in Figure 1.13. The locomotive can carry a selection of positioning instruments, such as GNSS receivers, Inertial Navigation Systems (INS) devices, and tracking prisms; and can travel at a speed of over three metres per second. The position of the track is accurately known, and has previously been scanned at a resolution of 2 millimetres (Gao et al., 2008b).

In order to test the positioning performance more thoroughly and under real-world conditions, experiments can also be carried out using the NGI's road vehicle (as shown in Figure 1.14), which carries a collection of on-board ground truth systems.

A varied selection of control systems can be employed on either the locomotive or the road vehicle, including:

- An Applanix POS/RS dual frequency GPS INS (Taha et al., 2009), including optional wheel odometer input;
- A NovAtel SPAN INS (SPAN-SE GNSS receiver and SPAN IMU);

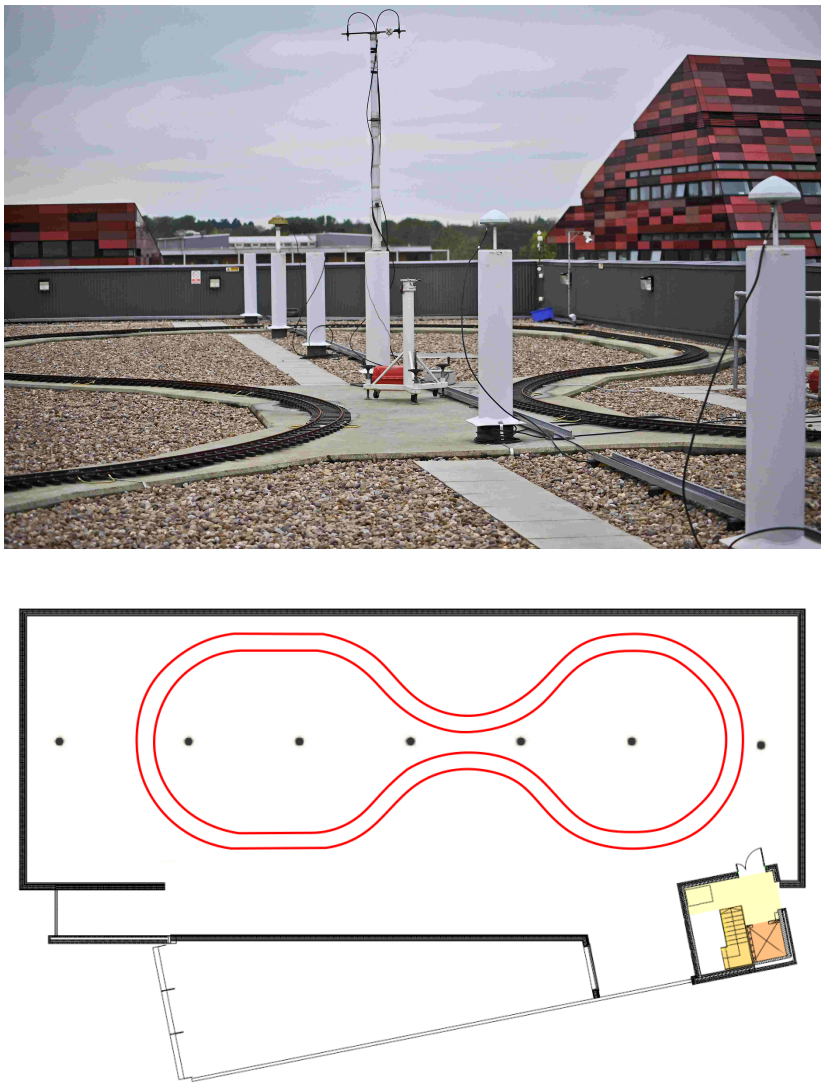


Figure 1.13 – The GNSS reference base station and electric locomotive track on the roof of the NGB.

- An RTK control solution, provided by a local static GNSS base station (Leica GS10 rover receiver, and Leica GR10 GNSS base station receiver);
- An N-RTK solution, based on the MAC standard (Leica GS10 GNSS receiver with SmartNet service);
- Tracking of the vehicle using a total station and reflective prism (Leica Nova TS50);
- Image capture using a Race Technology Video4 data logger, including GPS input for timing and positioning; and
- A proprietary Ultra-Wideband positioning system, using Thales UWB transceivers.

Figure 1.14 – The NGI road test vehicle.

1.6.2 Previous research carried out at the NGI

Since the introduction of N-RTK positioning in the UK by Leica Geosystems in 2006, research has been carried out into two aspects of its use: The adoption of the technology for land navigation applications; and the assessment and production of its quality measures.

In Aponte et al. (2008), the authors evaluated the performance of N-RTK positioning during road tests, mainly on the M1 motorway in the UK. During separate trials, the availability of the N-RTK solution was between 33% and 51%. Lower grade differential GNSS and stand-alone positioning solutions were typically available during the other periods. The authors noted that theoretically, the N-RTK solution was available for between 46% and 86% of the time. This discrepancy is due to the design of the GNSS receiver hardware and firmware, and its intended use as a high accuracy survey-grade positioning sensor.

During static and kinematic tests by Aponte et al. (2009), the accuracy of N-RTK positioning was found to be better than 5 centimetres for 98% and 50% of the time, respectively. Weaknesses in the kinematic tests were highlighted as GNSS signal disturbances and interruptions to the GPRS data link (serving the corrections).

The quality of the N-RTK positioning correction message was evaluated by Yang et al. (2009a). A combination of different data link configurations were tested to determine the quality of the transmissions; such as local Ethernet, long distance wired internet, and GPRS. It was found that the combination of GPRS and long distance internet link - the typical connection for the N-RTK positioning user - offered an average delay 0.85 seconds, with 20% message loss.

1.7 Thesis organisation

This thesis is laid out in a logical format in order to aid the understanding of the final solution.

Chapter 2 discusses ITS - the history and applications. This includes an introduction to future ITS and V2X applications, such as connected and autonomous vehicles. The chapter finishes by analysing some of these applications, and discussing the requirements of any positioning system.

Chapter 3 provides a detailed study of vehicle localisation and positioning requirements. This starts by outlining the movement of road vehicles, before relating these movements to the measurements required in a localisation system. The chapter ends by discussing the accuracy requirements

for ITS applications, and why accuracy is not the single characteristic used for vehicle positioning performance.

Chapter 4 gives a brief introduction to GNSS positioning for road vehicles. The GNSS positioning techniques that are relevant to vehicle positioning are discussed, drawing on the examples from real-world tests carried out at the NGI and using the NGI's test equipment that were introduced earlier in Chapter 1. The future development of GNSS is outlined, and the enhanced opportunities for vehicle positioning. The final part of the chapter reviews the non-GNSS technologies and techniques available for vehicle positioning - in particular, focusing on those technologies that can be integrated with GNSS positioning.

Chapter 5 goes into greater detail about N-RTK positioning for road vehicle positioning. This includes extensive real-world tests of N-RTK positioning using the facilities at the NGI, the local roads in Nottingham, and the M1 motorway. The chapter outlines the major limitations of N-RTK positioning for road vehicle positioning, and provides some quantifiable evidence for the assessment.

Chapter 6 takes the concepts of GNSS positioning and V2X to tackle the limitations of N-RTK positioning for road vehicles. The concepts of N-RTK positioning are adapted to create a method of sharing GNSS information between vehicles to increase the availability of a high precision solution. The concept is called Pseudo-VRS, and a series of tests are carried out to evaluate the system.

Chapter 7 concludes the thesis by relating the work carried out to the original aims and objectives. This chapter discusses the questions that have been answered, and what new questions have emerged. The contribution to knowledge from this thesis is outlined, including an assessment of its merit and implications.

Finally, the appendices include a list of publications made during the study period, the memberships to academic and industry organisations, and the bibliography.

Chapter 2

Intelligent Transport Systems: History and Applications

2.1 Overview

Vehicle safety systems have historically been protective rather than preventative. For instance, the introduction of seat belts, crumple zones, and air bags, have all reduced the probability of serious injury if the vehicle is involved in an accident - but were not designed to prevent an accident. More recent technology such as anti-lock brakes (ABS) would qualify as a preventative safety feature, but other technologies designed to avoid road accidents have been difficult to sell to potential car buyers.

Legislation from governments is trying to promote such preventative technology. This varies from the increased standards of driving tests to the development of cooperative ITS standards and related research.

Advanced Driver Assistance Systems (ADAS) have improved individual vehicle accident prevention. These include active braking, blind spot warning, collision warning and mitigation, and lane departure warning systems, which are now available on new mass market vehicles. The promotion of these technologies in advertising and vehicle periodicals is a clear indication that consumer demands are changing. This is also a gradual movement towards increased vehicle autonomy.

The next major development in vehicle safety is V2X. This would allow vehicles to work together to avoid accidents and incidents, improve traffic efficiency, and reduce emissions. The drive behind this concept is strong enough to influence the development of future transport infrastructure.

V2X may also influence the development of autonomous vehicles. The development of this seemingly futuristic transport is now much closer to deployment than anticipated. Through the allocation of dedicated lanes on motorways, increased car sharing (through social policies), and pilotless vehicles delivering goods, the concept of the connected autonomous vehicle is a close and viable technology.

However, most of these systems need to know where the vehicle is, where it is heading, and its dynamic situation. Hence, the localisation requirements will be very strict and demanding.

2.2 Intelligent Transport Systems

2.2.1 ITS history and definition

The PIARC ITS Handbook (Miles and Chen, 2004) defines ITS[1] as:

> ...a generic term for the integrated application of communications, control and information processing technologies to the transportation system.

[1] In the US, ITS is the acronym of Intelligent Transportation Systems, whereas the EU favours Intelligent Transport Systems.

Often termed Transport Telematics in Europe, this research area considers the transportation vehicle, the user or driver, and the operational infrastructure environment. Figure 2.1 describes the flow of data within an ITS. Typically data is acquired from the transport system (or infrastructure, such as road sensors), from the user or driver (such as position information), and from external sources (such as databases and parameters). This data is then processed to provide information to the user. Depending on the system, information can be pushed or pulled to the user, such as when congestion warnings are transmitted or when the user is searching for a point of interest (POI).

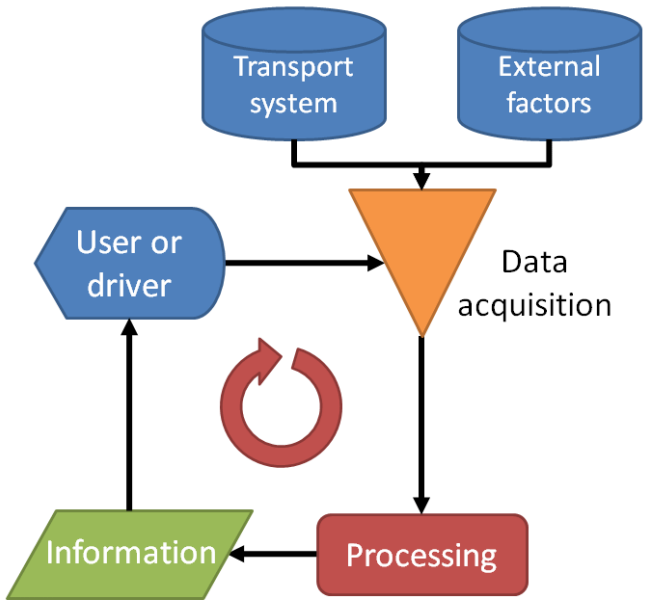


Figure 2.1 – Flow diagram of data in an Intelligent Transport System.

From this early success in merging ICT with transport infrastructure, other systems have been developed spreading ICT control deep into the road transport network. Systems are now in place that control access to highways (freeways, motorways, or autobahns), impose variable speed limits, advise on lane discipline, provide driver information about weather and journey times, and numerous other applications. These systems justify their investment through reduced congestion, reduced traffic incidents and accidents, reduced journey times, increased vehicle efficiency, reduced driver stress and fatigue, and can also provide revenue through toll charges. Although often difficult to quantify accurately, these advantages can lead to substantial financial savings, particularly to businesses.

2.2.2 Motivation for ITS

Several factors drive ITS projects and policies. The biggest concerns are typically regard road safety, economic impact, and environmental damage. More details are given in the following sections.

2.2.2.1 Road safety

The first road safety research was carried out in the late 1920s, due to the increasing numbers of road casualties (Shalom Hakkert and Gitelman, 2014). The earliest examples of research and safety improvements focused on the fallibility of the human driver. This is still reflected today in road accident investigation, where the drivers are immediately the focus of any investigation. This led most early attempts at improving road safety to focus on the driver, either by improving driving skills or introducing punitive measures. If the road was designed according to current standards they were considered safe, and vehicle manufacturers were generally considered to be designing safe

vehicles. By the 1970s, this focus had started to shift to improving the road infrastructure and vehicle design, and attempting to prevent accidents irrespective of the ability of the driver. This is now commonly referred to as a safe systems approach (World Health Organisation, 2011).

In the European Union (EU) in 2008, there were 38,875 fatalities on member states' roads (of which 2,538 were on UK roads), estimated to cost the EU economy €200 billion per year (€20 billion in the UK). The number of road deaths in the UK has declined consistently since the 1960s (7,985 in 1966), following significant improvements in road safety technology (such as compulsory seat belts and the introduction of airbags). However in recent years the decline has slowed per unit of traffic.

In the most recent report from the Department for Transport in the UK (United Kingdom Department for Transport, 2014a), the reduction in casualties appears to have stagnated. Although the number of road deaths decreased by 2% between 2012 and 2013 - representing the lowest number of road deaths since records began in 1926 - the decrease has slowed since 2010. Between 2005 and 2010 the fall in the number of road deaths was 43% (from 3,201 down to 1,850), but the decrease between 2005 and 2013 is only slightly greater at 47% (3,201 down to 1,713). The volume of traffic between 2010 and 2013 was approximately stable (United Kingdom Department for Transport, 2014b). There is a growing opinion that the fall in road casualties is beginning to plateau in the UK (Fosdick, 2014), and that more innovative solutions are required to break through this threshold.

However, these improvements in road safety in the UK are not representative of the situation in other parts of the world. The World Health Organisation estimates that by 2030 road accidents will become the fifth highest leading cause of death (World Health Organisation, 2013). Globally, 1.2 million people die every year due to road accidents, with approximately 20 million casualties in total.

The introduction of relatively basic road safety systems, such as safety barriers, child restraints, and better vehicle impact protection, are shown to significantly reduce the severity of road accidents. The studies that describe the statistical relationship between the reduction of road casualties and the implementation of various infrastructure and vehicle safety improvements is summarised by Shalom Hakkert and Gitelman (2014). Such studies help to define best practice guides for road and vehicle design.

Research carried out by the Insurance Institute for Highway Safety (IIHS) in the United States (US) has found that ADAS technology may be starting to have an impact on road safety, and may break this road death reduction stalemate (Transport Technology Today, 2014). It found that automatic braking systems are reducing property damage liability claims by around 14%, although systems that only provided a warning were less effective as they rely on additional driver input. Other less obvious ADAS systems were also effective at reducing the liability claims, such as adaptive headlights, even though there are only a small number of incidents for which this technology was designed to influence. The IIHS reasons that a third of all collisions on US roads could be avoided by using just four ADAS technologies: Forward collision warning, lane departure warning, blind spot detection, and adaptive headlights.

There are many different approaches to improving road safety and reducing casualty numbers. From a GNSS standpoint, a meeting of the Civil GPS Service Interface Committee (CGSIC) in 2003 forecast that GNSS technology would reduce the national annual traffic death rate by approximately 30% (Jacobson, 2007). Other forecasts relate to the impact of autonomous vehicle technology on road safety: GNSS technology has the potential to be a key positioning and timing sensor in such autonomous vehicle systems.

2.2.2.2 Congestion and emissions

Data from the UK Department for Transport's National Travel Survey 2013 shows that the average car travels 7,900 miles per year (down from 9,200 in 2002). The number of individual trips and their average distance has declined slowly since 1997, resulting in a 6% drop in the average distance travelled per person each year (6,584 in 2013) (United Kingdom Department for Transport, 2014c). Congestion continues to be an issue as the number of vehicles on the road increases every year. In

2013, there were 35.0 million vehicles licensed for use (29.1 million cars in 2002). The number has increased every year since 1945, with a single exception in 1991 (United Kingdom Department for Transport, 2014d).

Road vehicle congestion has a significant impact on a nation's economy. Congestion is a leading cause of increased vehicle emissions and increased travel time, but also a reduction in the reliability and predictability of journey times. The Eddington Transport Study in the UK found that congestion costs the UK economy £7 billion to £8 billion per year, and if left unchecked would eventually cost the economy £22 billion in the year 2025 (Eddington, 2006).

The estimated health cost of particulate pollution in the UK is £5 to £10 billion per year, including acute respiratory problems and chronic illness such as heart disease. It is estimated that the average person's life expectancy is reduced by 7 to 8 months. Road transport accounts for 92% of domestic transport emissions, and congestion exacerbates this problem. Simply reducing congestion will significantly reduce the environmental impact.

2.2.2.3 Transportation and the economy

The lack of accessibility to transportation significantly increases the inequalities found in society. For instance in the UK, 75% of all households have access to a car or van, but for the unemployed person this figure falls to 36%. This fact is compounded by the clustering of unemployed people in deprived areas, who struggle to find affordable transport options to take them to other places to find work.

The ITS industry in the US was estimated at US$48 billion in 2009, including technology such as travel information systems, electronic payment collection, and vehicle safety. On top of this implementation of established technology, state-of-the-art research is being carried out into future ITS solutions, such as autonomous vehicles. This traditionally niche area of research now attracts significant investment from companies and organisations. Several multi-million dollar collaborative projects have displayed the future potential, involving car manufacturers, universities, and research organisations. General Motors, Audi, Volvo, BMW, Volkswagen, and technology giant Google are amongst those who have demonstrated prototype vehicles that can drive autonomously (as discussed in more detail in Section 2.3).

2.2.2.4 Government policy

The UK government's Business Plan for 2011-2015 outlines transport as the catalyst of economic growth, as well as aiming to make it greener and safer, and to improve the quality of life of communities (United Kingdom Department for Transport, 2010). However, transport budgets are also being cut over the same period. This will mean that potential solutions will need to be smarter and driven by innovation, such as those delivered by ITS. Advanced technology in ITS can be used to tackle key economic growth obstacles, such as road congestion, carbon emissions, and the social inequality of communities.

Many schemes have been implemented against strong opposition from road users, as a restriction to freedom, and concern about increased charging and a waste of local taxes. However, most schemes have been able to prove their cost effectiveness, financially and socially. For instance, the Active Traffic Management (ATM) scheme on the M42 motorway in the UK reduced congestion, journey times, fuel consumption, and emissions. It also completed this at a cost of £12.4 million per kilometre less than traditional road widening (ITS-UK and Institute of Engineering and Technology, 2011). It has a benefit to cost ratio of 7.6, compared with 2.3 for road widening.

2.2.3 ITS and GNSS

A common stumbling block for the implementation of ITS is that a typical application covers a very small proportion of the total road network. Specific areas or sections of road are chosen due to their potential success rate. For example, the area is an accident black spot or suffers from regular heavy traffic congestion.

Many systems are operated on major roads, such as on motorways and major trunk roads in the UK. For instance, induction loops and traffic sensors cover the majority of the motorway network in Great Britain to monitor traffic congestion and provide traffic statistics (Trafficmaster Ltd, 2011; Department for Transport, 2011). However, motorways account for only 0.9% of the total road network, albeit they carry 19.7% of the traffic (Department for Transport, 2010). At a high ITS planning level, this creates the problem known as *islands of functionality*, where systems are incompatible with neighbouring areas or systems.

It is at this point that GNSS positioning solutions hold the advantage; the fundamental feature of a GNSS positioning system is that it has global coverage, which is consistent given a good view of the sky, and does not suffer from the perceptive horizon of terrestrial ranging sensors.

Theoretically, GNSS positioning could replace some existing ITS technologies, from road signs to radar guidance systems. The advantages of GNSS positioning over existing solutions are:

- The cost of the GNSS hardware is falling year by year, a simple GPS chip now costs less than £3 (van Diggelen, 2010);
- GNSS devices are very portable, with the GNSS hardware and user interface often housed in the same unit; and
- It is possible to retro-fit GNSS positioning systems to existing vehicles.

However, there are some major hurdles yet to overcome. Namely:

- There are small yet significant periods when GNSS positioning is not available or the accuracy provided is poor, such as in tunnels or dense urban canyons (availability and continuity);
- Occasionally the reported positioning accuracy is unreliable (integrity);
- There is a dependence on external technology, out of the control of the end-user; and
- The accuracy of the GNSS position of the individual vehicle may be high, but this does not guarantee the direct link to other ITS systems and infrastructure.

Many of the solutions to ITS applications require that all vehicles are equipped with GNSS devices, and provision needs to be made for malfunctioning devices. GNSS devices are viewed as direct competition for terrestrial positioning systems based on radar, lidar or imaging cameras, which also have their own environmental limitations. These systems have been favoured by vehicle manufacturers as they are easy to control and easily integrated from an Original Equipment Manufacturer (OEM) point of view.

GNSS positioning and timing are used for various applications in the automotive industry. The following sections describe some well known examples of GNSS technology use, as well as some novel and less known applications. Figure 2.2 shows images related to some of these GNSS applications.

2.2.3.1 Navigation

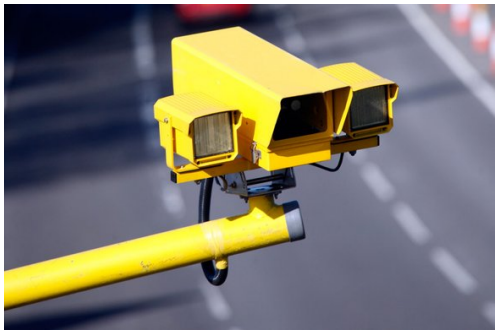
The market for GNSS navigation devices first emerged in Japan around 1990. It took several years to build the market up, but it was made possible by the significant advances made into creating digital maps of the country (Jacobson, 2007). The devices became much more prevalent in the US and Europe following the deactivation of Selective Availability in 2001, and the subsequent improvement in positioning accuracy and lower device cost. The image in Figure 2.2a is an example of an aftermarket Sat Nav device supplied by TomTom. Vehicle manufacturers installed Sat Nav systems in premium models from the late 1990s - although at a high price - and traditionally favour established technology over state-of-the-art systems. Infortainment systems are increasing viewed as an important component of a passenger vehicles (particularly amongst younger buyers), and the Sat Nav device is commonly at the heart of such systems.

The advantage of the built-in system is the integration of additional sensors, such as vehicle speed and heading, to aid the positioning algorithms (such as during GNSS outages). More complex systems layer on additional location-based services (LBS), such as road assistance, concierge

a). Sat Nav device from TomTom.

b). GPS dart for Police use.

c). Generic GPS tracker.



d). Average speed enforcement camera.

Figure 2.2 – Examples of automotive applications using GNSS.

services, and weather and traffic information. Some of these services require an additional purchase, and are often referred to as p-commerce (position) or m-commerce (mobile) (Jacobson, 2007).

A more unusual application of GNSS navigation involves plowing roads that are covered in snow (Jacobson, 2007; Shankwitz, 2010). In some cases the roads are not visible below the snow, and the devices can assist the driver in correctly clearing lanes and spreading salt. The devices are also used to track the vehicles, which improves deployment and identifies routes in need of plowing. A system in Alaska uses differential GNSS to clear the Thompson pass, which is renowned as the snowiest place in Alaska (Shankwitz, 2010).

2.2.3.2 Vehicle tracking

GNSS vehicle tracking is used extensively in the logistics industry. Fleet tracking applications actually preceded navigation applications (Kaplan and Hegarty, 2009), with services now typically provided by fleet management companies, such as Teletrac in the UK (formerly TrafficMaster) (Teletrac Inc, 2014). The systems, often called Automatic Vehicle Location Systems (AVLS), are promoted as improving operating efficiencies, providing better customer service, and optimising routing (Kaplan and Hegarty, 2009). The vehicles are often a major asset, and vehicle tracking is used to improve security and reduce loss. Vehicle tracking also allows fleet operators to achieve just-in-time (JIT) deliveries, which minimise the time the vehicles are inoperational and help to contribute to lower congestion in urban areas (Miles and Chen, 2004). The image in Figure 2.2c is an example of a generic low-cost GPS vehicle tracking device.

Vehicle tracking allows the accurate management and efficient routing of work teams or assets between jobs sites (Jacobson, 2007). In many examples, commuter transit vehicles are tracked to provide accurate time of arrival information, allow real time management, and enable several safety applications (Kaplan and Hegarty, 2009). In the US, the Americans with Disabilities Act requires that transport authorities provide real time audible and visual information for those with sight

and hearing disabilities (Kaplan and Hegarty, 2009). Many of the public transport systems take advantage of low-cost GNSS vehicle tracking systems for this purpose.

GNSS receivers are widely used to track racing cars. The data is not only useful for recording lap times, but can be used to analyse vehicle performance throughout the lap and identify areas for improvement (when combined with other sensor data). The GNSS receiver also provides an accurate system of time synchronisation for other sensors. At the German round of the World Rally Championship in August 2005, the European Geostationary Navigation Overlay Service (EGNOS) was used to enhance the positioning accuracy of the on-board GPS receivers (Jacobson, 2007).

Law enforcement agencies and insurance companies have developed several systems designed for vehicle security. Vehicle tracking devices are popular with owners of premium cars, to protect their valuable asset and aid the recovery if it is stolen. Police forces in Los Angeles with the help of StarChase LLC developed a novel tracking device to assist them during high speed pursuits. A dart with embedded GPS receiver and radio communications was fired at the stolen vehicle. The vehicle could then be tracked safely from a distance. The image in Figure 2.2b is an example of a GPS dart.

Police forces are also assisted by GNSS timing in speed camera enforcement systems. Time-over-distance speed camera enforcement systems are now utilised to avoid the inherent issues of spot speed camera enforcement systems. Two cameras are set at a fixed distance along a stretch of road, and the time that a vehicle takes to travel the distance is measured. If the time is under the minimum achievable at the required speed limit, a speeding fine will be issued. Some of these cameras utilise GNSS receivers for accurate time stamping. An example camera is shown in Figure 2.2d.

2.2.3.3 Geo-fencing

Geofencing is an established concept, which has found prominence in Geographic Information Systems (GIS). Geo-fencing can be realised with the use of GNSS positioning devices in the automotive sector. Enforcement applications such as congestion charging schemes in city centres can utilise GNSS positioning for billing purposes. Many schemes have been theorised and tested, such as the pan-European Electronic Toll Collection (ETC) system, although the congestion charging scheme in Singapore is the first major project to adopt GNSS positioning for such an application (Singapore Land Transport Authority, 2014a). Geo-fencing is also used to alert operators when a vehicle exits or enters a predefined area.

2.2.3.4 Pedestrian tracking

For various modern applications, additional situational awareness is needed to correctly inform automated systems. This includes knowledge of the whereabouts of pedestrians, which is often provided by GNSS-enabled smartphones (which are prevalent in modern societies), or increasingly through other wearable smart devices such as watches or glasses with embedded positioning sensors, of which a low-cost GNSS receiver is one of the sensors. Identifying where pedestrians are in the network, is a sub-class of V2X called vehicle-to-pedestrian (V2P) applications (Jacobson, 2007; Basnayake, 2011).

2.2.3.5 Infrastructure timing

Timing has been an important aspect of transportation for centuries. Until John Harrison invented a clock in the 1770s capable of keeping London time accurate to 50 milliseconds per day over several months, sea navigation and the calculation of longitude was very difficult. GNSS satellites carry highly accurate atomic clocks for the generation of GNSS observation signals, which are ultimately used to calculate the satellite to receiver range. A side product of this range calculation is that the receiver is accurately time synchronised with the GNSS network and other users of the system (Jacobson, 2007). State-of-the-art hydrogen maser clocks on board GNSS satellite vehicles are capable of keeping time to better than 1 second in a million years. Modern communications

networks, internet protocols, and system calibrations now routinely rely on this accurate time source.

GNSS Electronic Payment Systems (EPS) have been suggested and promoted regularly since the relaxation of Selective Availability of GPS in 2001. The European Commission initiated the creation of the ETC system based on GNSS positioning and GSM communication technologies. The proposal was created, in part, to promote the use of the Galileo GNSS constellation.

The Swiss Performance-related Heavy Vehicles Fee (LSVA) has been operating in Switzerland since 2001 (Miles and Chen, 2004). This is a distance related road pricing scheme for heavy vehicles (those exceeding 3.5 tonnes), and uses a combination of Dedicated Short Range Communication (DSRC), GPS, and vehicle tachometer to measure the location of the vehicle and record the time, from which the distance travelled can be calculated. Singapore was the first city in the world to introduce an electronic road toll collection system aimed at congestion charging. The Electronic Road Pricing (ERP) system, which began in September 1998 and uses cameras mounted on overhead gantries, is due to be replaced by satellite positioning technology. The aging infrastructure of the ERP is increasingly difficult and expensive to maintain, and a GNSS positioning-based system is seen as fairer to motorists. An interactive and intelligent on-board unit (OBU) will support a number of value-added services including the application of congestion charging (Singapore Land Transport Authority, 2014a). It is anticipated that the new system will allow more tailored congestion charging for motorists, based on various factors such as distance travelled and time of day.

2.2.3.6 Mapping

Mapping is increasingly considered a key ingredient for ADAS and the next generation ITS applications. In particular, the near-real time information. For instance, a partnership between the Sat Nav manufacturer and mapping provider TomTom and tier 1 automotive supplier Bosch is looking to integrate mapping and navigation technologies more closely with ADAS technology (TomTom, 2014). Obtaining the most up-to-date map and navigation data is seen by the partnership as an essential component of ADAS, giving drivers a more detailed picture of the road ahead.

2.2.3.7 Intelligent Speed Adaptation

A selection of Intelligent Speed Adaptation (ISA) systems have made use of GNSS technology. During the world's largest Intelligent Speed Adaptation (ISA) trials between 1999 and 2002 in Sweden, GPS receivers were used to report the location of thousands of vehicles. The trials were operated by the Swedish National Road Administration, and were generally regarded as successful (Miles and Chen, 2004).

In the Flanders area of Belgium, the Flemish Traffic Centre carried out research into the use of Dynamic Intelligent Speed Adaptation in 2003 (Miles and Chen, 2004). The on-board technology made use of GPS receivers to report the vehicle's location to the traffic centre, where a digital speed map was interrogated and the appropriate speed limit reported back to the vehicle. Actuators on the accelerator pedals of the vehicles were used to enforce the speed limit.

2.2.3.8 Floating Vehicle Data systems

A Floating Vehicle Data (FVD) system utilises cellular devices in road vehicles to gather information about traffic congestion and travel times. The first major FVD system was established in 2000 by ITIS Holdings, which was subsequently acquired by Trafficlink, who have since been acquired by INRIX (INRIX Inc, 2014). FVD systems are used to monitor journey times by collecting floating vehicle data directly from probe vehicles. The system relies on GNSS positioning and GSM communication technologies (Miles and Chen, 2004).

The initial system relied on a small network of probe vehicles, which grew slowly but now has a database that increases by millions of vehicle miles per day. This enables real time traffic information applications, as well as historical assessment of traffic and congestion.

2.3 The future of driving and autonomous vehicles

The widespread prediction of a future dominated by flying cars has been a feature of tomorrow's world for over a century[2]. However, this clichéd prediction is unusual in that it has not yet become reality.

For a series of postcards in 1899, a group of French artists were asked to draft their predictions of the future (Hill, 2012). Amongst the transport-themed postcards were various flying vehicles, a rolling house, battle cars, and a most unusual whale bus. Each of these have become reality in the forms of drones, camper vans, tanks, and the airship (the modern version of the Hindenburg or Graf Zeppelin). Figure 2.3 shows some of these predictions alongside their modern equivalents.

[2]A good example is the commonly cited *Jetsons' flying car* when referring to future modes of transportation. *The Jetsons* was a cartoon series that originally ran from 1962 to 1963, but was set in the year 2062. The primary mode of transport was an aerocar that resembled a flying saucer. This premonition of future transport is particularly interesting as the *The Jetsons* has a strong track record in predicting future technology. Also present in the cartoon were flatscreen 3D televisions, newspapers on computer screens, video calling, a robot vacuum cleaner, a tanning bed, and a moving sidewalk that resembles the travelator commonly found in airports. All of these predictions became reality (Parekh, 2012).

Figure 2.3 – Predictions of future transport by French artists in 1899 and their modern real-world equivalents.

2.3.1 The future of driving

2.3.1.1 The shift away from traditional vehicle manufacturers

The motoring press regularly expresses its surprise at the lack of response to autonomous vehicle technology development from established vehicle manufacturers. Whereas large technology companies such as Google and Apple, and new vehicle manufacturers such as Tesla Motors (founded in 2003), are taking the initiative (Kuchinskas, 2012). At the same time, vehicle manufacturing in other parts of the world is catching up to that of traditional vehicle OEM's. In 2011, China became the world's largest vehicle manufacturer, overtaking Europe and North America (Malek, 2012).

The development of infotainment systems and services, and its inherent connected nature, may have a strong influence on the development of potential vehicle safety systems. This is evident from the recent foray into vehicle development from the US technology giants Google and Apple (Kuchinskas, 2012). The preferred communication mode is likely to be 4G LTE (Long Term Evolution) - due to its high data rates and smartphone compatibility - which will allow current business models to be adapted (Malek, 2012).

This new perspective from the vehicle purchasing consumer shows that their priorities are changing. A report published by ABI Research following a connected car consumer survey, stated (ABI Research, 2011):

> Among those who do not currently use any infotainment services, connected navigation was named as the most desired infotainment service by between 59% and 72% (extremely/very interested) in all countries except China, where the greatest interest was in concierge services.

This finding, from 2011, suggests that vehicle OEM's need to build infotainment systems around navigation. There was also a high awareness and interest in safety and security services. High costs and lack of awareness were things that would put people off.

The Consumer Electronics Association (CEA) believes that the car will become another tool in the 'seamless, connected experience no matter if you're home, walking down the street with a smartphone or behind the wheel' (Parmar, 2012).

2.3.1.2 Vehicle ownership

For many decades, the private purchase of a road vehicle has been seen as a sign of aspiration. It enables the free movement of people to engage in social and business activities previously impossible to achieve. As a major part of a country's transport infrastructure, it has been shown to drive economic growth and prosperity. However, this insatiable desire for private vehicle ownership is diminishing with the young population of developed nations. The appeal of the open road is a distant memory, due to traffic congestion, speed enforcement, and modern-day digital distractions. And in large cities, there are better transport alternatives to the car.

The car is not dead however. Some journeys are still only possible using a private vehicle. This has led to the development of car sharing or hire schemes. The individual will subscribe to a service that allows them to use a private vehicle on demand, in exchange for a small fee. Such schemes are popular with governments and city authorities, as they typically use modern, fuel efficient, and safe vehicles, and reduce the number of vehicles as a ratio of population. The success of these schemes has gathered attention from traditional vehicle manufacturers (Vlasic, 2011).

Helsinki in Finland aims to make private car ownership in the city pointless (Greenfield, 2014). A major transformation will see the existing transport network developed into a *point-to-point* system offering *mobility on demand*. The goal is to achieve the kind of multi-modal transport system that many have been working towards for many years - enabled through the smartphone. By focusing on connectivity, this forms a gateway to a generation no-longer concerned with the joys of motoring, and more concerned with environmental issues.

2.3.1.3 V2X and connected cars

The EU will implement its eCall system in 2018. This initiative will require all new vehicles sold in the EU to be equipped with a device that will contact the emergency services in the event of an accident (Digital Agenda for Europe, 2015). A *Minimum Set of Data* is sent from the car to a data centre - including the vehicle's position - and opens a voice channel to enable the data centre operator to communicate with the vehicle's passengers. Several independent systems are currently operated by vehicle manufacturers such as BMW, Peugeot, and Citroën. The US and Russia are also due to implement their own systems, termed E911 and ERA respectively.

In the US, the National Highway Traffic and Safety Administration (NHTSA) recently commented that connected car technology 'can transform the nation's surface transportation safety, mobility and environmental performance', with industry experts predicting the widespread uptake of the technology within 5 to 6 years (Partyka, 2013). This provides an opportunity for road vehicles to share GNSS information.

The US federal government carried out a trial in Ann Arbor, Michigan, which aimed to pilot connected vehicle technology (from August 2012). The Connected Vehicle Safety Pilot Program tested everything from the enabling technology to human factors and government policies, in order to better understand the safety benefits of connected vehicles (United States Department of Transportation, 2015). The study equipped 3,000 vehicles with devices and was originally anticipated to last one year, but was extended by six months to further explore the issues.

In a related action in August 2014, the NHTSA announced its rule making intention regarding V2V communications technology (Howden, 2014). As part of the announcement, the NHTSA stated:

> Safety is our top priority, and V2V technology represents the next great advance in saving lives.

Road vehicle platooning has been successfully demonstrated by the SARTRE project (Safe Road Trains for the Environment, funded by the European Commission under the Framework 7 programme) (SARTRE, 2009). This innovative project outlines the major benefits of vehicles working together on unmodified roads in order to lessen the negative impacts of road vehicles, in particular on the environment. The basic principle is that 'the following vehicles repeat the motion of the lead vehicle', and it is implemented through the use of current and new technology; mainly radar sensors and data links. The technology has gained widespread interest.

2.3.2 Autonomous vehicles

Research and development into advanced vehicle autonomy has progressed from trying to minimise the negative effects of road transportation towards preventing them altogether. For instance, personal passenger vehicles available in 2013 generally come equipped with multiple airbags, some form of traction control, anti-lock brakes (ABS), and generous crumple zones, which all help to minimise the impact of accidents.

Many vehicle manufacturers now offer vehicles equipped with ADAS, such as adaptive cruise control and lane assistance. This is typically enabled through the combination of radars and camera systems. Manufacturers such as Volkswagen Group, Volvo Group, Daimler AG (Mercedes-Benz), and Ford offer these systems - giving drivers a taste of vehicle autonomy.

The logical conclusion to this development is the autonomous car. The concept has been discussed for decades, but took a significant step forward when the Defense Advanced Research Projects Agency (DARPA) organised the DARPA Grand Challenge in 2004. It aimed to demonstrate the technical feasibility of autonomous vehicles over a 150 mile route. In the first year, the most successful team only managed to cover seven miles. However, the following year five teams completed the course.

A second challenge was organised in 2007, but this time the course was designed to represent urban driving. The DARPA Urban Challenge required autonomous vehicles to obey traffic rules, and navigate around obstacles and other road users (human drivers and other autonomous vehicles). The winners of the Grand and Urban Challenges are shown in Figure 2.4.

Figure 2.4 – The winners of the DARPA Grand (left) and Urban (right) Challenges.

Members from the team that won the Grand Challenge, and were runners-up in the Urban Challenge, went on to work for Google on their autonomous vehicle project, detailed further in Section 2.3.2.4.

Most major passenger vehicle manufacturers are developing some form of autonomous vehicle. Volvo, Mercedes-Benz, Nissan, and General Motors have all announced their plans to sell autonomous vehicles before 2020. More details are described in Section 2.3.2.4.

Legislators are also working towards providing the environment for autonomous vehicles. European and US national and local governments have generally moved towards enabling vehicle autonomy, and the United Nations recently amended Article 8 of the Convention on Road Traffic to allow autonomous vehicles to operate. Several US states have enacted bills to regulate autonomous vehicle licensing and operation, and the European Commission has provided significant funding for autonomous vehicle research.

According to Lux Research, the autonomous vehicle market will be worth an estimated US$87 billion (£54 billion) by 2030. Although this is still only 8% of the automotive market (Jacques, 2014).

2.3.2.1 Terminology

Different terms are used by different groups to describe autonomous vehicles. The most common term is *driverless car*, which is widely adopted in the popular press (much like horseless carriage was used when the first motorcar was developed), but generally disliked by the ITS industry as it is reminiscent of a runaway car. The term *self-driving car* is more popular with developers when describing the concept to the layman. In early research and development the most common term was *autonomous vehicle*, an extraction from *Unmanned Ground Vehicle* (UGV) and *autonomous UGV* from military research. The terms *automated road vehicle, robotcar* and *robocar* are also used, depending on the preference of the author and the particular technology under discussion.

2.3.2.2 History

Attempts to build road vehicles that involve some element of autonomy have been in development since the 1930s, with the General Motors' automated vehicle highway system concept at the 1939 World's Fair (Bishop, 2005). Generally, the early approach was to adapt the highway infrastructure as well as the vehicle, such as the Automated Highway Systems (AHS) developed by the California State Department of Transport (Caltrans) in the 1980s and 1990s. This research culminated in 1997 with Demo '97, an exercise on Interstate Highway 15 in San Diego[3] (Miles and Chen, 2004). Twenty autonomous vehicles used various technologies to drive autonomously, including vision-based techniques, magnetic nail and radar reflective strip following, and lidar headway measurement (Thorpe et al., 1997). An image from the trial is shown in Figure 2.5.

[3]Officially called the National Automated Highway Systems Consortium Technical Feasibility Demonstration. Held in August 1997 in San Diego, California.

Figure 2.5 – An image from the Automated Highway Systems trials in Demo '97, San Diego, 1997.

Despite the success of Demo '97 the focus of transport research in the US shifted towards improving road safety, primarily due to budget constraints (Miles and Chen, 2004). However, research in this field has increased rapidly over the past decade, due to the significant improvements in computer processing speed. This enables techniques that were previously only theoretical, such as the real time processing of images and laser scanning measurements. This has also moved the focus away from adapting the highway infrastructure towards technologies that allow the vehicle to navigate alongside non-autonomous vehicles. Recent examples of these vehicles are shown in Figure 2.6 and described in Section 2.3.2.4.

2.3.2.3 Potential benefits

The benefits of autonomous vehicles are significant, and often undersold. Small progress steps are typical in the automotive sector - such as the slow impact on road safety following the introduction of seat belts and anti-lock brakes - due to the relatively long design cycle and replacement of existing vehicle stock. A comparison is often made to the smartphone market, where technology improvements are much more rapid, due to the short product design and life cycle.

The largest impact would be from the transfer of vehicle command from the human to a computer. Of the 5.5 million road accidents every year in the US, it is estimated that 93% are primarily caused by the human driver. The economic cost of the road accidents is estimated at US$300 billion (£186 billion) (Fagnant and Kockelman, 2014). The major causes of fatal road accidents include (in some cases multiple causes are stipulated):

- Alcohol use (31%);
- Speeding (30%);
- Distracted driver (21%);
- Failure to stay in lane (14%);
- Failure to yield the right of way (11%); and
- Wet road surface (11%).

Autonomous vehicles can be programmed to adhere to traffic laws. They do not drink and drive. Their reaction times are quicker and they can be optimized to smooth traffic flows, improve fuel economy, and reduce emissions.

A detailed study of the potential benefits, risks, and costs of autonomous vehicles is made in Fagnant and Kockelman (2014). It summarises that the potential economic benefit to the US economy would be US$450 billion (£280 billion) with a 90% market penetration. This would also save a staggering 22,000 lives per year in the US. Worldwide there are 1.2 million people killed on the roads every year, which would make the global impact of autonomous vehicles significant (World Health Organisation, 2013).

Some of the less obvious benefits include the reduction in vehicle insurance premiums, likely to decrease from 4 pence per mile to less than 1 penny per mile. In the US, there is an accident for every 250,000 miles driven, which is anticipated to be much farther for autonomous vehicles. Dedicated lanes for autonomous vehicles would require less infrastructure, as the vehicles could follow wheel tracks. There would be less requirement for roadworks, and rubbernecking whilst passing other accidents would not be an issue for a computer driven vehicle. The demographic make up of the driver population would change, as typically higher risk drivers such as the young and old would find their transport flexibility increase, and legislation to limit their human driving ability would be more palatable (such as increased driving limits or medical examinations) (Fagnant and Kockelman, 2014).

2.3.2.4 Examples in major press

The most successful examples of autonomous vehicles use either lidar or visual cameras (Gross, 2010). The following three examples are widely reported by general news sources.

Google self-driving vehicle.

Up to May 2014, their vehicles have covered a distance of 700,000 miles autonomously (Urmson, 2014). An example of a Google autonomous vehicle is shown in Figure 2.6a. One of Google's founders, Sergey Brin, answered a question at a press conference in 2012 by suggesting that the public will be able to access this technology within 5 years (O'Brien, 2014). More recently, Google announced its intention to carry out a pilot study using 100 fully autonomous vehicles (Markoff, 2014). These small, light-weight, two passenger vehicles will not have driver controls, and they are powered by a small electric motor that provides a range of approximately 100 miles. The prototype is shown in Figure 2.6b.

Robotaxis in Singapore.

Singapore's Land Transport Authority (LTA) is to study the viability of autonomous vehicles as *Robotaxis* (Singapore Land Transport Authority, 2014b). The study - based on earlier research that culminated in the development of an autonomous vehicle using low-cost, off-the-shelf lidar sensors (Spieser et al., 2014) - will determine the feasibility of replacing all of the city's passenger vehicles with autonomous vehicles. This could reduce the number of vehicles in the city by 70%.

Volvo Drive Me.

Volvo aims to introduce an autonomous vehicle as early as 2017 (Tannert, 2014). The Drive Me pilot project includes an everyday Volvo S60 test vehicle that looks very similar to the standard model. Existing technology that is already available on Volvo models, such as Adaptive Cruise Control (ACC) and steering assist, is paired with additional terrestrial sensors (forward-facing camera, laser scanner, radar and sonic sensors) and two unobtrusive GPS antennas. The project will utilise 100 of these fully autonomous vehicles in real-world tests on selected roads in Gothenburg, Sweden. An example of a Volvo Drive Me vehicle is shown in Figure 2.6c.

a). Google self-driving research car.

b). Google light autonomous vehicle.

c). Volvo Drive Me autonomous vehicle.

Figure 2.6 – Examples of autonomous vehicles.

2.3.2.5 United Nations' 1968 Convention on Road Traffic

A major hurdle to overcome before the widespread adoption of autonomous vehicle technology was Article 8 of the United Nations' 1968 Convention on Road Traffic . This required that:

1. Every moving vehicle or combination of vehicles shall have a driver.

And:

5. Every driver shall at all times be able to control his vehicle or to guide his animals.

Clearly this was outdated, and meant that the 72 countries who were party to the convention could not introduce vehicles that allowed the driver to remove their hands from the steering wheel. However, in May 2014 the UN Working Party on Road Traffic Safety introduced an amendment to Article 8, which allows the driver to remove their hands from the steering wheel of an autonomous vehicle, as long as the driver remains present and is able to re-take control of the vehicle as he or she deems appropriate. The amendment reads:

> 5bis. Vehicle systems which influence the way vehicles are driven shall be deemed to be in conformity with paragraph 5 of this Article and with paragraph 1 of Article 13, when they are in conformity with the conditions of construction, fitting and utilisation according to international legal instruments concerning wheeled vehicles, equipment and parts which can be fitted and/or be used on wheeled vehicles.
>
> Vehicle systems which influence the way vehicles are driven and are not in conformity with the aforementioned conditions of construction, fitting and utilisation, shall be deemed to be in conformity with paragraph 5 of this Article and with paragraph 1 of Article 13, when such systems can be overridden or switched off by the driver.

Article 13, paragraph 1 of the original Convention reads:

> 1. Every driver of a vehicle shall in all circumstances have his vehicle under control so as to be able to exercise due and proper care and to be at all times in a position to perform all manoeuvres required of him. He shall, when adjusting the speed of his vehicle, pay constant regard to the circumstances, in particular the lie of the land, the state of the road, the condition and load of his vehicle, the weather conditions and the density of traffic, so as to be able to stop his vehicle within his range of forward vision and short of any foreseeable obstruction. He shall slow down and if necessary stop whenever circumstances so require, and particularly when visibility is not good.

2.3.2.6 Levels of automation

The Society of Automotive Engineers (SAE) in the US has released an information report from their On-Road Automated Vehicle Standards Committee, which contains a useful set of levels of driving automation. Table 2.1 lists the six levels of driving automation. As the levels increase, there is less interaction with the human driver, and more reliance on the control system (Smith, 2013). Similar sets of levels are provided by the NHTSA and Germany's Federal Highway Research Institute (BASt), and are also listed in the table. Each set of levels is broadly in line with the others. It should be noted that these levels are not a guide to development or evolution of vehicle autonomy, and that technology development could deliver level 4 driverless vehicles without passing through the previous levels. Examples of vehicle autonomy can also span different levels. It can also be misleading to state level 5 as the end goal, as it has not been determined whether such a system would be desired or would be financially viable.

Table 2.1 – The SAE summary of levels of driving automation.

Level	Name	Definition	NHTSA level	BASt level
Human driver monitors the driving environment				
0	No automation	Driver is in complete control, but may have additional help from warning or intervention systems.	0	Driver only
1	Driver assistance	Individual driving tasks may be performed by the system (for example, steering or acceleration), using information from the environment.	1	Assisted
2	Partial assistance	The system executes multiple driving tasks (for example, steering and acceleration), with the driver performing all remaining aspects.	2	Partially automated
Automated driving system monitors the driving environment				
3	Conditional automation	The system performs automated driving, with the human expected to intervene as requested.	3	Highly automated
4	High automation	The system performs automated driving, even when the human driver does not respond to a request to intervene.	3 or 4	Fully automated
5	Full automation	Full automated driving under all conditions that can be managed by a human driver.	4	

2.4 V2X

Enabling road vehicles to communicate between themselves, the local infrastructure, and the wider environment, is generally expected to deliver the next major safety advancement in ITS Neale et al. (2005). The principles and technology is similar to that of the IoT, occasionally referred to as the Internet of Vehicles (IoV) in this context (Nanjie, 2011). Many decades of research has looked at the benefits of communication to vehicle and road safety, and although not widely implemented in today's vehicles, many candidate communication technologies are now fighting it out to provide the solution.

Communication between agents in the road transport environment is slowly becoming a reality. Recent announcements from the NHTSA in the US, and CEN and the European Telecommunications Standards Institute (ETSI) on behalf of the European Commission, show that governing bodies are moving towards legislation for Cooperative ITS (C-ITS). Vehicle manufacturers also see the benefit of V2X, such as Volvo's study regarding road condition monitoring and subsequent hazard warnings to surrounding vehicles, and platooning research carried out with heavy goods vehicle manufacturer Scania.

It has long been anticipated that the communication mode of choice will be Dedicated Short Range Communication (DSRC), using short- to medium-range wireless communication channels around 5.8 to 5.9 Gigahertz (depending on geographic location). Current commercial use of this technology includes ETC in Japan and ERP in Singapore. Significant improvements to road safety, pollution, congestion, and related economic benefits, are expected to be delivered through DSRC implementation. However, widespread use of DSRC is not expected until approximately 2030. This provides a significant opportunity for cellular communications to be established as the primary communications medium for V2X applications, and the development of the standards for the fifth

generation of cellular communications suggests that peer-to-peer applications such as V2X are under significant consideration. There could also be a hybrid communication mode between cellular and DSRC will help to enable many V2X applications.

This close communication between neighbouring road vehicles offers additional benefits for GNSS positioning. Fundamentally, nearby GNSS receivers share many of the same systematic error sources, such as atmospheric errors, and are likely to be receiving signals from the same GNSS satellites. This means that innovative solutions can be used to combine the GNSS information, and provide more accurate and reliable positioning solutions, and crucially provide higher availability than current implementations.

2.4.1 V2X terminology

V2X systems are often called connected vehicles, cooperative driving, cooperative ITS (C-ITS), or car-to-car (C2C). The US tends to favour the term V2X, whereas EU funded projects vary usage but have recently moved towards C-ITS.

Connected car is not a synonym for V2X, as it purely relates to a vehicle that has a connection to the internet. The connected car is part of the Internet of Things.

2.4.2 Vehicle-to-vehicle and vehicle-to-infrastructure

Real time vehicle localisation is one of three key enabling technologies for the concepts of vehicle-to-vehicle and vehicle-to-infrastructure (V2V and V2I, collectively termed V2X), a classification of ITS. The further enabling technologies are ad-hoc dynamic networking of agents and accurate local traffic maps (Meng et al., 2008). The position must be accurate, reliable, available, and continuous, as described in the RNP (Ochieng et al., 2003; International Civil Aviation Organization, 1999).

V2X technology is a natural evolution in road transport that has been claimed to be 'the next major safety breakthrough' (Consumer Reports, 2012). The concept moves away from vehicles making individual decisions about road safety (such as in ADAS), towards a cooperative driving approach that further shifts the emphasis from collision protection to collision prevention. A graphical representation is shown in Figure 2.7.

In the EU, the European Commission published a White Paper in 2011 stating aims to reduce transport emissions by 60% by 2050, partly through intelligent mobility that will improve the flow of transit, and the efficient use of infrastructure and communications networks (European Commission, 2011).

With technology currently available, it is more accurate and reliable to share the position and velocity information between vehicles (that may be out of sight of each other or hiding around the corner), than trying to measure this information with vehicle borne sensors (such as with vision and terrestrial measurement devices). Other information about the state of the vehicle can also be transferred including data about the condition of the road ahead - such as whether the road surface has low traction or that there is traffic congestion - allowing the vehicle to enhance its situational awareness. Vehicles in V2X applications require ubiquitous positioning, operating in environments ranging from highly developed regions with dense infrastructure and communications networks to areas of undeveloped dirt tracks in barren landscapes. Satellite-based positioning is a strong contender that can deliver widely available absolute positioning globally.

According to the NHTSA, such a system has the potential to help drivers avoid or minimize up to 80% of crashes involving unimpaired drivers, and describes it as a natural evolution in automotive safety development (Consumer Reports, 2012):

> The past 50 years have been about surviving vehicle crashes; the next 50 will be about preventing them.

The US is a particularly unique example in that many collisions and fatalities occur at road intersections, due partly to the historically inadequate prioritisation and drivers who like to take a chance.

Toyota's manager of safety and quality communications describes the change in safety system development (Consumer Reports, 2012):

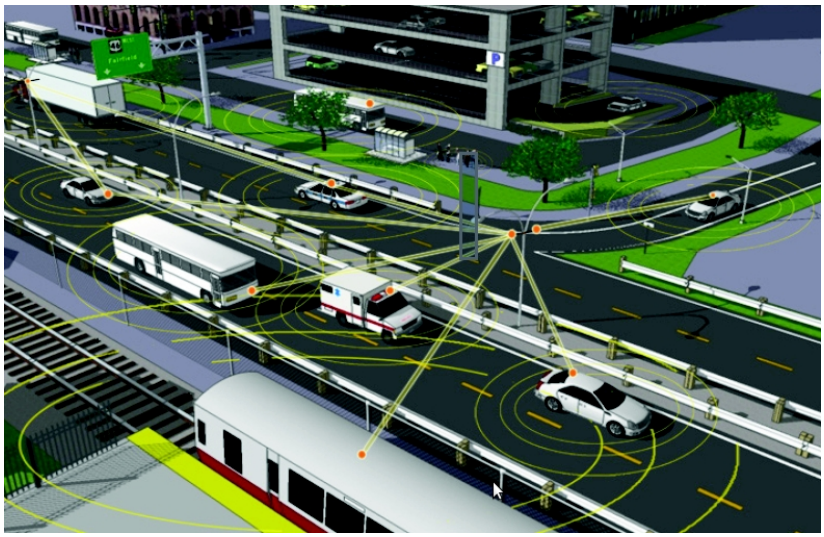


Figure 2.7 – Graphical representation of V2X.

> "The first phase was about passive systems—air bags and so on... The second was about active safety, including electronic stability control, collision-avoidance systems, etc. The third phase will be about car-to-car communication that can dramatically reduce the number of crashes on our roads."

Anecdotal comments by NHTSA experts and driver assistants at the clinics in the Ann Arbor pilot study indicate that V2X is being well received.

Consumer Reports (2012) outlines the limitations of current safety systems, and how V2X systems can decrease the number of false positives that beleaguer current systems:

> Because current collision-warning systems have a narrower field of view, they probably wouldn't be able to give you advanced warning of, say, a stopped car around a bend, with the same effectiveness as a V2X system. Our auto experts note that getting a direct feed of a car's location and speed is more accurate than having to guess that from cameras and radar.

NHTSA experts say even a low level of vehicle penetration will provide safety benefits, although in the US this is particularly evident from the high number of accidents that occur at road intersections.

The connectivity concept often includes other road users, such as pedestrians, cyclists, heavy goods vehicles (HGV), and public transport vehicles (for instance, trains, buses, and trams). This has spawned additional terms such as V2P (vehicle-to-pedestrian) and V2C (vehicle-to-cyclist). This has expanded the collective term V2X.

2.4.3 VANET

The Vehicular Ad-hoc NETwork (VANET) concept is a special form of a Mobile Ad-hoc NETwork (MANET), where the nodes are vehicles. The vehicles can communicate with each other and local infrastructure without support from dedicated communication infrastructure. The aim of a VANET is to enable the rapid distribution of data between vehicles to provide safety, efficiency, navigation, and driver comfort applications (Lèbre et al., 2014).

Due to the increased interest in VANETs from research and commercial organisations, the Institute of Electrical and Electronics Engineers (IEEE) has created an amendment to the IEEE 802.11 standard to allow wireless access in vehicular environments (WAVE). The Wi-Fi amendment 802.11p suggests that data transmission delays are of the order of tens of milliseconds for high priority data. In the UK, the 5.9 Gigahertz frequency band is reserved for road safety applications (Lèbre et al., 2014), which is compatible with 802.11p.

The survey review carried out by Karagiannis et al. (2011) provides a thorough overview of the projects using VANET's in the US, Japan, and throughout Europe.

2.4.4 Connected cars and V2X in commercial production

The great body of academic and industry research into connected cars and V2X technology is rapidly developing into production vehicles that carry such connectivity. General Motors have announced that their first intelligent connected vehicle is due to enter the market by the end of 2016. The Cadillac CTS Sedan will be the company's first V2V system enabled car in the 2017 model year. The system has been developed by Delphi Automotive using software from Cohda Wireless.

2.5 Vehicle localisation requirements

Vehicle borne ADAS technology is developed and tested by vehicle manufacturers and their suppliers. Some of the systems are independently tested by organisations such as Euro-NCAP and Thatcham, and scored for the benefit of consumers and insurance providers (Thatcham, 2014). The most common ADAS performance tests regard Autonomous Emergency Braking (AEB).

Positioning based systems such as route guidance do not specify their positioning accuracy, but state subjective claims such as being able to correctly identify the road on which the vehicle is travelling. Testing and designing vehicle positioning systems requires localisation requirements for different ITS and ADAS applications - for instance, vehicle platooning has different requirements to accident black spot notification.

Existing ITS and ADAS standards are varied, and do not specify the positioning requirements for specific location-based applications. For instance, ETSI has published extensive guidance regarding V2X communication (including the communication of positioning information) (European Telecommunications Standards Institute (ETSI), 2015). The SAE, the NHTSA, and BASt have each defined the levels of automation for autonomous vehicles (see Section 2.3.2.6 and Table 2.1).

Further details can be found in Chapter 3, and a list of application requirements is found in Table 3.5.

2.6 ITS applications

In order to determine the localisation requirements for ITS applications, current ADAS that require position information will be examined. GNSS positioning may not be the only sensor used in these systems, but it will help to define the positioning parameters. For a discussion about vehicle movement and driver behaviour, refer to Chapter 3.

2.6.1 Current applications

A number of ADAS technologies are being implemented in current private passenger vehicles. The enabling technology is typically some form of terrestrial measurement, such as radar, lidar, or visual cameras, although GNSS receivers are sometimes used to provide positioning data for these applications. The following are examples of some of the applications that use ADAS technologies.

Black spot or hotspot warning.

In this application, a warning is provided to the driver about an area that is susceptible to vehicle accidents. This type of hazard may be created from real time data, but is primarily defined by historical trends. Figure 2.8 shows a graphical representation of the application. As shown in Table 3.6, the level of positioning accuracy is low (5 metres), which is similar to that required for basic navigation, but additional information is required beyond digital map data. The update rate at which warnings are provided needs to be 10 Hertz, in order to ensure the time to event accuracy of 1 second is met. The application is not considered safety critical, as the driver is in full control

of the vehicle's movements, and a failure of the system would only slightly increase the risk of an accident.

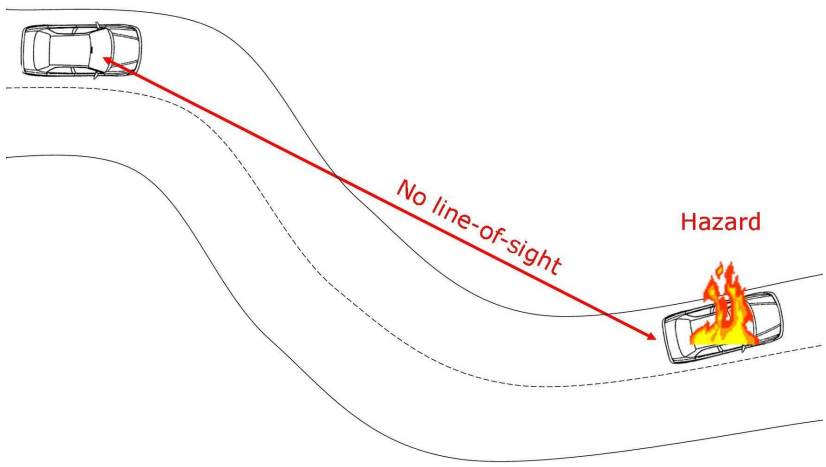


Figure 2.8 – Black spot or hotspot warning.

Blind spot warning.

A common source of vehicle accidents is vehicle lane changing. Rear visibility from vehicles is fundamentally poor, as it is provided either by using rear-facing mirrors or by the driver physically turning to face the rear direction. A blind spot area exists in which following vehicles are not visible to the driver. Typically, this zone extends 1.5 to 6 metres behind vehicle, but within 4.8 metres - hence covering a short section of the adjacent lane. Figure 2.9 shows the blind spot of a vehicle, and the typical dimensions and road layout in the UK.

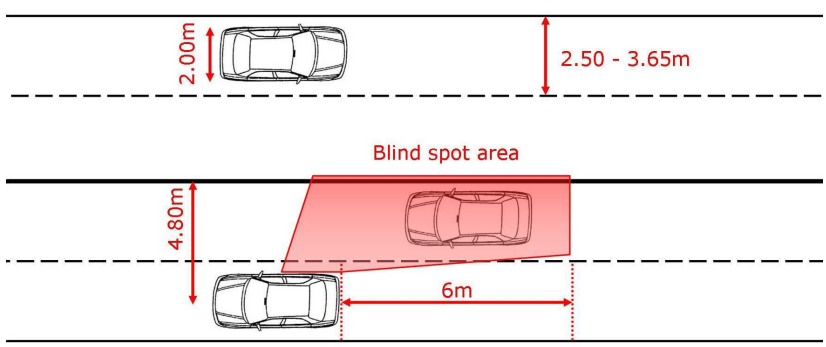


Figure 2.9 – Blind spot warning.

Table 3.6 shows the positioning performance requirements for such a blind spot warning system. These requirements are based on the road dimensions in Figure 2.9, which includes providing a warning of an object in the blind spot (within 6 metres of the rear of the leading vehicle) and in the outside lane (within 4.8 metres). Due to the relatively close proximity of the vehicles in such a situation, the possible absolute and relative velocities, and the driver's reaction time, the positioning accuracy of a blind spot warning system is 0.7 metres. This translates into a heading accuracy requirement of 0.2 degrees, and a position update rate of 100 Hertz.

Overtaking vehicle warning.

The judgement of the speed of a vehicle approaching from behind is made difficult by limited rear visibility, and the two-dimensional view provided by rear view mirrors (distances are estimated based on experience and the relative position of objects). As shown in Figure 2.10, the danger is present when a vehicle wishes to move lanes and the vehicle approaching from behind may enter the blind spot area. Given a minimum time to reaction of 1.25 seconds, the leading driver needs to be aware of any vehicle approaching from behind in the range of 6 to 70 metres. This is due to the relative speed of the two vehicles ranging from 8 kph to 36 kph (2.2 - 10 m/s), the reaction time of the drivers, and the time required to safely slow the following vehicle.

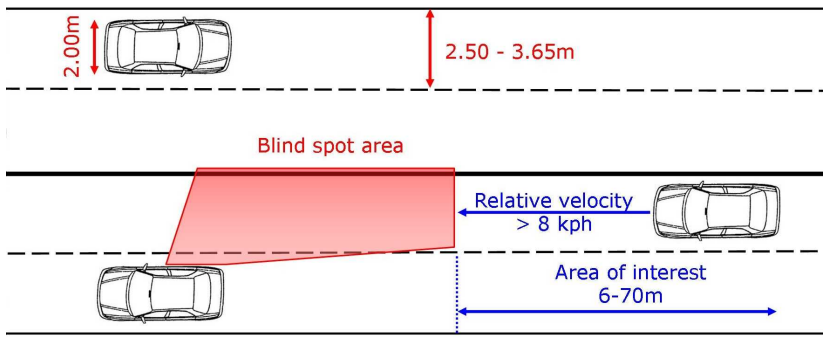


Figure 2.10 – Overtaking vehicle warning.

Inter-vehicle hazard warning.

A basic version of this application is commonly used by drivers using Sat Nav devices with real time data connections to traffic notification services. Following an incident on the road network, and a brief validation process to confirm the authenticity (now more commonly completed through crowd sourcing), a notification is delivered to all relevant road users.

In the V2X concept this process would be much faster. An incident occurring on the route ahead would be immediately relayed to all surrounding vehicles. This would significantly alter the benefit of hazard warning, from notification of incidents in order to improve journey times to the notification to improve the road safety. For instance, the notifications could include details about slippery road surfaces or foreign objects in the road.

As shown in Figure 2.11, the inter-vehicle hazard warning approach could be to push the data to any and all nearby vehicles (one way communication), or to push and pull data with specific vehicles (for instance, vehicles in convoy or using the same route). More details regarding V2X can be found in Section 2.4 and Chapter 6.

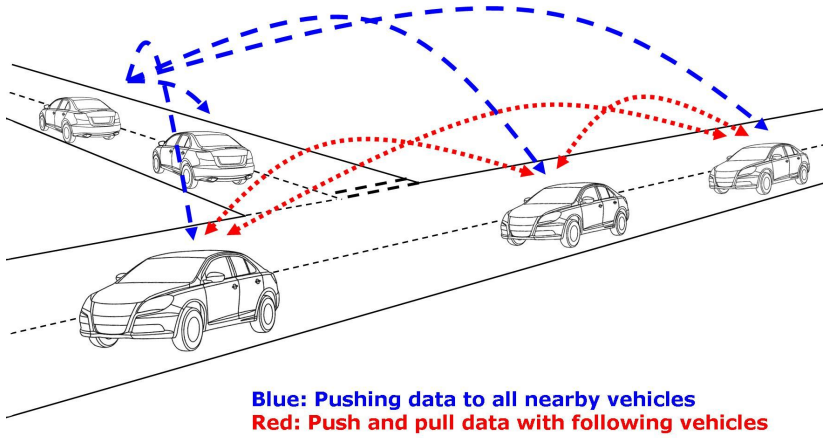


Figure 2.11 – Inter-vehicle hazard warning.

Active braking or forward collision avoidance.

This application is now commonplace on new passenger vehicles, and is not limited to high-end models. Due to the fundamental constraints of road vehicle movements - vehicles generally drive in lanes and follow other vehicles - the automated control of relative speed can help to minimise or avoid forward collisions. As shown in Figure 2.12, a vehicle travelling behind another vehicle requires 10 metres to avoid a collision if the relative speed is 50 kph (13.9 m/s). However, a driver also requires 17.4 metres to react to any unexpected event (1.25 seconds) if a warning system is to be employed. This additional time and distance is why automated braking and forward collision systems have become popular on modern vehicles - the automated system reacts immediately to events and stays vigilant. In the example shown in Figure 2.12, the following vehicle would be able to safely reduce the headway distance by over half.

Clearly, any automated or warning system requires a high positioning accuracy and a high update rate. As shown in Figure 2.12, a position accuracy of 1.4 metres translates to 0.1 seconds at 50 kph (13.9 m/s), and correspondingly an update rate of 0.1 seconds (10 Hertz) translates to a position accuracy of up to 1.4 metres. In modern passenger vehicles, the preferred technology for inter vehicle distance measurement is radar. Radar allows the range measurement to be made at a very high rate, with a maximum range of approximately 200 metres.

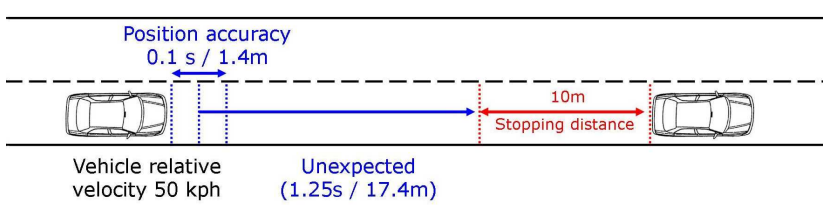


Figure 2.12 – Forward collision avoidance.

Lane departure.

The majority of lane departure warning (LDW) systems on passenger vehicles use camera measurements (Bevly and Cobb, 2010). However, lidar systems can be used to determine the lane

position, and additionally provide three dimensional ranging information. An example of the LDW concept is shown in Figure 2.13, which shows the terrestrial scanning principles used to detect lane markings.

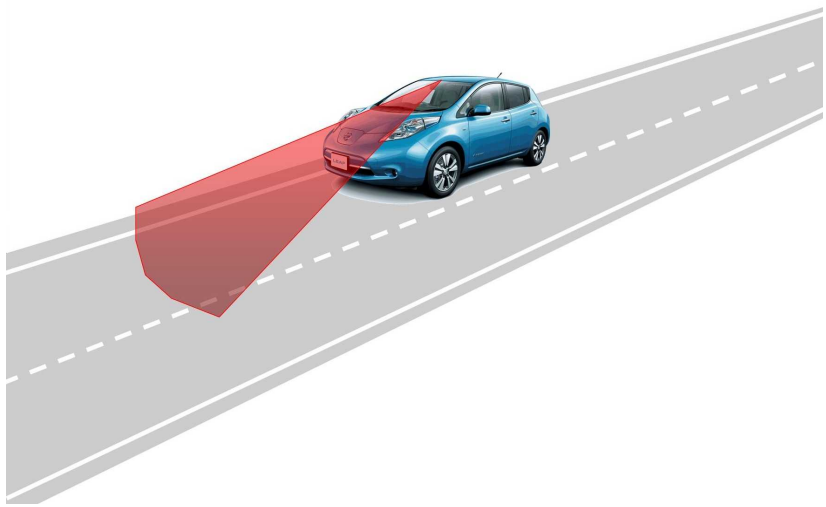


Figure 2.13 – The concept of lane marking scanning in a lane departure warning system.

A LDW system must determine whether the vehicle is departing the lane at an instant, or is predicted to depart in the very near future. If the vehicle is travelling at 50 kph (13.9 m/s), the vehicle will depart the lane if the tangential angle between the vehicle trajectory and the lane boundary is greater than 5.31 degrees. This assumes that the driver reaction time is 0.7 seconds (the standard reaction time to an expected event). As the vehicle velocity increases, this tangential angle decreases, so that by 250 kph (69 m/s) the maximum angle is 1.06 degrees. Another measurement to consider is the lateral movement of the vehicle in relation to the lane boundary. Assuming typical lane and vehicle dimensions, the clearance between the vehicle and the lane boundary is 0.9 metres. The driver reaction time is 0.7 seconds, which makes the maximum lateral velocity 1.2 m/s, as the vehicle will have moved laterally 0.84 metres during the driver reaction time.

Figure 2.14 shows the general dimensions that need to be considered in a LDW system. The intersection angle *(ϑ)* of the vehicle trajectory and the lane boundary is important in the determination of a probable lane departure. The intersection angle threshold ϑ_{max} is a factor of the vehicle velocity, vehicle and lane dimensions, and driver reaction time. If the measured intersection angle is greater than the threshold ($\vartheta > \vartheta_{max}$) then there is a strong probability that the driver will not be able to react in time to avoid a lane departure. The ϑ_{max} equation is shown in Equation 2.1, where: α is the angle between the longitudinal and lateral directions of travel; υ is the velocity of the vehicle in the longitudinal direction (m/s); t_r is the reaction time of the driver (seconds); and c_l is the clearance between the vehicle and the lane boundary (metres).

$$\theta_{max} = \alpha - sin^{-1}\left(\left(\frac{sin\,(\alpha)}{(\upsilon.t_r)}\right).\sqrt{(\upsilon.t_r)^2\,.\,(c_l)^2}\right) \tag{2.1}$$

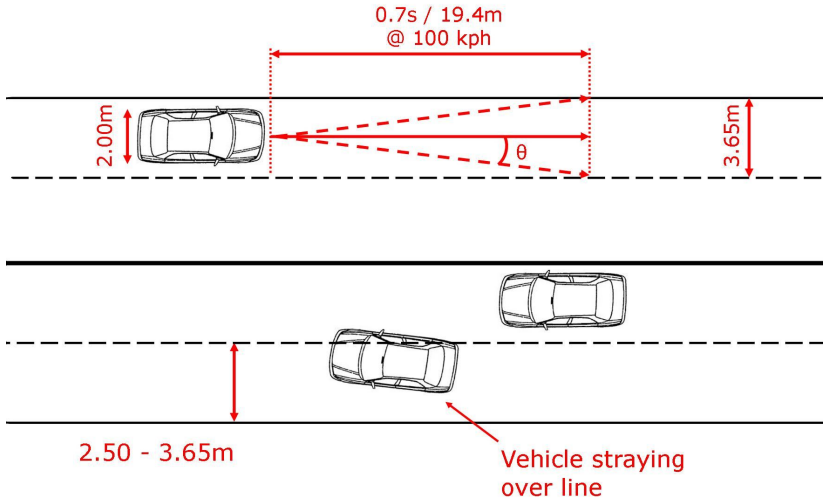


Figure 2.14 – The movement of a vehicle prior to a lane departure.

2.6.2 Future applications

The following is a selection of future ITS applications, or those that are starting to enter the consumer market.

Vehicle platooning or Adaptive speed control.

Vehicle platooning has been a popular research application for many years. There are numerous advantages to platooning vehicles, including increased fuel efficiency, reduced workload for drivers, and increased road capacity as shown in Figure 2.15. In normal conditions, the minimum safe vehicle headway is approximately 40 metres at 100 kph (27.8 m/s). If vehicles can travel in a convoy or platoon this headway can be greatly reduced. For instance, in Figure 2.15 the headway is reduced to 2 metres. This significantly increases the number of vehicles that can use the available road space.

The best known examples of this application are the Demo '97 research demonstration (Thorpe et al., 1997) and the European SARTRE project (SARTRE, 2009). Each project successfully demonstrated vehicle platooning. The success of the SARTRE project has led to further research in the COMPANION project led by Scania, a leading manufacturer of trucks and buses. A similar approach has been made in Japan, where the New Energy and Industrial Technology Development Organization (NEDO) have demonstrated truck platooning with a 4 metre gap at 80 kph (22.2 m/s) (Ashley, 2013).

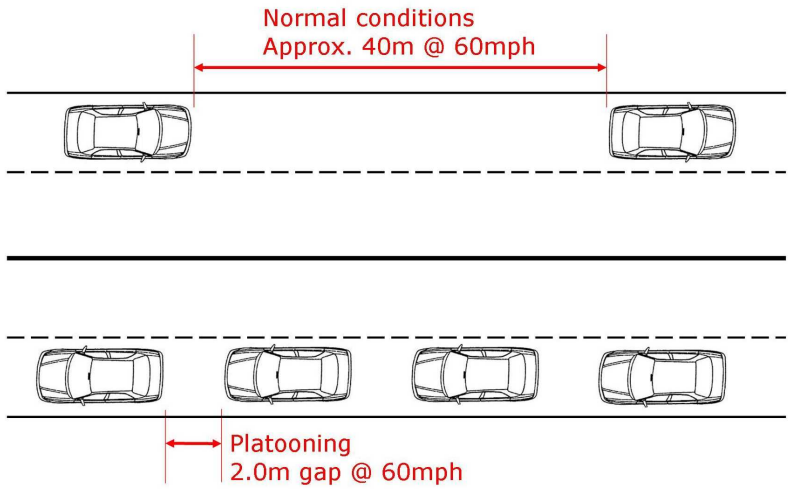


Figure 2.15 – Vehicle platooning.

Motorcycle lane position at curves.

The in-lane position of a motorcycle is an important factor when riding around a corner. Simple physics demonstrates that the angle of approach, speed, and weight of the motorcycle determines the exit trajectory. The most dominant factor is Newton's first law of motion:

> Every object persists in its state of rest or uniform motion in a straight line unless it is compelled to change that state by forces impressed on it.

For motorcycle driving this translates as the faster the motorcycle is travelling, the less it is willing to turn. Other factors such as the lean of the vehicle and the tyre to road contact area determine the possible rates of acceleration or deceleration (known as the tyre grip trade off). As shown in Figure 2.16, if the motorcycle is travelling too fast or positioned on the inside of the lane whilst approaching a corner there is the potential for a lane departure and possible collision. Yet if the motorcycle was positioned towards the outside of the lane, it would be possible to safely negotiate the corner at the original speed.

The investigation of these issues was carried out in the SAFERIDER project (SAFERIDER, 2010), where rider warnings were issued. These included speed alert, curve warning, frontal collision warning, lane change support, and intersection support.

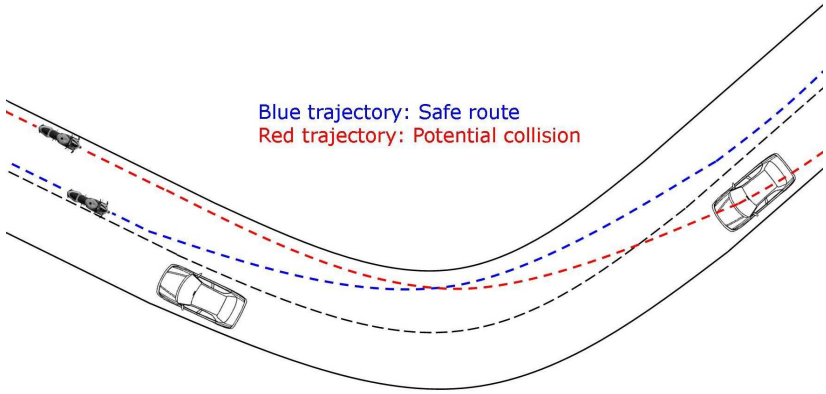


Figure 2.16 – Motorcycle lane position at a curve.

Intelligent speed control.

In the UK the speed limits are clearly marked on the side of the road using circular signs made of highly reflective material. Legislation governs the number of signs required and their size and spacing. Speed enforcement is also commonplace, with fines in place for those drivers caught breaking the speed limits. Despite this, drivers are often unaware of the current speed limit or feel they attribute a large proportion of their concentration and attention to managing their speed and looking out for speed limit changes.

As shown if Figure 2.17, a vehicle can encounter multiple speed limit changes in a short distance. In this scenario, vehicles travelling along the main road encounter a short stretch that has a speed limit reduction from 60 mph to 50 mph. The side road is further reduced to 30 mph. These speed limits are established, and do not vary without significant additional signage to warn the driver of a speed limit adjustment.

Intelligent speed control is the automated control of the maximum vehicle speed. It is possible in two ways: Location-based maximum speed control; and vision-based speed limit sign recognition.

To enable location-based maximum speed control a digital map and database of speed limits is required, as well as the accurate position of the vehicle. A speed limiter can be actuated on the vehicle based on its location and the corresponding speed limit from the digital map.

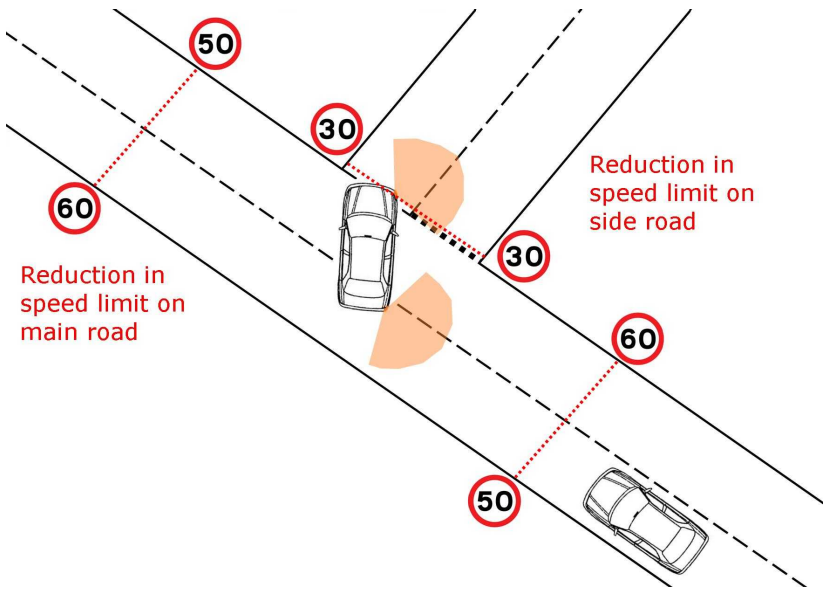


Figure 2.17 – Intelligent speed control.

Vision-based speed limit sign recognition is currently being offered by a number of vehicle manufacturers. Cameras on the front of the vehicle are used to scan the roadside ahead looking for speed limit signs. Initially, the systems were designed to display any signs on a digital display on the vehicle's dashboard, and the driver would be required to manually adhere to the speed limit. This was a useful feature if the driver had missed a sign or wanted to reduce the attention required to search the roadside for speed limit signs. The systems have since been developed to include an automatic speed control function, which limits the maximum speed of the vehicle (this can be overridden by the driver if desired) (Ford Motor Company, 2015).

Intersection collision avoidance.

Vehicles approaching an intersection are in danger of colliding with other vehicles approaching from other routes, as shown in Figure 2.18. This is a particular problem in the US, where intersections may not have a priority direction and are designed so that all vehicles must stop to check the way is clear. However, some drivers disregard the highway rules and proceed through the intersection without stopping to check the route is clear. In the simple scenario where two vehicles

are approaching an intersection from separate directions, there is a high probability of collision if they are due to arrive at the intersection at the same time. The time of arrival is calculated from the distance to the intersection (this may not be a straight line distance), and the speed of the vehicle. Clearly, the speed of the vehicle is likely to change as approaching the intersection (most likely a deceleration), so the probability of collision needs to be re-calculated repeatedly. In order to take account of possible discrepancies in the calculation, the driver's reaction time, and driver comfort, it is also necessary to implement a buffer zone around the intersection, so as to avoid near-miss situations. The buffer zone should equate to at least 1.5 seconds, which is the driver's natural reaction time to a surprise event.

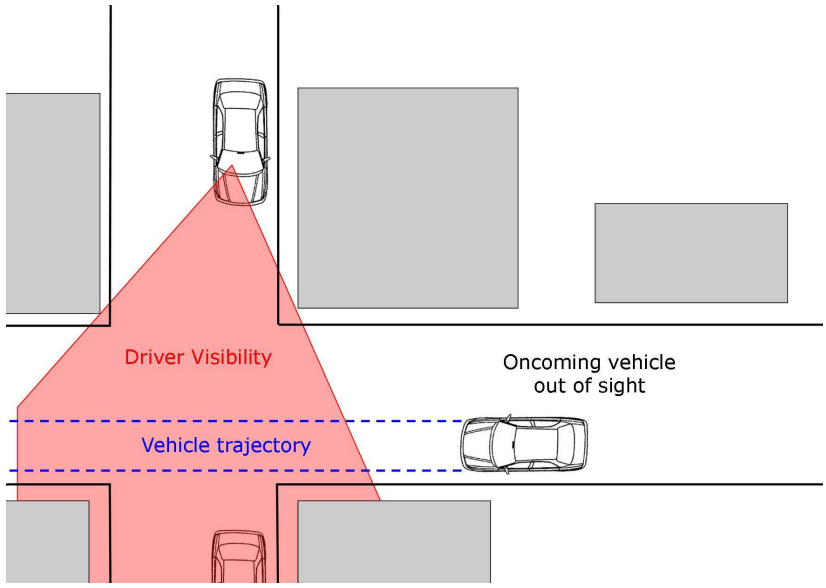


Figure 2.18 – Intersection collision avoidance.

Driver monitoring.

Driver fatigue and distraction are major causes of vehicle accidents. As shown in Figure 2.19, a driver can lose control of a vehicle if they are too tired. Various driver monitoring systems have been researched, including the use of eye tracking and physiological monitoring. It is also possible to detect driver fatigue through monitoring the driving behaviour and performance, such as lane discipline, the frequency and severity of steering corrections, and over- or under-speeding.

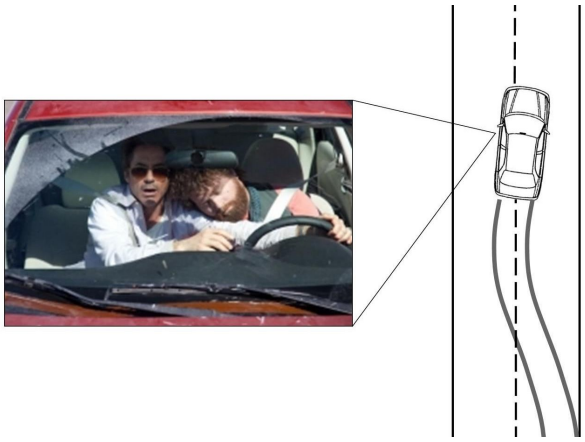


Figure 2.19 – Driver fatigue monitoring.

Autonomous vehicles.
Autonomous vehicles are described in more detail in Section 2.3.2.

2.6.3 Location-Based Services

A Location-Based Service (LBS) is a special case of a context-aware service, where data is delivered to the user, which has been filtered according to a particular context or various contexts (Küpper, 2005). In the case of LBS, one of these contexts is location. The Open Geospatial Consortium describes LBS as (Open Geospatial Consortium, 2011):

> A wireless-IP service that uses geographic information to serve a mobile user. Any application service that exploits the position of a mobile terminal.

Figure 2.20 shows the generic representation of an LBS. It consists of a mobile device that uses a communication method to access a Geographic Information System (GIS). For instance, a mobile phone using the GPRS communication network is used to find the nearest post office to its present location. If one of these three components is missing, then it is not a Location Based Service.

The term LBS is now most closely associated with mobile phone applications. Example applications include searching for points of interest (POI) (for example, Yelp), socialising with friends (for example, Foursquare and Google+), and location based direct marketing and advertising. Services are driven by mobile service providers (such as Vodafone, SFR, Telefonica, or Verizon), mobile phone manufacturers (such as Nokia, Apple, RIM, or Samsung), vehicle manufacturers, and new media and technology companies (such as Google, Apple, Facebook, or Twitter).

It has been forecast that in 2017, approximately 270 billion applications will be downloaded worldwide for mobile phones (Statista, 2013). This will increase from 2.5 billion in 2009 and from 139 billion in 2014. North America dominates the market for LBS by the number of users, but is behind Japan in market value.

A recent forecast by Juniper Research predicts that global revenues from LBS could soar to US$12.7 billion by 2014, up from US$3 billion in 2009. In terms of automotive-related LBS, ABI Research states that the global number of traffic information users is expected to grow from 57 million in 2010 to more than 370 million in 2015 (GPS Daily (Editorial), 2010).

An issue that achieves widespread media coverage is privacy. Asked directly, users are very reluctant to give up their privacy, and the media in particular enjoy reporting on organisations that take user's data. But in exchange for a simple service, such as social networking, users freely give up their location and contact data. Most services are obliged to provide an opt-in or opt out (typically the latter), although large companies such as Google and Apple have been involved in controversial media stories about collecting users' data.

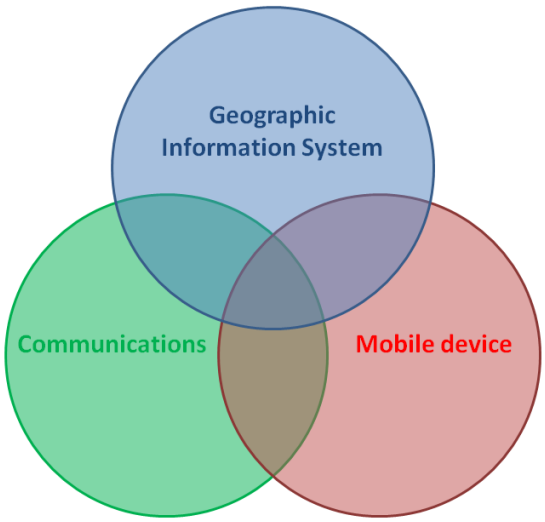


Figure 2.20 – Venn diagram describing Location Based Services.

Europe and the US have legislation on their agendas that will require all mobile phones to be GNSS enabled, in order to assist emergency responders. The US Federal Communications Commission has made this a requirement by 2018 (Federal Communications Commission, 2015).

Vehicle manufacturers are encouraged to design their infotainment systems to focus on navigation. This continues to be a strong selling point for private vehicles, as previously discussed in Section 2.3.1.1.

The most popular paid-for LBS automotive applications are also navigation based, whilst other services tend to favour advertising-based funding models. Developers of LBS applications are looking forward to the widespread roll out of 4G communications, as in many areas this lack of communication coverage is a major hurdle.

Chapter 3

Vehicle Localisation and Positioning Requirements

3.1 Overview

As was discussed in Chapter 2, ITS and V2X applications demand different information to assist with automation. For instance, information about vehicle position, speed, or heading. This information will help to define the localisation and positioning requirements of the applications, but another important factor is the vehicle itself.

Vehicles have specific characteristics when considering their movement. The road environment has shaped the way that vehicles are designed, and the way they move. Vehicles make the majority of their movements in a longitudinal direction, with reference to a road, but some of the most import information regards the lateral movement (for example, changing lanes or keeping on the road).

This chapter looks at the characteristics of a vehicle's movement, discusses some of the localisation systems used to define it, and concludes with an assessment of the RNP for road vehicle positioning and details the position accuracy requirements for ITS and V2X applications.

3.2 Vehicle movement

The International System of Units (SI[1]) metric system describes movement in terms using metres (m) for position and distance, and seconds (s) for time intervals. Angular momentum is described in radians (ra) (Bureau International des Poids et Mesures, 2014).

3.2.1 Longitudinal and lateral movement

Vehicles on roads tend to travel in a disciplined manner along rigid lanes. The nature of vehicle and road design means that the majority of movement is in the longitudinal direction (in a direction parallel to the road line markings). Lateral movement of a vehicle is considered perpendicular to the road line markings. Lateral movement therefore considers lane changes and vehicle side slip.

Section 3.2.2 gives details about the orientation of the vehicle.

Position.

The position of a vehicle at an epoch is fundamental to many ITS applications. The knowledge of the location of the vehicle either relative to other objects or in absolute terms, enables applications from navigation and collision avoidance to LBS.

[1] Abbreviation from the French: Le Système International d'Unités.

The position can be one-, two-, or three-dimensional. For instance, the one-dimensional (1D) longitudinal distance along a highway, the two-dimensional (2D) plan position, or the three-dimensional (3D) global coordinates relative to the centre of the Earth. A fundamental requirement for any ITS application using position data is to understand precisely the nature of the position data, its accuracy, and the coordinate system and reference frame.

Displacement.

The displacement of an object is defined as the change in position, and is described by a position vector from the reference position to the current position, using the SI units m.

In mathematical formula and physics notation, displacement describes the vector from the origin (or reference point) to the current position.

Velocity.

The velocity of an object is defined as the rate of change of position, and is described using the SI units m/s or ms^{-1}.

Modern road vehicles can travel at speeds of over 200 mph (322 kph, 90 m/s), although many high performance vehicles are limited to 155 mph (250 kph, 70 m/s), and global speed limits on major highways are generally between 60 and 80 mph (97-129 kph, 27-36 m/s).

The velocity of a vehicle can be found through the differentiation of two position measurements at different epochs - described as the rate of change of position (or displacement). Velocity is defined by the object's speed and direction.

In its simplest form, the velocity (ν) of an object moving in a straight line through a displacement (Δx) and time interval (Δt) is shown in Equation 3.1.

$$\nu = \frac{\Delta x}{\Delta t} \tag{3.1}$$

Figure 3.1a shows an example of the relationship between vehicle velocity and distance travelled. Data was gathered using a Leica GS10 GNSS receiver attached to a road vehicle. It is notable that velocity varies during the entire period, but as it is always positive it contributes to a continuous increase in distance travelled.

Acceleration.

The acceleration of an object is defined as the rate of change of velocity, and is described using the SI units m/s/s or ms^{-2}.

Acceleration of a road vehicle is generally not constant over time. For instance, it can be influenced by the available engine torque, mechanical grip, or friction forces. The maximum acceleration of the average car is 3 to 4 m/s/s. At the extreme, the Bugatti Veyron hypercar will accelerate at a maximum of 12 m/s/s. During braking, a professional driver will decelerate at 10 m/s/s, whereas the average driver will decelerate comfortably at 5 m/s/s.

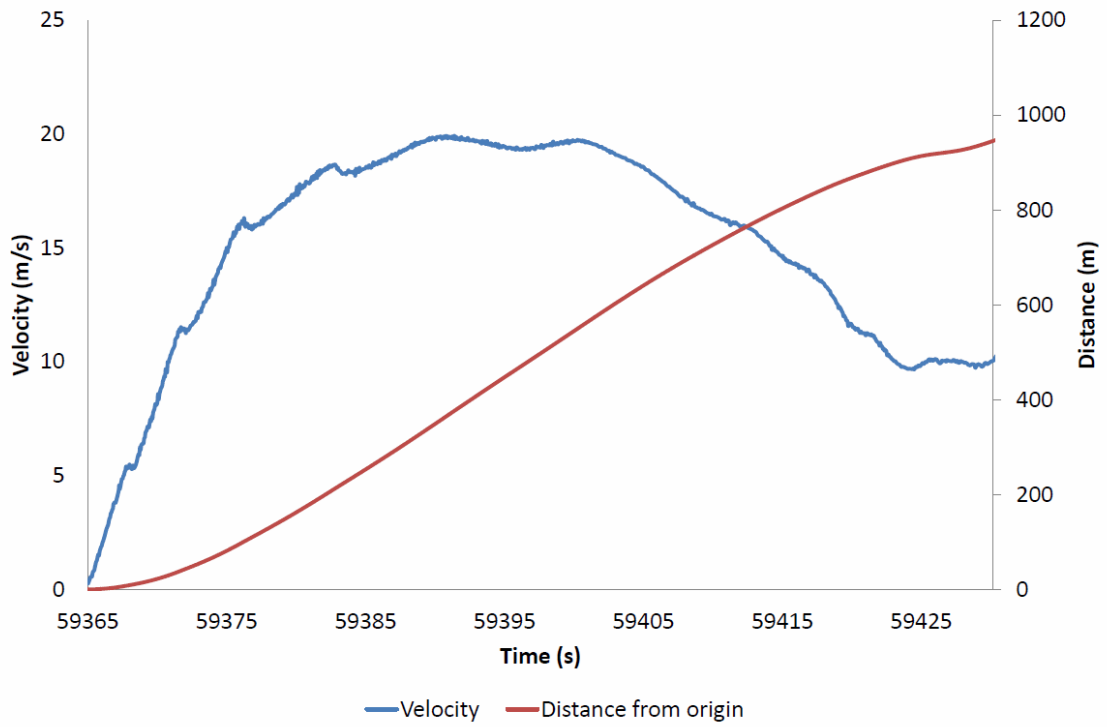
The linear acceleration (a) of an object moving in a straight line, undergoing a change in velocity ($\Delta\nu$) over a time interval (Δt), is shown in Equation 3.2.

$$a = \frac{\Delta\nu}{\Delta t} \tag{3.2}$$

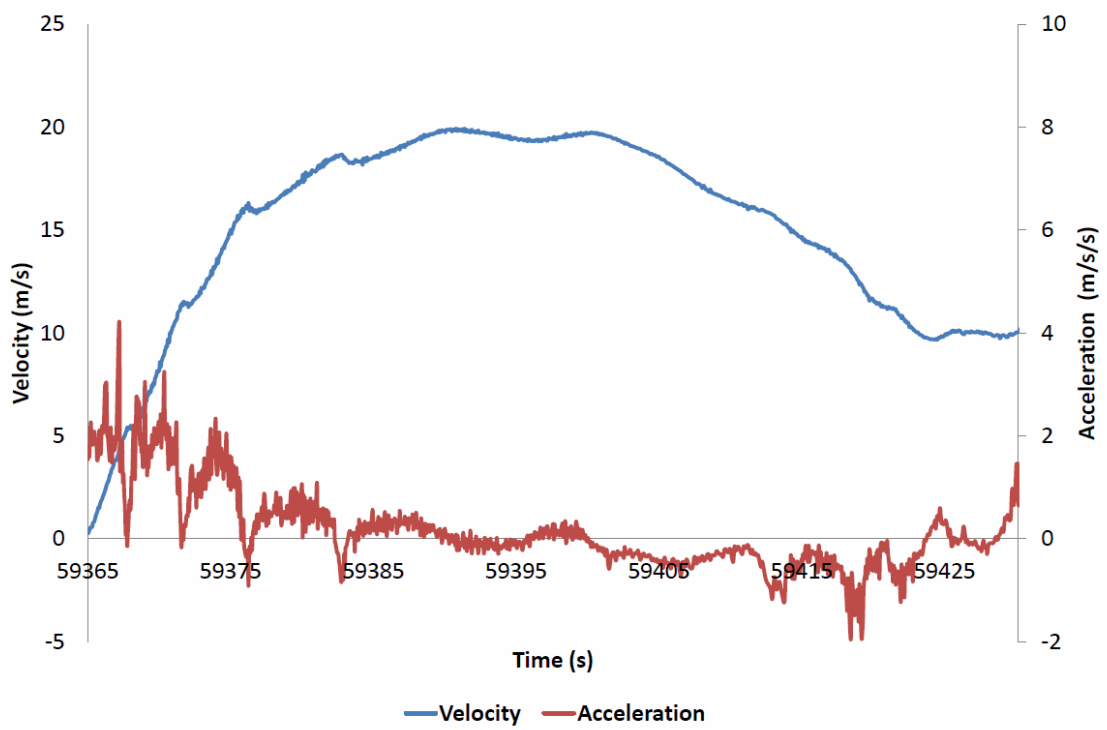
In Figure 3.1b it is possible to see the gear changes during a gentle period of acceleration from stationary up to 20 m/s followed by a slow deceleration to 10 m/s/s. They appear as irregularities in the otherwise smooth blue curve. The data is taken from observations made with a Leica GS10 receiver together with N-RTK corrections from Leica SmartNet. The observations were recorded at 20 Hertz, although the acceleration data is calculated using data recorded at 5 Hertz (otherwise it is very noisy).

Deceleration is more important when modelling vehicle movement, as it is critical to vehicle safety. For instance, stopping distances are affected by the position accuracy of any distance assessment (either by a human driver or the driver assistance system).

The rate of deceleration is determined by the driver, the vehicle, and the road conditions. In the UK, the Highway Code determines that the braking distance of a vehicle from 60 mph (96.5 kph or 26.8 m/s) to standstill is 55 metres (see Table 3.1). However, this is a constant deceleration of 6.5 m/s/s, whereas vehicles are capable of decelerating at much greater rates. For instance, at a deceleration of 10 m/s/s, the braking distance from 60 mph is approximately 37 metres, which corresponds to a reduction of the maximum time-to-event from 4.1 to 2.7 seconds.



a). Velocity versus distance.



b). Velocity versus acceleration.

Figure 3.1 – Velocity of a road vehicle compared: a). Distance travelled from the origin; b). Acceleration of the vehicle.

Table 3.1 – Braking distances according to the UK's Highway code (not including driver reaction time, and assuming favourable weather and road conditions).

Speed (mph)	Speed (m/s)	Distance (m)
30	13.4	14
40	17.9	24
50	22.4	38
60	26.8	55

Jerk.

The jerk of an object is defined as the rate of change of acceleration, and is described using the SI units m/s/s/s or ms^{-3}. The terms jolt, surge, and lurch are often used to describe jerk. Figure 3.2 is a graphical representation of jerk during a lane change manoeuvre. The figures used for the graph are simulated. Equation 3.3 describes the relationship between jerk (j) and acceleration, with reference to time.

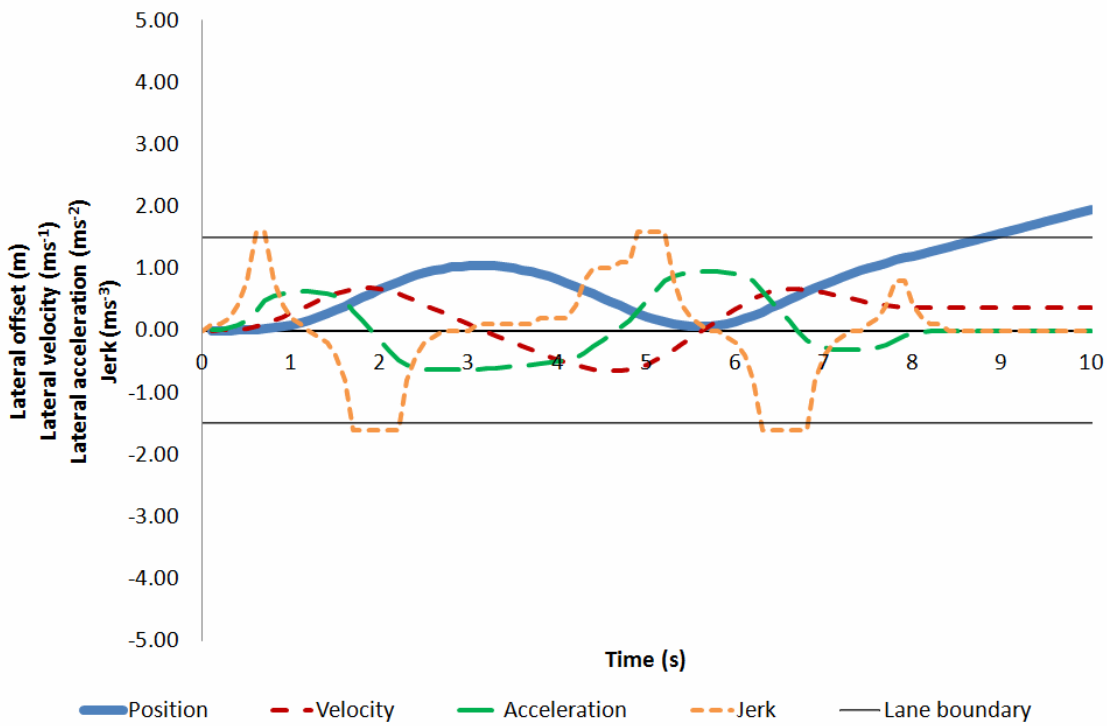


Figure 3.2 – Jerk during lane departure.

$$j = \frac{\Delta a}{\Delta t} \tag{3.3}$$

Higher order derivatives of position.

Further derivatives of position are not relevant to the movement of road vehicles. The rate of change of jerk (known as jounce or snap) has no particular relevance to ITS applications, and its estimation becomes inaccurate if it has been differentiated from displacement or velocity measurements.

The relationship of each of the previous derivations is shown in Equation 3.4, where j represents jerk, a represents acceleration, v represents velocity, and r represents position (Bevly and Cobb, 2010). A summary of the above derivations is also shown in Table 3.2.

$$j = \frac{\Delta a}{\Delta t} = \frac{\Delta^2 v}{\Delta t^2} = \frac{\Delta^3 r}{\Delta t^3} \tag{3.4}$$

Table 3.2 – Summary of the derivatives of position.

Derivative	Description	Notation	Units	Scalar
0	Position	r	m	Displacement
1	Velocity	v	m/s	Speed
2	Acceleration	a	m/s/s	Pickup
3	Jerk	j	m/s/s/s	-

3.2.2 Vehicle attitude

For a road vehicle, the roll angle represents the rotation about the front-rear axis and describes the side lean such as experienced whilst driving round a corner. The pitch angle represents the rotation about the left-right axis and describes the dip or sag experienced under acceleration or deceleration. The yaw angle represents the rotation around the z-axis, perpendicular to both the roll and pitch axes, and is synonymous with the vehicle heading (or in some cases bearing). Figure 3.3 shows the relationship between roll, pitch, and yaw.

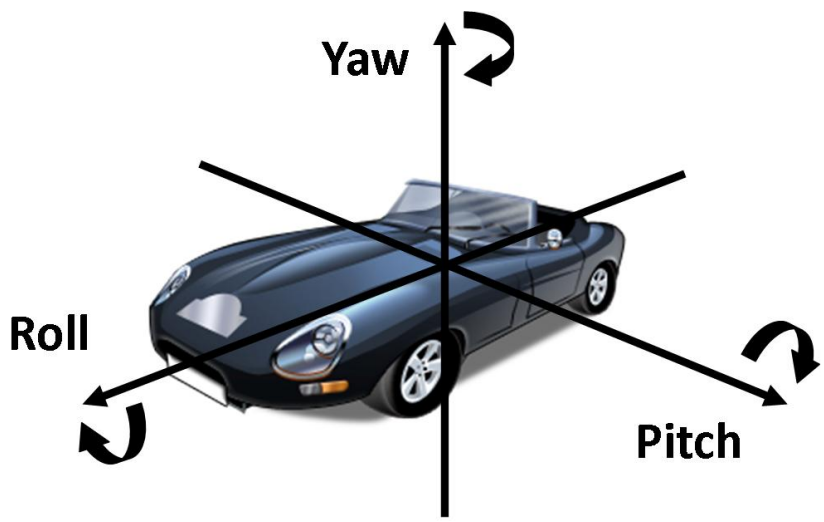
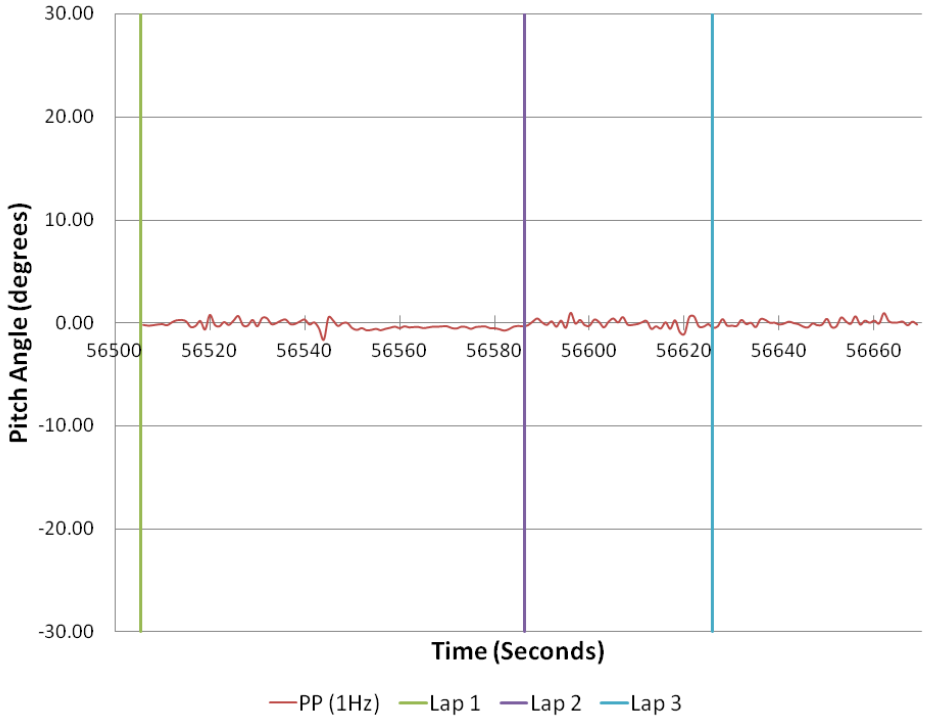
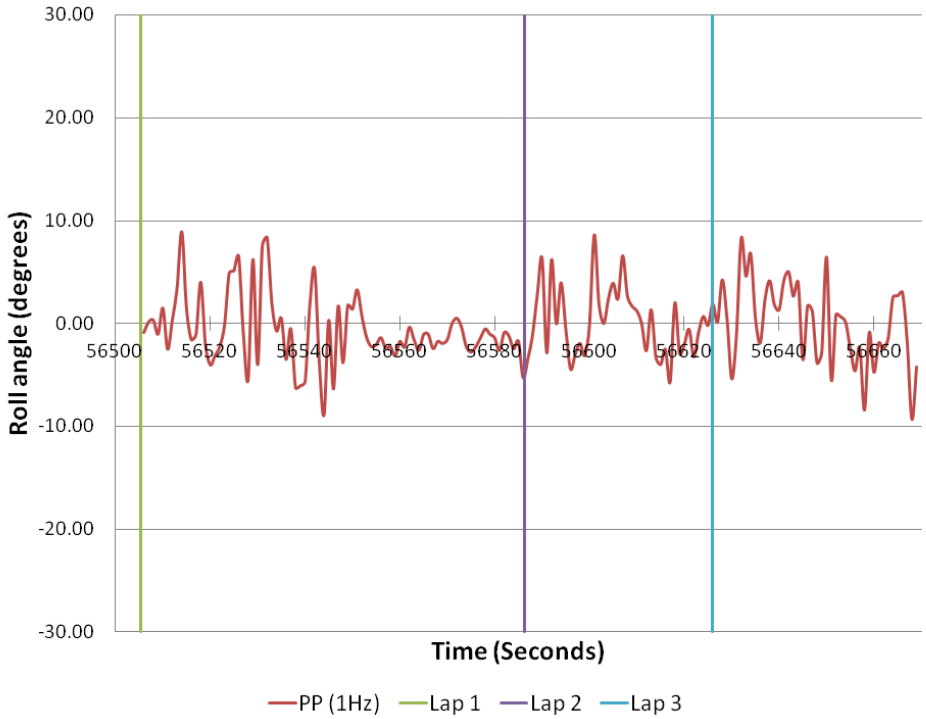


Figure 3.3 – The roll, pitch, and yaw axes of a road vehicle.

Figure 3.4 shows the results of pitch and roll calculations from GNSS data collected from the NGI electric locomotive. Four GNSS receivers with separate antennas, located at the front, the rear, and one at either side of the centre, were used to collect GNSS position data. The angles are calculated by comparing the 3D coordinates of the antennas. Due to the horizontal nature of the locomotive track on the roof of the NGB and the stiff suspension of the locomotive, the pitch angle does not vary significantly. The locomotive exhibits significant roll angles, in particular as it travels around curves of the track. The data was collected over three laps of the locomotive track, although at different velocities. During the period 56550 to 56580 the locomotive was stationary - a period when the pitch and roll angles should remain constant. However, the measurements exhibit some movement, due mainly to the combination of short baselines between the antennas and the accuracy of the position measurements (typically 5 centimetres at 1 standard deviation).



a). Pitch angle.



b). Roll angle.

Figure 3.4 – The pitch and roll angles calculated using GNSS observations on the electric locomotive at the NGI. (PP is the post-processed solution using the NGB2 reference station).

3.2.3 Driver performance

The human driver provides a notoriously difficult set of driving parameters to predict. Although drivers must all obey the rules of the road, individuals exhibit wildly different performance. The contributing factors include driver age, physical ability, temperament, and cultural etiquette. This variety contributes a major unknown for advanced automotive applications, which is particularly evident when accounting for driver reaction times.

3.2.3.1 Reaction times

A typical driver will react to an event depending on anticipation. The reaction time is the period between an event occurring and the driver beginning the driving action required.

If the event is expected, such as the vehicle in front braking for a red stop light, the reaction time is approximately 0.7 seconds. If the event is unexpected, such as a vehicle pulling out in front of the driver from a side street, the reaction time increases to approximately 1.25 seconds. For a surprise event the reaction time is approximately 1.5 seconds (Green, 2000). Although these reaction times are short, the distance travelled by a vehicle moving at high speed can be significant. Figure 3.5 shows the total distance travelled by a vehicle travelling at 50 kph (31 mph or 13.9 m/s) during an emergency stop situation. At 50 kph the stopping distance is 10 metres. If the event is a surprise, the total distance travelled including the driver's reaction and stopping manoeuvre is 30.8 metres. An expected event is 19.7 metres. Clearly, as the vehicle speed increases, the distance travelled during the driver's reaction increases as well as the stopping distance required to bring the vehicle to a halt.

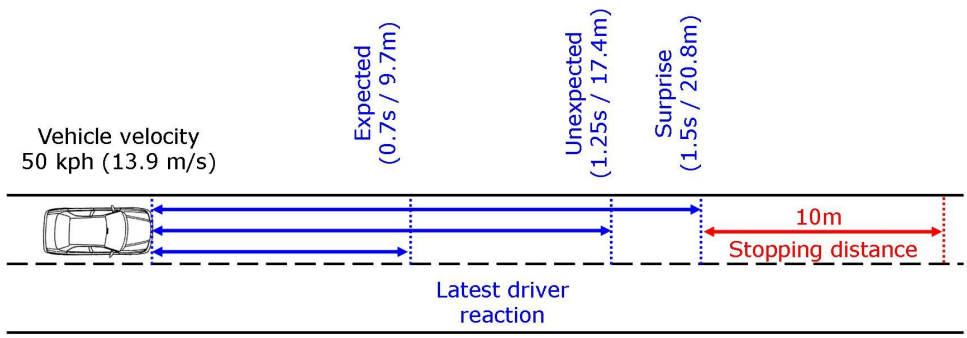


Figure 3.5 – The stopping distance and distance travelled during a driver's reaction to an emergency stop situation.

These figures assume the driver is concentrating on the driving task and is in good physical condition. The following driver attributes will also contribute to a driver's reaction time:

Awareness.
Driver distraction is a major contributing factor in vehicle accidents and near-misses. It has been estimated that around 80% of accidents in the US have an element of distraction (Neale et al., 2005). Recent US legislation has been introduced to reduce driver distraction (for example, caused by interaction with infotainment systems).

Agility.
In the UK, once the driving test is passed no further age-related checks on the driver are carried out until the age of 75 (Driver and Vehicle Licencing Agency, 2015). Traditionally, many drivers voluntarily stop driving when they deem their driving skill capacity puts them in unnecessarily high danger. This most commonly includes reduced agility or poor eyesight.

Many driving skills are developed through experience, and the creation of muscle memory. This takes time to acquire, and helps to explain why newly qualified drivers are the most susceptible to road vehicle accidents.

Driver skill.
A variety of personal characteristics contribute to a driver's ability. These include nervousness, courage or bravery, judgement, perception, and hand-eye coordination.

3.2.3.2 The affect of driver performance on positioning accuracy

Typically drivers cannot perceive less than 0.1 second time differences. Table 3.3 shows the distance travelled after 0.1 seconds at various velocities. At 30 kph (18.6 mph or 8.3 m/s) the distance travelled is 0.8 metres, but at 110 kph (68.4 mph or 30.5 m/s) the distance is 3.2 metres.

Table 3.3 – The distance travelled at different velocities during the shortest time period that drivers can perceive.

Velocity (kph)	Distance after 0.1 s (m)
10	0.28
30	0.80
50	1.40
70	2.00
90	2.50
110	3.20
330	10.00

This relates directly to the required positioning accuracy of any ITS application that requires interaction with a driver. To deliver a message to a driver or take active control of a vehicle that is currently under the control of a driver, the application needs to do so in a consistent manner. Hence, the action must be completed within a tolerance of 0.1 seconds.

For road vehicle positioning, this creates a direct relationship between the vehicle velocity and the required positioning accuracy. The faster the velocity the smaller the required position accuracy.

The impact of this relationship is demonstrated in Figure 3.6. A vehicle is travelling at 50 kph (31 mph or 13.9 m/s) towards an event or object that is 20 metres ahead. If the position accuracy of the vehicle is 0 metres, the minimum time-to-event (TTE) is 1.44 seconds. A driver will demand that the warning about the event is within 0.1 seconds of the real time.

If the position accuracy is 1 metre, according to the theory the vehicle is located somewhere between 21 and 19 metres away from the object. The minimum time to event must reflect this, and in this case it is reduced to 1.37 seconds, but this is still within 0.1 seconds of the original minimum time to event and the driver is unlikely to perceive a difference. As the figure shows, if the position accuracy of the vehicle is 5 metres, then the minimum time to event is 1.08 seconds. This difference of 0.36 seconds would be easily perceptible for the driver, and there is a risk that the application will not be tolerated as it is inconsistent or inaccurate.

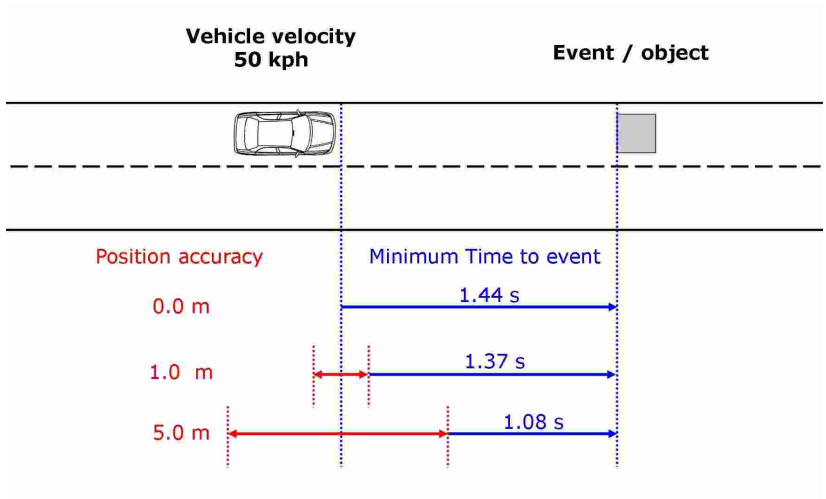


Figure 3.6 – The affect of position accuracy on the minimum time-to-event (TTE).

3.2.4 Vehicle action implementation

Once the driver or the vehicle control system decides to action a vehicle manoeuvre and inputs such an action to the vehicle controls, the vehicle does not typically react instantly. There is a slight delay that is caused by a combination of processing time, mechanical implementation, electronic prediction and adjustment, communication of information between different systems, the limitations of data bandwidth of the communications system, and integrity checking (such as data completeness).

Most processing and communication delays are imperceptible to a human driver, creating a time lag of only a few milliseconds. Mechanical implementation can create longer delays, as the engine must create power and torque, action various levers, pulleys, cams, gears, and axles, and eventually transfer the energy to the wheels (for a typical combustion engined vehicle). If the vehicle requires a gear change or is not running at the correct engine speed, then an action to increase speed may be delayed significantly, perhaps for several seconds.

In contrast, the delivery of power to the wheels of an electrically powered vehicle may be more complimentary to vehicle automation. The torque curve is generally flat, with maximum torque available from standstill (given sufficient tyre traction), giving the sense of instant response. There is no delay whilst gears are selected - as often there are no gears, only an electric motor.

3.2.5 Vehicle modelling

Vehicle modelling is used to describe the physical dynamics of a vehicle (Bevly and Cobb, 2010). Various models have been developed to describe these motions and conventions have been established on coordinate frames and systems (see Section 3.3.3). The basic vehicle model is the bicycle model. Instead of two wheels on each axle, the wheels of a standard vehicle are represented by one wheel at the centre of each axle. This model assumes that the slip angles and steering angles of each wheel on the axle is the same, and that there is no shift of weight from one wheel of the axle to the other. The body-fixed reference frame of the bicycle model is centred on the vehicle's centre of gravity.

The model allows a number of basic considerations to be made on the vehicle. These include lateral and longitudinal tyre slip, air drag, and under- and over-steer. To monitor the effects of roll, pitch, and yaw, the bicycle model can be modified into a four wheel bicycle model (Bevly and Cobb, 2010). This model mainly takes into account the shift of weight between the wheels of an axle.

Additional models are commonly used to describe the behaviour of the tyres and body roll. Tyres are an important aspect of a vehicle's dynamic movement, as they dictate the way the vehicle deals

with vertical load and are used to transfer the lateral and longitudinal forces used for acceleration and cornering. Body roll is often analysed to improve vehicle handling and avoid rollovers. A detailed body roll model will include parameters based on the performance of the vehicle springs and shock absorbers.

3.3 Localisation systems

The systems used to locate a vehicle can be defined using a set of parameters and characteristics. This allows for the comparison of sensors and the measurement of localisation performance. For instance, the heading of a vehicle can be measured using a GNSS sensor or a dead reckoning sensor - although the output value may be the same, it is achieved using different methods. Table 3.5 in Section 3.4 provides a list of the most common location requirements of ITS applications.

The following sections discuss the ways in which localisation systems can vary. These include positioning parameters, external factors (such as human driver input and sensor limitations), and the coordinate systems used.

3.3.1 Positioning parameters

Accuracy is the primary parameter used to compare positioning systems. However, it is rare to find a common accuracy definition between positioning systems. For instance, there is no shared unit of measurement in the specifications of a GNSS positioning system and a terrestrial radar system to allow direct comparison. The GNSS positioning system will provide a measurement accuracy of a three-dimensional point on the Earth's surface relative to any other point on the Earth's surface, whereas the radar system will specify the accuracy of a terrestrial measurement in one-dimension, with an upper limit for the measurement range.

Accuracy can be measured in absolute or relative terms, in one, two, or three dimensions. It could be the position of an object or its orientation. The accuracy could be qualified in terms of being able to determine a state (for example, which lane the vehicle is located in) rather than an explicit number. The measurement can be a distance, a velocity, an angle, or time; and the units of measurement are numerous.

Vehicle dynamics are important when considering positioning parameters. For instance, the range of velocities that can be achieved, the maximum acceleration and deceleration, the braking distances required to bring the car to a stop, and the tightest steering radius that is possible.

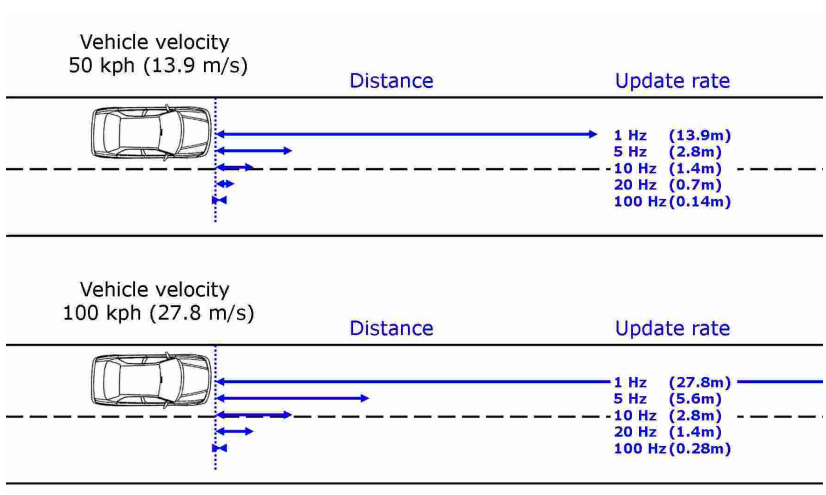


Figure 3.7 – The distance travelled per epoch at different position update rates, at 50 and 100 kph.

Time must also be considered. In particular the update rate of any measurements being taken, the reaction times of drivers, TTE, and the processing time of any system. Figure 3.7 shows the distance that is travelled by a vehicle at 50 and 100 kph between updates at different rates. At 1 Hertz update (one measurement per second), a vehicle travelling at 50 kph covers a distance of 13.9 metres, whereas at 100 Hertz the distance covered is only 0.14 metres. Clearly a vehicle travelling faster will cover more distance in the same time.

3.3.2 External factors

Some ITS applications are safety critical. These require any localisation system to be highly robust and provide information with exceptional integrity. Other applications will rely heavily on detailed digital map data, or real time updates from dynamic databases located elsewhere.

Localisation systems must also account for the position of external fixed infrastructure. The position of such equipment is not typically stored in a database, or it is stored at an unknown position accuracy.

3.3.2.1 Driver comfort

The positioning system must also adhere to strict time and output demands. The time-to-event (TTE) is a useful measure of the performance requirements of a system. For instance, if an ITS application requires a warning to a driver with a TTE of 5 seconds, it is possible to work back from this in order to determine the position accuracy required (together with other geometrical and vehicle movement measurements).

As described in Section 3.2.3.2, and in relation to driver warnings and TTE, drivers cannot typically perceive less than 0.1 second time differences. Hence, the maximum position error to avoid the driver noticing a difference in time to event is related to velocity. Therefore, the faster the velocity, the lower the required position accuracy, as shown in Table 3.3. Drivers also have zones of perception, which may not overlap precisely with that of localisation systems. It may be important for some areas of the zone to be considered under the observation of the driver, whereas others may need more support from the localisation system.

The localisation system must also determine the appropriate information that will ensure the vehicle does not undergo unnecessarily violent driving manoeuvres. For instance, the vehicle attitude should move relatively smoothly and centrifugal forces would not be overly high. To instill confidence in the system, a buffer zone between the vehicle and other objects on the road should be acknowledged where possible. An example of this is the careful selection of headway distance in vehicle platooning - the headway that allows the system to perform at its best may not be comfortable for the driver.

3.3.2.2 Sensor characteristics

Taking into consideration the requirements of vehicle localisation, it is sensible to compare these with the characteristics of potential sensors. For instance, to measure the roll angle of a vehicle it is clearly important that the sensor can measure the angle to the required accuracy. However, there are other specifications that must be met: The dynamic range of values the sensor can measure; the time period within which the value should be reported; the output rate; whether the sensor is activated or acts passively; and the format of the output. A more detailed account of these characteristics is found in Özgüner et al. (2011). A brief description of the main sensor characteristics is given in Table 3.4.

Table 3.4 – Sensor characteristics and their definitions.

Sensor characteristic	Brief description
Accuracy	A range within which the correct value is likely to be (with a high confidence).
Sensitivity	The smallest value that can be detected.
Resolution	The minimum difference between two measurements.
Dynamic range	The difference between the maximum and minimum measurement values.
Perspective	The field of view of the sensor.
Active or passive	Whether the sensor emits energy.
Timescale	The update rate and bandwidth frequency.
Output technology	Analogue or digital, serial or network data streams.

3.3.3 Vehicle coordinate systems

Most ITS applications will require position information. For instance, a 3D coordinate or simply a 1D distance. The nature of the position information required is detailed in earlier sections of this chapter.

All position information is related to a reference frame. The reference frame is part of a reference system.

A global coordinate frame, such as the WGS84 reference frame used by GPS (an Earth-Centred, Earth Fixed (ECEF) reference system), allows any position to be related to any other within the entire globe. A local coordinate frame, such the OSGB reference frame used by the Ordnance Survey, allows positions to be related to one another locally (or in this case nationally). Hyper-local reference frames such as lane positions are also considered a local coordinate frame. Coordinate systems are discussed in more detail in Section 4.2.4.

A body coordinate frame is a reference frame used for a vehicle. The centre of the frame is typically the vehicle's centre of gravity. The SAE has defined the SAE Vehicle Coordinate System used for body-fixed coordinates (Bevly and Cobb, 2010). In this system, the x-axis is heading, y-axis is lateral position, and the z-axis is up and down. Rotation around the x-axis is roll, rotation around the y-axis is pitch, and rotation around the z-axis is yaw.

The origin of each coordinate frame is highly unlikely to be the same, so that a transformation will require at least a rotation and offset (Bevly and Cobb, 2010). Depending on the transformation, it may also require scaling. It is critical that the transformation from one coordinate system to another, or from one reference frame to another, is completed accurately and efficiently.

3.4 Meta-analysis of positioning requirements

Table 3.5 lists the most common technical requirements of ITS applications. These are grouped into localisation, vehicle dynamics, module design, time, and other. The table includes a brief description of each requirement and summarises the typical units employed, and the minimum and maximum range of measurements.

Table 3.5 – ITS application requirements.

Application requirement	Units	Range		Description / notes
		Max	Min	
Localisation				
Position accuracy	m	10	0.001	Position accuracy must be better than. Quoted as 2-SD, 3-SD, or CEP.
Position precision	m	10	0.001	Position precision must be better than. Quoted as 2-SD, 3-SD, or CEP.
Position integrity (alert limit)	m	10	0	The position error at which an alert must be issued by the system.
Position integrity (time to alert)	s	1.5	0	The maximum time between the positioning system providing an error above the alert limit and notification to the user.
Position integrity (integrity risk)	%	100	0	The probability that the position error is below the alert limit.
Position continuity	%	100	0	Probability that the system will continue to provide solutions of a given accuracy within a defined time period.
Position availability	%	100	0	Likelihood that the accuracy, integrity, and continuity are met.
Tilt accuracy	deg	10	0.1	Lateral tilt of the vehicle (for example, roll or pitch).
Tilt range	deg	90	0.0	The maximum and minimum tilt that a vehicle can undergo.
Heading/trajectory accuracy	deg	90	0.1	Accuracy of the heading angle is related to predicting the future position of the vehicle.
Heading/trajectory range	deg	360	0	The maximum and minimum range of the vehicle trajectory or heading.
Vehicle Dynamics				
Absolute velocity accuracy	m/s	3	0.01	With respect to the coordinate system.
Absolute velocity range	m/s	90	0	The maximum and minimum absolute velocity of a vehicle.
Relative velocity accuracy	m/s	3	0.01	Between two or more vehicles (may be greater than absolute velocity for oncoming vehicles), +/- velocity range applicable.
Relative velocity range	m/s	180	0	The maximum and minimum relative velocity of a vehicle.
Lateral velocity accuracy	m/s	1	0.01	The velocity perpendicular to the direction of travel.
Lateral velocity range	m/s	20	0	The maximum and minimum lateral velocity of a vehicle.
Acceleration (XYZ) accuracy	m/s/s	1	0.01	Either defined relative to the coordinate plane (for instance, XYZ or ENH), or the vehicle body frame (for instance, XYZ).
Maximum acceleration	m/s/s	20	0	For example, the Bugatti Veyron accelerates from 0-60mph in 2.3s (or 11.6m/s/s); whereas an average car accelerates at 3-4m/s/s.

Table 3.5 – ITS application requirements.

Application requirement	Units	Range		Description / notes
		Max	Min	
Maximum deceleration	m/s/s	20	0	For example, a professional driver will decelerate at 10m/s/s (1g); whereas the typical driver decelerates comfortably at 5m/s/s.
Maximum velocity	m/s	90	0	90 m/s is the equivalent of 324 kph and 201.3 mph.
Minimum velocity	m/s	90	0	For example, collision warning systems only activate above 30 kph.
Braking distance at 30mph	m	14	-	In normal conditions, and not including thinking time (UK Highway Code figures).
Braking distance at 40mph	m	24	-	In normal conditions, and not including thinking time (UK Highway Code figures).
Braking distance at 50mph	m	38	-	In normal conditions, and not including thinking time (UK Highway Code figures).
Braking distance at 60mph	m	55	-	In normal conditions, and not including thinking time (UK Highway Code figures).
Steering radius	m	550	5	Cornering radius will be dependent on the vehicle speed.
Module design				
Module cost	£	-	-	Total cost of all equipment, including subscriptions.
Module size (volume)	m^3	-	-	The volume of the postioning sensor hardware located on the vehicle.
Module power	W	-	-	The power demand of the unit.
Time				
Update rate	Hz	1	1000	Update rate of the position solution.
Driver reaction time	s	2	0	Events include expected, unexpected, or surprise. Time is measured between recognising the event and acting.
Time-to-event	s	60	0	The minimum time required before an event. To include all actions.
Position processing time	ms	1	0.001	Maximum time to process the position solution.
Other				
Safety critical	(Y/N)	Y	N	Whether the application is critical to safety or not.
Vehicle environment	Desc.	-	-	Description of typical working environments (For example, urban, motorway, tunnels).
External infrastructure	Desc.	-	-	Reliance on external infrastructure, and type.
Communication system speed	Mbps	-	-	If required, the data transmission speed of communications is required.

Table 3.5 – ITS application requirements.

Application requirement	Units	Range		Description / notes
		Max	Min	
Communication system continuity	%	100	0	If needed, what continuity of communications is required? And what percentage of data is delivered for a given time period.
Interference	(Y/N)	N	Y	Is the measurement subject to any interference?
Digital map accuracy	m	10	0.001	Accuracy of mapping data that is required. Assuming it is up to date.
Acitve control / driver warning	Desc.	-	-	Does the application take control of the vehicle or deliver a message to the driver?
Single vehicle / cooperative		Single	Coop.	Is the system cooperative, or unique to one vehicle?
Buffer zone required	m or s	63 m or 2 s	0 m or 0 s	For comfort and contingency. For example, a buffer around an object, headway to following vehicle in the platoon. A two second vehicle headway is generally considered sensible, and at 70 mph this equates to approximately 63 metres.

3.5 Accuracy requirements for ITS applications

When considering accuracy requirements for ITS applications, it is sensible to create accuracy categories to which applications can be assigned. It may not be possible to quantify the accuracy requirements of some emerging and future applications, but the following classification allows such flexibility and foresight to accommodate them.

Table 3.6 and Table 3.7 summarise the RNP that would be required of any positioning system for a selection of current and future ADAS, respectively. A description of the applications can be found in Section 2.6. Other non-positioning requirements exist, but are not discussed here. The units are specified in metres, seconds, degrees, and combinations of the three. A basic assumption has been made regarding the maximum speed of the vehicle, based on the common European vehicle OEM agreement limiting maximum speed to 155 mph (the equivalent of 69 m/s).

Table 3.6 – Required Navigation Performance of current ITS applications.

Parameter (units)	Black spot warning	Blind spot warning	Overtaking vehicle warning	Inter-vehicle hazard warning	Active braking	Lane departure warning
Position accuracy (2D)	5.0	0.7	1.0	5.0	1.4	0.2
Abs. velocity accuracy	6.7%	8.0%	8.0%	6.7%	6.7%	14.3%
Rel. velocity accuracy	6.7%	8.0%	8.0%	6.7%	8.0%	-
Abs. velocity range (m/s)	0 - 69	9 - 69	9 - 69	0 - 69	5 - 69	14 - 69
Rel. velocity range (m/s)	0 - 69	0 - 10	2.2 - 10	0 - 69	0 - 32	-
Update rate (Hz)	10	100	100	10	100	500
Time to event accuracy (s)	1.0	0.1	0.1	1.0	0.1	0.1
Min. reaction time (s)	1.5	1.25	1.25	1.5	0.7	0.7
Heading (degrees)	45	0.2	0.2	45	24	0.1
Buffer zone (m)	-	-	6	-	2	-
Time critical?	N	Y	Y	N	Y	Y

The values in Table 3.6 and Table 3.7 were created by analysing the characteristics of the ADAS, such as the vehicle dynamics, driver inputs, and physical contraints. For instance, maximum and minimum velocities, driver reaction times, and general lane widths. Some of the RNP parameters are fixed, such as maximum and minimum velocities, whereas others were tailored to each ADAS by adjusting the numbers to fit.

It is interesting to note that the position accuracy parameter is the main limiting factor when determining the viability of GNSS positioning techniques. Stand-alone GNSS positioning could be used for black spot warning and inter-vehicle hazard warning, but it would be unsuitable for autonomous vehicles. Whereas RTK GNSS positioning could be used for those applications that require a high position accuracy, although there are other factors outside the parameters of these tables that need to be considered.

Table 3.7 – Required Navigation Performance of future ITS applications.

Parameter (units)	Vehicle platooning	Motorcycle lane position	Intelligent speed control	Intersection collision avoidance	Driver monitoring	Autonomous vehicles
Position accuracy (2D)	0.2	0.2	2.0	2.0	0.05	0.05
Abs. velocity accuracy	6.7%	14.3%	6.7%	10.0%	6.7%	6.7%
Rel. velocity accuracy	6.7%	-	-	10.0%	-	-
Abs. velocity range (m/s)	0 - 69	0 - 69	5 - 36	0 - 69	0 - 69	0 - 69
Rel. velocity range (m/s)	0 - 69	-	-	0 - 69	-	0 - 69
Update rate (Hz)	100	100	20	10	100	500
Time to event accuracy (s)	-	-	-	1.0	-	0.1
Min. reaction time (s)	1.5	0.7	1.5	1.25	1.5	-
Time critical?	Y	N	N	Y	Y	Y

3.5.1 Position accuracy categories

A method first described in Alves et al. (2010) outlined three main classes: Which Road; Which Lane; and Where In Lane. The next logical step would then be Active Control. These four simple classes succinctly describe the level of accuracy required for different ITS applications and allow appropriate technologies to be developed and implemented. They are shown in Figure 3.8.

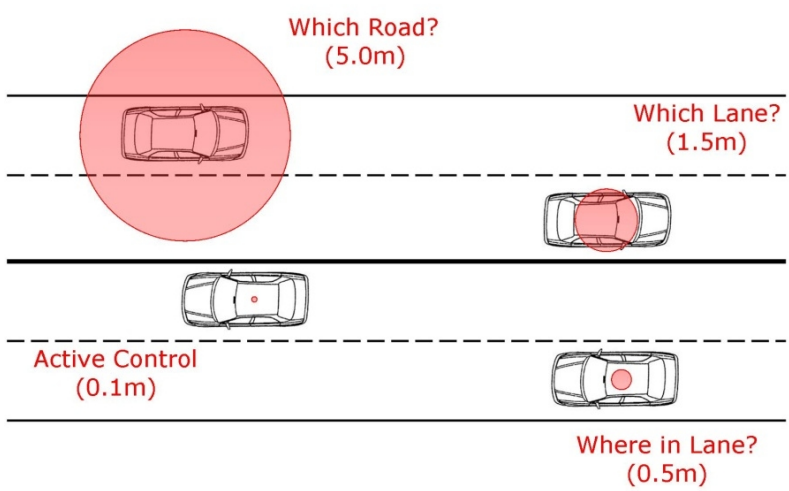


Figure 3.8 – Positioning accuracy categories.

Which Road.
Applications would typically require an accuracy of 5 metres or better. This is the type of accuracy currently available with consumer grade Sat Nav devices, or PNDs and smartphones. This would allow the application to locate a vehicle's position on a particular road, such as for journey planning and navigation, accident black spot warning, environmental monitoring, and congestion relief.

Which Lane.
Applications require an accuracy of better than 1.5 metres. This allows the application to position the vehicle on a road, and describe which lane it resides in. Applications in this class include road user and congestion charging, lane departure warning, variable speed adaptation, incident detection, emergency vehicle prioritisation, and those applications in the Which Road class.

Where In Lane.
Applications require a positioning accuracy of better than 0.5 metres, and possibly to the nearest decimetre. For applications at this level, such as driver monitoring, pre-crash restraint, collision avoidance, and road condition monitoring, the vehicle location is needed for some passive safety systems and uncritical monitoring. In some circumstances, vehicle platooning may also be viable at this level of positioning accuracy.

Active Control.
Applications require the highest accuracy. In these applications the accuracy needs to be better than a decimetre. Control of the vehicle is actively made by these applications, such as vehicle platooning, roll over prevention, autonomous vehicle control, and automated road trains. Positioning of the vehicle in these applications is critical to safety, and often classified as Safety of Life (SoL).

3.5.2 Required Navigation Performance

Position solutions from GNSS are typically Gaussian or normally distributed within the 2-standard deviation (SD) limit (Petovello, 2008). Beyond this, and depending on the particular technology in use, the distribution can be abnormal. There are too many variables with systematic errors or biases. Therefore, looking at accuracy is useful to compare solutions under normal conditions, but as road and vehicle incidents tend to take place under abnormal conditions, it is important to provide further information on the positioning solution. Traditionally, this further information is correlated under the RNP classification, consisting of accuracy, integrity, continuity, and availability (International Civil Aviation Organization, 1999; Ochieng et al., 2003).

Accuracy.
This is classically described as the deviation from the true value. As the position solution is estimated, and the truth is unknown, the value tends to be a statistical quantity. Most commonly used in civil applications, the accuracy is quoted as either 1- or 2-SD. In military applications, there is a preference for describing the accuracy as either circular error probable (CEP, 2D) or spherical error probable (SEP, 3D), where the value represents the median position error.

Integrity.
This is a measure of how well errors larger than the accuracy can be avoided, and if a large error occurs it is recognised. There are typically three parameters of integrity: The alarm limit at which the integrity is lost; the time to alarm; and the integrity risk or probability. For instance, the system has a 99.99% chance of detecting an error greater than 10 metres, and delivering a warning message within 10 seconds.

Continuity.
The continuity of a position solution is defined as the probability that the system will not deliver a solution of a certain quality over a particular time period (assuming that the quality was met from the start). It is also often referred to as the reliability of a positioning system. For instance, during a period of 10 minutes, there is a 0.01% probability that the system will not satisfy the accuracy and integrity parameters, and hence will not provide any navigation solution. It is important to note that continuity can be broken by false alarms. For instance, an integrity monitor excluding good measurements incorrectly as poor measurements would lead to an unnecessary loss of integrity, and hence continuity (Petovello, 2008).

Availability.
The cornerstone of the RNP classification is the measure of position solution availability. This takes into account the accuracy, integrity and continuity, and determines the percentage of time that the specifications of these three performance characteristics are met. Due to the fundamental nature of GNSS, where the satellites do not have a fixed coverage area and may become unavailable for various reasons, the availability is difficult to measure. For this reason it is estimated through design and modelling (Ochieng et al., 2003).

3.5.3 Required Autonomous Driving Performance

An autonomous vehicle is required to perform many of the applications discussed in this Chapter. Based on the accuracy requirements analysis detailed earlier in this Chapter, it is possible to create a Required Autonomous Driving Performance (RADP). An autonomous vehicle will likely carry people, so it will be required to react in a manner that is comfortable for passengers: Any action of the autonomous vehicle must be consistent, where the variation of the reaction of the vehicle to events is imperceptible to passengers (less than 0.1 seconds).

As outlined in Table 3.7, an autonomous vehicle requires 2D positioning accuracy of 0.05 metres at an update rate of 500 Hertz, based on a maximum velocity of 155 mph (69 m/s). GNSS positioning can provide this level of positioning accuracy, albeit with some limitations which are explored further in Chapter 4.

Chapter 4

Vehicle Positioning with GNSS

4.1 Overview

GNSS positioning continues to be the only global absolute positioning option, and is low-cost, compact, mobile and generally free to the end-user (for instance, no additional subscription or licence fees). However, it does not have 100% availability, as GNSS signals are very weak and cannot pass through most solid objects, although modern signals and techniques can mitigate this factor to some extent. Signal interference is also an increasing issue due to increased demand for frequency bandwidth - GNSS signals are electromagnetic, and hence highly susceptible to signal interference.

These fallibilities have led to the rapid development of an integrated sensor approach to positioning, with the GNSS receiver an important partner. For instance, a combination with inertial sensors is commonly used in transport applications as the sensors are complimentary - the limitations of each are offset well by the strengths of the other. Integrated satellite-based navigation devices in modern passenger vehicles take advantage of the vehicle's embedded sensors (such as the wheel odometer) and map matching techniques, to bridge GNSS outages during navigation or route guidance (such as through tunnels). The success of this integration delivers almost complete availability of a positioning solution for most route guidance scenarios. GNSS chip manufacturers have also developed low-cost modules that combine a GNSS receiver with an inertial measurement unit (IMU), which can bridge significant GNSS outages such as driving inside a multi-storey car park (GPS World (Editorial), 2014). The accuracy achieved is suitable for most basic guidance applications.

These integrated devices will improve many of the passive driver assistance systems, such as lane-level route guidance, and enable the development of cooperative vehicle applications such as hazard warning and congestion relief. The availability of a position solution is a key advantage for these devices, as it can be provided nearly all of the time (short term GNSS outages are manageable, but the vehicle needs to know its initial position).

In order to enable some of the more advanced active driver assistance systems and automotive applications, the position solution will need to be much more accurate, with high availability, providing continuity, and delivered with high integrity. These applications include active control of the vehicle or some form of semi-autonomy. Fully autonomous vehicles also require positioning solutions; to compliment their situational awareness.

GNSS positioning techniques have been developed that can match aspects of this specification: High precision, high accuracy Real Time Kinematic (RTK) GNSS positioning can provide centimetre-accuracy solutions; given a clear sky view, several GNSS positioning techniques can deliver complete availability and continuity; and many services have been designed to measure and improve GNSS positioning integrity. However, in the automotive environment these aspects are more difficult to achieve. A road vehicle is highly mobile, in a highly dynamic and evolving environment, where simply keeping lock on the weak and noisy GNSS satellite signals is a complex and difficult task.

An advanced form of RTK positioning uses a network of Continuously Operating Reference Stations (CORS). Network RTK (N-RTK) GNSS positioning has been primarily developed to aid surveyors in the field, who would traditionally set up their own local GNSS reference receiver to provide corrections to a GNSS roving receiver. In the United Kingdom (UK), a network of approximately 150 GNSS receivers is spread evenly across the country. They continuously record and transmit their GNSS observations to a central server, which distributes them to the end-user. This distribution, typically using mobile internet, allows the end-user to utilise the CORS instead of establishing their own local GNSS reference station.

N-RTK positioning can provide better than 5 centimetre absolute accuracy, and unlike other high precision GNSS positioning techniques, it can quickly re-establish a high accuracy solution following interruptions of the GNSS signals. Previous real-world road trials at the University of Nottingham have shown that N-RTK positioning can deliver this accuracy with high availability. The trials identified two limitations however: The communications system used to deliver the GNSS corrections can be unreliable; and GNSS signal outages continue to be a problem in some driving environments. This thesis continues to explore these limitations.

Multi-constellations and new signals will improve the overall performance of GNSS positioning. However, it is apparent that there are existing technological hurdles before the wide adoption of current high precision and robust GNSS positioning systems into ITS operations. The identification of feasible solutions to these problems, and their systematic research, forms a major focus of this thesis.

This chapter gives a brief introduction to GNSS positioning, with particular relevance to vehicle positioning. This includes outlining the main positioning techniques available, and a comparison of their performance in real-world tests. The test results highlight the possible improvement in vehicle positioning from high precision GNSS techniques such as RTK; typically, the accuracy of a solution will be better than 5 centimetres. However, RTK positioning does not give a consistent performance, and the reasons for this are explored.

The future development of GNSS services includes the implementation of new GNSS constellations such as Galileo and BeiDou, and the replacement of old satellites with their upgraded replacements in the GPS and GLONASS constellations. Over the next decade, the number of GNSS satellite vehicles is expected to grow substantially, with multi-constellation and multi-frequency GNSS receivers becoming ubiquitous. Adopting high precision GNSS positioning for road vehicle positioning may become significantly cheaper, and provide better performance.

This Chapter finishes by discussing the integration of GNSS positioning with other sensors for road vehicle positioning. As has been demonstrated recently by the development of autonomous vehicles (see Section 2.3.2), the GNSS receiver has been demoted from the primary role in vehicle positioning. Other devices, such as inertial sensors or laser scanners, can provide reliable positioning information. However, their is no panacea solution to road vehicle positioning, so the integration of multiple sensors will be the key to unlocking many ITS and V2X applications.

4.2 Introduction to GNSS positioning

There are now four major GNSS services: GPS, GLONASS, Galileo, and BeiDou. Satellite-based positioning continues to be the only technology to provide absolute positions with global coverage (Wang et al., 2005).

Satellite-based positioning works using the basic principle of resection, where either ranges or range differences from a user to a number of satellites are used to calculate a position (Hofmann-Wellenhof et al., 2008). The satellites have a known position in a reference frame, and transmit a coded signal towards the user that can be used to calculate the transmission time from the satellite to the user, and subsequently the range. These ranges can be used to find the position of the user by trilateration, as shown in Figure 4.1. Each satellite-receiver range defines a surface of a sphere of possible positions; each pair of spheres defines a circle of possible positions between them; and the intersection of these three circles defines the location of the receiver. As the user receiver does not typically have a clock capable of providing accurate system time, a fourth satellite is required to account for this added unknown time offset.

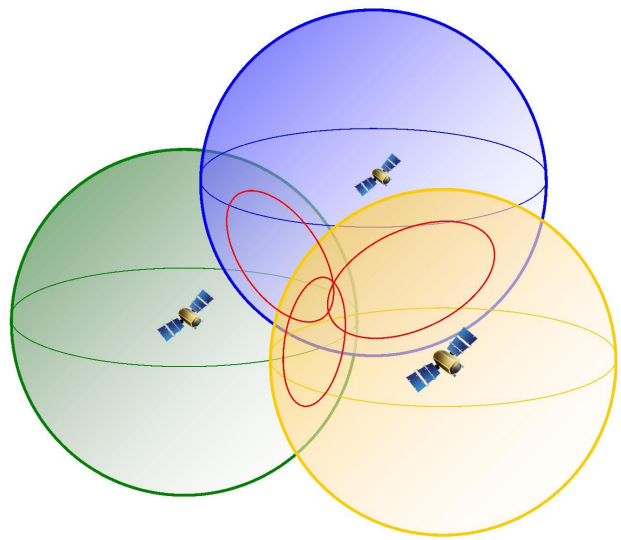


Figure 4.1 – GNSS signal trilateration.

The ranges measured from each satellite to the user receiver are known as pseudoranges (R) as they require a range correction ($\Delta\rho$) based on the receiver clock error or bias (δ) (Hofmann-Wellenhof et al., 2008), as shown in Equation 4.1 (where c represents the speed of light).

$$R = \rho + \Delta\rho = \rho + c\delta \tag{4.1}$$

This simple equation makes the assumption that the range can be accurately measured, whereas in reality there are several factors that need to be mitigated, including:

- Timing (or clock) errors;
- Signal propagation;
- Signal obstructions;
- Receiver design; and
- Satellite ephemeris errors.

These factors are discussed in more detail throughout Section 4.3. Commonly, these errors are broken down into space, atmosphere, and receiver errors, although Section 4.3 outlines how the situation is much more complicated.

4.2.1 A brief history of GNSS

The precursor to today's GNSS constellations was the Navy Navigation Satellite System (NNSS), or Transit system, developed in the 1960s by the US military. The Transit system operated until 1996. The system eventually had six Low Earth Orbit (LEO) satellites in nearly circular polar orbits at an altitude of 1,100 kilometres. The satellites broadcast two carrier frequencies, which allowed single frequency receivers to achieve a position accuracy of better than 100 metres, and dual frequency receivers achieving an accuracy of 20 metres. A similar Russian system called Tsikada (or Cicada) consists of two constellations of satellites; six satellites for military use and four satellites for civilian use. The system has been operational since 1974 (Hofmann-Wellenhof et al., 2008). Much of the technology and techniques used in these systems can be seen in current GNSS services.

The Transit and Tsikada systems were very limited by today's standards, as a position fix was difficult to achieve (computationally intensive) and had low availability (between 30 and 110 minutes

in the Transit system) (Kaplan and Hegarty, 2009). This made the system unusable during highly dynamic operations, such as for aircraft navigation, and led to the development of GPS (originally called NAVSTAR (Navigation System Using Timing and Ranging)).

GNSS satellites orbit the Earth using methods that are characterised by their height and movement. The three main methods are:

- Medium Earth Orbit (MEO); which is an orbit between 2,000 and 35,786 kilometres above the Earth's equator;
- Geostationary Earth Orbit (GEO); which is a circular orbit at 35,786 kilometres above the Earth's equator, and follows the Earth's rotation; and
- Inclined Geosynchronous Orbit (IGSO); an orbit similar to a GEO orbit that appears to track a figure eight pattern in the north-south direction.

Global Positioning System (United States).

GPS became the first fully operational global satellite-based positioning system in 1995. In May 2000, the US Department of Defense officially switched off Selective Availability, which had been in place to degrade the position accuracy for civilian users. This sudden significant improvement in positioning performance led to the rapid expansion of GPS-enabled devices, services, and applications. In particular, pedestrian and vehicle navigation applications made the largest impact.

The new millennium saw GPS make significant development in satellite design and capability - such as adding additional signals, better timing systems, and greater anti-jamming resilience - but the replacement of the older generation satellites was delayed by their continued strong performance. The GPS III program conceived in 2000 aims to achieve sub-metre position accuracy for military and civilian users by 2030 (Brigadier General Haywood, 2010).

GPS continues to dominate consumer devices, and operate successfully at full operational capacity. The main disadvantage of the GPS system is that new modernised satellite vehicles are not due to replace existing satellite vehicles until needed, but the existing satellite vehicles are operating beyond their life expectancy, delaying the arrival of the new technology. The next generation GPS III satellite vehicles are currently being manufactured and launched, to replace older satellite vehicles in the GPS constellation.

The current GPS constellation consists of 31 operating satellite vehicles, with 7 satellite vehicles in reserve and 1 satellite vehicle under test (January 2015) (Langley, 2015).

GLONASS (Russian Federation).

The development and eventual success of GPS encouraged the Russian Federation (then the USSR) to develop its own system, known as GLONASS. Like GPS, GLONASS is a military system operated by the Russian Space Forces (Roscosmos) for the Russian government, although both GPS and GLONASS are stated to serve dual purposes by being available for civilian use. The race to achieve Full Operational Capability (FOC) was narrowly won by GPS, which achieved it in early 1995 (Kaplan and Hegarty, 2009). GLONASS was declared FOC later the same year, but shortly after the system began a decline that eventually led to a significantly reduced constellation. This was related to a lack of investment and maintenance after completion in 1995 and the collapse of the Russian economy.

Since 2003, further investment enabled the system to achieve 100% coverage of Russian territory by 2010, with 26 satellite vehicles in orbit, 20 of which were operational (Revnivykh, 2010). GLONASS then became the second fully operational GNSS system in December 2011 (for the second time, the first time ended in 1996). The 24 satellite vehicle constellation is complemented by additional spare and in-commission satellite vehicles, and Roscosmos is now well funded and developing the next generation of GLONASS satellite vehicles (GLONASS-K and GLONASS-KM). GLONASS traditionally uses the FDMA method of separating their frequencies, but the GLONASS-K satellites are to broadcast new CDMA frequency signals, which will bring further compatibility with GPS and Galileo. FDMA and CDMA are discussed in Section 4.2.3.

The current GLONASS constellation consists of 26 operating satellite vehicles (January 2015) (Langley, 2015).

Galileo (European Union).
The EU decided to develop their own satellite-based navigation system in 1998. Although it would be designed in a very similar way to GPS, the EU system would not be a military asset, and would be primarily for civilian use (Kaplan and Hegarty, 2009). The European funded Galileo system has been under test, and aimed to have 18 satellite vehicles operational by 2014, and the full 30 satellite vehicles in an MEO constellation around 2018 (Oosterlinch, 2010). Galileo is operated by the European Space Agency, with global positioning coverage supported by a global control network. A key element of Galileo is that it is fully compatible with GPS. The initial schedule aimed to have Galileo fully operational by 2008, although various delays to development and implementation meant that only 4 satellite vehicles were orbit at the start of 2015.

The Galileo project took a significant step forward in December 2011 with the broadcast of the first test navigation signal via the first of the two in-orbit validation (IOV) satellites. Two further IOV satellite vehicles were launched shortly after in October 2012. The first position was calculated using live signals (from the two IOV satellites and the two existing GIOVE (Galileo In-Orbit Validation Element) test bed satellites), and although the system was far from complete, it was possible to calculate a position with all four satellites in view. The next generation of Galileo satellites were launched in 2014, with an aim to establish the Initial Operational Capability (IOC) of 18 satellite vehicles by 2015.

Galileo plans to offer five services when fully operational, including:

- An open service;
- A commercial service;
- A SoL service;
- A public regulated service (for government authorised users); and
- A search and rescue service.

The current Galileo constellation consists of 4 IOV satellite vehicles (January 2015) (Langley, 2015).

BeiDou Navigation Satellite System (BeiDou II[1]) (People's Republic of China).
The People's Republic of China began developing its own satellite-based positioning system in the early 1980s, which led to the establishment of BeiDou I in 2003. This was a regional system that used two-way communications between an operation centre, three geostationary satellites, and the end-user. China joined the Galileo project as a partner in 2003, but after becoming dissatisfied with its role, decided to develop its own solution. BeiDou II, which operates in a manner that is more closely related to that of GPS, has seen rapid development and deployment since 2009, with the aim of becoming a fully operational global constellation by 2020.

The signal structure Interface Control Document (ICD) was released to developers in December 2012, and will have a similar structure to that of the GPS and Galileo systems (Pace, 2010). This mostly regional system is seen as central to China's future economic growth, although essential details about the system have not been made available to researchers outside of China.

BeiDou II was declared operational for the China region in December 2011, with FOC in this area declared in December 2012. The aim is to have 35 satellite vehicles in operation, including 5 IGSO satellite vehicles, by 2020 (GPS World (Editorial), 2010). Currently, BeiDou II has launched 16 satellite vehicles (six GEO, five IGSO, and five MEO), although not all are available (Langley, 2015).

4.2.2 GNSS segments

Each of the four major GNSS's includes the same general segment arrangement. Namely, there is a space, a control, and a user segment in each system. Figure 4.2 shows a simple graphical representation of each segment.

[1] BeiDou is Chinese for the "Big Dipper" asterism. The BeiDou II system was known as COMPASS for a short while, before the release of the Interface Control Document in December 2012. BeiDou II is not a development of the existing BeiDou I system.

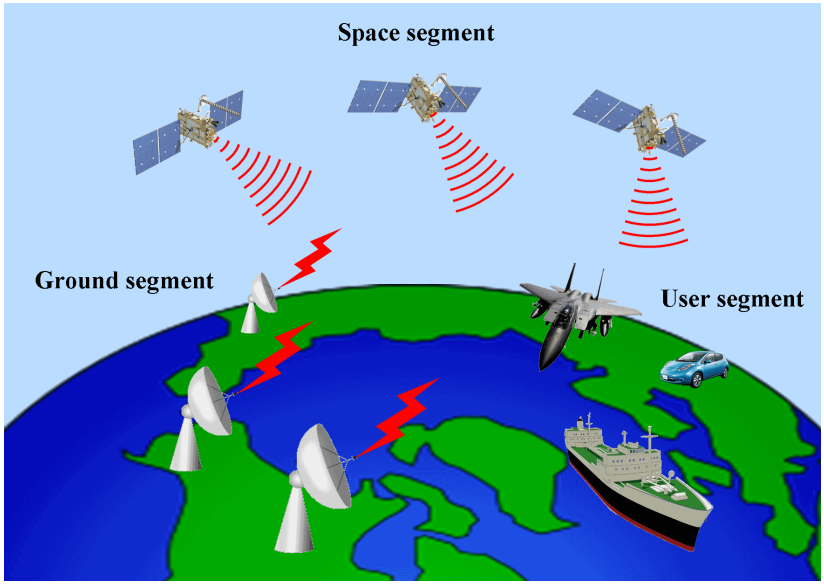


Figure 4.2 – GNSS segments.

The following sections give a brief introduction and overview of the three segments, but more detail can be found in Kaplan and Hegarty (2009) and Hofmann-Wellenhof et al. (2008).

4.2.2.1 Space segment

The space segment consists of the satellites in orbit around the Earth, their ranging signals and the data message (Kaplan and Hegarty, 2009). The satellites transmit a coded signal, from which the user can calculate range measurements.

Satellite constellation.
The GPS constellation uses a 24 satellite vehicle configuration, using six orbital planes of four satellite vehicles. Each nearly circular orbital plane is separated by 60 degrees, and is set at a nominal inclination of 55 degrees to the equator. The orbital radius is approximately 26,600 kilometres. A graphical representation of the GPS constellation is shown in Figure 4.3. The size of the satellites is not to scale, but their approximate relative locations at a single epoch are representative.

The GPS constellation provides global coverage all of the time. The orbital period of each satellite is slightly shorter than one sidereal day (11 hours and 58 minutes), which makes the constellation layout vary from one day to the next from the perspective of a ground user.

Each satellite can be identified in one of three ways:

- A letter and number representing the orbital plane and the number of the satellite vehicle (for example, C2 for orbital plane C, satellite number 2);
- The NAVSTAR satellite number, referred to as a Satellite Vehicle Number (SVN); or,
- The Pseudo-Random Noise (PRN) code generated by the navigation payload (unique to each satellite).

The constellation design is a compromise of good satellite geometry against the number of satellites. The GPS constellation provides a good geometry for the main purposes of the US Department of Defense. However, the other GNSS's have approached the problem slightly differently. The GLONASS constellation consists of three orbital planes at 64.8 degrees inclination with eight satellite vehicles on each, at an altitude of 19,100 kilometres, and an orbital period of 11 hours

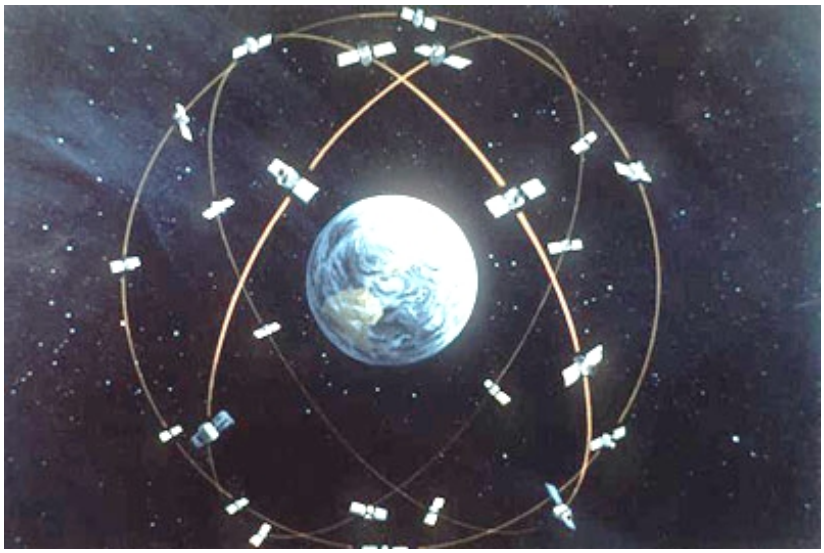


Figure 4.3 – A graphical representation of the GPS constellation.

and 55 minutes. This provides better geometry for uses at high latitudes - useful for the geography of the Russian Federation. Likewise, the Galileo constellation is designed to use three orbital planes, but at 55 degrees inclination and with eight satellite vehicles each, and at an altitude of 23,222 kilometres. BeiDou II will offer a total of 35 satellite vehicles, but whereas the other GNSS's use only MEO satellites, BeiDou II will use a combination of MEO, GEO, and IGSO satellites.

The geometry of the GNSS constellation can be measured using the parameter known as dilution of precision (DOP).

Satellite design.
The satellites carry a number of payloads, including:

- A vehicle control system payload to manoeuvre the satellite, and orientate the antennas to Earth and the solar panels to the Sun;
- A navigation payload to provide the GNSS position, navigation, and timing service; and,
- A nuclear detonation detection payload, used to detect radiation phenomena on Earth.

New satellites are typically more advanced than those that are to be replaced. Improvements in hardware design lead to more accurate clocks, better power consumption, and more reliable components (such as data storage and antennas).

Satellite replacements are usually only carried out as older satellites begin to fail, hence some of the earlier GPS Block II satellites launched in the 1990s with a design life of several years are still operating today. This has delayed the overall performance improvement of the GPS constellation, as only a small number of the satellites carry the latest hardware and transmit the modern signals. Part of this satellite replacement process is the use of reserve satellites in close orbit to those expected to fail soon, which leads to the number of satellites in the constellation (31 in January 2015) to be above the 24 required for a full constellation.

4.2.2.2 Control segment

The control segment is a ground-based system that tracks and controls the satellites in the space segment (Kaplan and Hegarty, 2009). It monitors satellite health, signal integrity, and issues instructions to the satellites to maintain the service. For instance, the control segment monitors the satellite clock corrections and ephemerides, and updates the satellite data message when necessary.

Ground control receivers are located around the globe, providing continuous monitoring of all orbiting satellites. They monitor the downlink L-band signals, contribute to navigation message updates, and identify satellite failures. Each GNSS has a main control centre, which coordinates the activities of the others. The GPS Master Control Station is located at US Air Force Space Command, Schriever Air Force Base in Colorado Springs, Colorado. The GLONASS System Control Centre is located at Krasnoznamensk, close to Moscow. The Galileo Ground Control Centre is located at Oberpfaffenhofen, close to Munich. Other locations are used by each of the GNSS's as monitoring stations, ground antenna uplink stations, or both.

4.2.2.3 User segment

The user segment consists of the GNSS receivers that are used to provide position, navigation, and timing information (Kaplan and Hegarty, 2009). The user segment receives the signals generated by the satellites in the space segment; the signals are passive, which allows an unlimited number of users to receive the signals simultaneously.

Through extensive product development, simple GNSS receiver chipsets have become miniaturised and very low-cost. If bought in a large quantity, individual unit costs can be approximately US$1. High accuracy GNSS receivers continue to be relatively bulky, as there is less desire for compact electronics. Figure 4.4 compares an early GPS receiver and its modern high precision descendant.

Figure 4.4 – GPS receivers then and now. Left: An early GPS receiver Manpack. Right: The latest Trimble GNSS backpack.

A typical GNSS receiver consists of an antenna, a signal receiver, a navigation processor, some form of input/output control, and a power supply.

Antenna.

The primary role of the GNSS antenna is to transform the electromagnetic satellite signals into an electrical signal. It should also minimise signal multipath and interference (Hofmann-Wellenhof et al., 2008). Satellite signals are received by a right-hand circularly polarised antenna, allowing near hemispherical reception. This allows the reception of satellite signals from any azimuthal direction, and from zenith to horizon (Kaplan and Hegarty, 2009). Antennas are also designed to have low gain for left-hand circularly polarised signals, as these have been reflected. There are various GNSS antenna types available - depending on the application - but the most common antennas for the user are patch, helix, and planar antennas. Most antennas act passively, but may include signal

preamplifiers and filters (a balance between removing out-of-band signals and creating additional signal distortion) (Hofmann-Wellenhof et al., 2008).

For static applications, the antenna typically uses a ground plane or choke ring design to minimise signals arriving at the antenna from below the horizon (for instance, those reflected from the ground). Mobile applications however, often require the ability to receive signals from below this angle due to the roll or pitch of the antenna during dynamic movements - such as experienced during the motion of a ship (Hofmann-Wellenhof et al., 2008).

A thorough examination of GNSS antennas is found in Rao et al. (2012). The experiments carried out in this thesis primarily used a Leica Geosystems AS10 antenna - a dual frequency wideband antenna that supports GPS, GLONASS, Galileo, BeiDou, and SBAS signals. The AS10 also has a built in ground plane.

Receiver[2].

The main purpose of the signal receiver is signal acquisition and tracking. The receiver is typically defined by the number and type of GNSS signals that are tracked. For instance, a basic receiver will track only the C/A code on the L1 frequency, whereas a state-of-the-art receiver will track multiple signals from multiple GNSS constellations. The receiver has multiple channels to allow the continuous tracking of satellite signals. Given the increased number of GNSS satellites in orbit, receivers have recently been developed that are capable of tracking hundreds of signals simultaneously.

The receiver front-end receives and conditions the incoming signal (Hofmann-Wellenhof et al., 2008). Receiver designs vary, but the receiver front-end typically consists of :

- A pre-filter to reduce out-of-band interference;
- A pre-amplifier to increase the signal strength; and
- An analogue to digital converter, which takes samples at a rate that is dictated by the signal frequency, and attempts to minimise the introduction of analogue to digital quantisation noise (Kaplan and Hegarty, 2009).

The signal is then passed to a digital signal processor, which is made up of multiple channels to track individual satellite signals. The digital signal processor may output three measurements: Pseudoranges; delta pseudoranges, and integrated Doppler. These measurements are passed to the processor along with the demodulated navigation message (Kaplan and Hegarty, 2009).

Navigation processor.

The navigation processor takes the information from the digital signal processor, then computes the time and decodes the ephemeris and almanac data message, before finally determining the position, velocity and corrected time (Hofmann-Wellenhof et al., 2008).

Some receiver designs include additional processors at different stages of the signal acquisition, tracking, and navigation processing. For instance, additional processing may be carried out in the digital signal processor. This is commonly the case in receivers designed for dynamic or high precision applications, as each processor will determine an independent position, velocity, and time solution, which can then be compared (Kaplan and Hegarty, 2009).

Input/output control.

The input/output (I/O) device is the interface between the GNSS receiver and the user. It is heavily influenced by the purpose and application of the GNSS receiver. For instance, a Sat Nav device will simply display navigation information and utilise the data for navigation guidance. Whereas a survey-grade receiver will allow the user to configure certain parameters of the navigation processor - such as the GNSS constellations to track, the elevation cut-off angle, and the implementation of any correction services - and observe the performance of the receiver in greater detail.

[2]The term GNSS receiver is commonly used to describe the whole user system.

Increasingly, the I/O device is required to interface with other devices, such as in an integrated navigation system. Common digital interfaces are well defined in electrical engineering (Kaplan and Hegarty, 2009).

Power supply.
The power supply is either integral or external (or a combination of both): A built in battery pack or an external power supply for integrated systems (Kaplan and Hegarty, 2009). Those receivers that primarily use external power typically include a small back-up battery to protect random access memory and maintain an accurate time and date, if a power failure occurs.

4.2.3 GNSS signal characteristics

GNSS satellites transmit electromagnetic signals to enable passive one-way ranging (Hofmann-Wellenhof et al., 2008). The signal contains all the information required for a receiver to calculate a range, including the transmission time of the signal from the satellite antenna. As described by Hofmann-Wellenhof et al. (2008), the signal is composed of three layers:

- The data-link layer, which contains the data message (for instance, the satellite ephemerides and time of transmission);
- the ranging code layer, which allows the receiver to calculate the signal propagation time; and
- the physical layer - the carrier frequency that is modulated by the data-link layer and the ranging code layer.

The data-link and ranging code layers are modulated on the carrier frequency. For the legacy signals this is performed using Binary Phase Shift Keying (BPSK), where the carrier frequency is subjected to a 180 degree phase shift (Kaplan and Hegarty, 2009). To allow the signals from multiple satellites to be distinguished from one another, multiplexing techniques are used. For GPS, the signals are identified through Code Division Multiple Access (CDMA) - a process where each satellite broadcasts a signal with the same frequency, but uses different ranging codes (known as the PRN codes). The legacy GLONASS signals use Frequency Division Multiple Access (FDMA), which allows the satellites to all broadcast the same ranging code, but at different frequencies.

Each GPS satellite actually broadcasts two PRN codes: A short Coarse/Acquisition (C/A) code, with a length of 1 millisecond; and a long precision (P)-code, that has a length equivalent to seven days. The P-code is encrypted (denoted as the P(Y)-code), and is generally only available to US military users. The C/A code is that used by the majority of civilian low-cost receivers (such as PND's, smartphones, and Sat Navs).

A number of GNSS signals are available, including legacy and modern signals, and there are variations between the different GNSS constellations. The legacy GPS signals are L1 and L2 (operating in the L-band of the electromagnetic spectrum). Both signal frequencies are broadcast from a satellite using the same PRN code (common navigation message). The L1 frequency is $150f$, and the L2 frequency is $120f$, where f is the fundamental frequency 10.23 MHz (Kaplan and Hegarty, 2009).

The modern GPS signals include L1C, L2C, L5, and two new military signals on frequencies L1 and L2. L1C and L2C are civil signals designed to improve the tracking performance of GNSS signals in challenging environments, such as indoors or under tree cover. This is primarily achieved by modulating two PRN codes onto the same signal, which are different lengths. The L5 signal also uses two PRN codes, but in this case the codes are the same length but the modulation is performed differently.

Single point positioning uses the C/A code on the L1 frequency - the signal with the greatest availability. Receivers developed in the future may utilise the L1C, L2C and L5 frequencies when all satellites are broadcasting (Kaplan and Hegarty, 2009).

For those who have access to the cryptographic equipment, precise point positioning uses the encrypted code (P(Y)-code) on the L1 and L2 signals. The C/A code on L1 is used to begin the

signal tracking process, before the tracking switches to the P(Y) code on L1 and L2 (Kaplan and Hegarty, 2009). For users who do not have access to cryptographic equipment, techniques have been developed to bypass the encrypted P(Y) code. This is enabled using semi-codeless receivers, which were developed to track the carrier-phase of the L1 and L2 signals. Due to the relatively short wavelength of the signals, the carrier-phase can be used to measure the fractional part of the wavelength, and with the correct hardware this allows sub-centimetre measurement accuracies. This is the basis for carrier-phase positioning, described in Section 4.3.5.

Table 4.1 summarises the available GNSS signals from the four GNSS services. The current status of the GNSS services can be found in Langley (2015).

Table 4.1 – Current and future GNSS constellations and signals (as of August 2015).

System			Signals											
GNSS	**Launched**	**Satellite Type**												
GPS	1990-1997	Block IIA	L1 C/A	L1/L2 P(Y)										
	1997-2004	Block IIR	L1 C/A	L1/L2 P(Y)										
	2004-2009	Block IIR-M	L1 C/A	L1/L2 P(Y)	L2C									
	2009-	Block II-F	L1 C/A	L1/L2 P(Y)	L2C	L5								
GLONASS	2003-	GLONASS-M	L1SF	L2SF	L1OF	L2OF								
	2011-	GLONASS-K1	L1SF	L2SF	L1OF	L2OF	L3OF							
	2015-2021	GLONASS-K2	L1SF	L2SF	L1OF	L2OF	L3OF	L1OC	L3OC	L1SC	L2SC			
	2021-	GLONASS-KM	L1SF	L2SF	L1OF	L2OF		L1OC	L3OC	L1SC	L2SC	L10CM	L2OC	L5OC
Galileo	2005	GIOVE-A (decom.)	E1-BOC(1,1)	E6										
	2008	GIOVE-B (decom.)	E1-CBOC	E5										
	2011-2012	IOV	E1	E5a	E5b									
	2014-2020	FOC	E1	E5a	E5b	E6								
BeiDou	2007	BeiDou-2 MEO												
	2009-2020	BeiDou-2 GEO	B1	B2	B3									
	2010-2020	BeiDou-2 IGSO	B1	B2	B3									
	2007-2020	BeiDou-2 MEO	B1	B2	B3									

4.2.4 Coordinate systems

Coordinate systems are required to enable the calculation of the positions and movements of the GNSS satellites and the user, and it is important that the choice of the coordinate reference system is applicable to both. The most common representation in these circumstances is to utilise a Cartesian coordinate system, which describes the states of the satellites and GNSS receivers in terms of position and velocity vectors (Kaplan and Hegarty, 2009).

The following paragraphs describe the coordinate reference system and reference frame of GPS. The principles are similar for the other GNSS services.

Reference systems.

To determine the orbits of the satellites an Earth Centred Inertial (ECI) coordinate system is used. The origin of the system is the centre of mass of the Earth, and the axes are fixed in relation to stars. This is sensible as the motion of the GNSS satellites obey Newton's laws of motion and gravitation (Kaplan and Hegarty, 2009). Due to the natural variation in the shape of the Earth, mainly due to the pull of the Sun and the Moon - the orientation of the axes in the ECI coordinate system is fixed at specific time: 12:00 (UTC) on the 1st of January 2000. As the axes are considered fixed at this epoch, the ECI coordinate system is considered inertial for GPS.

It is more sensible to use an ECEF coordinate system when referencing the position of a GPS receiver, as the calculation of the latitude, longitude, and height from the Cartesian coordinates (x, y, z) is less complex.

The orientation of the x, y, and z axes in each of these systems is described as a right handed coordinate system, due to the familiarity of the configuration to the fingers on the right hand.

During the calculation of the GPS orbits and satellite positions by the GPS receiver, the transformation between the two systems is controlled through the application of rotation matrices and velocity vectors. The precise orbits generated by service providers also deliver the GPS satellite information in the ECEF coordinate system.

Reference frames.

As the surface of the Earth is not a sphere, a model must be used to translate Cartesian coordinates into geodetic coordinates - generally this is x, y, and z to latitude, longitude, and height. GPS uses the World Geodetic System 1984 (WGS84). WGS84 uses an ellipsoid to represent the surface of the Earth. This is defined by its major and minor axes that create an eccentricity of $e^2 = 0.00669437999014$. As with the ECEF system, the origin of WGS84 is the centre of the Earth. This relationship allows the translation of the coordinates from the ECEF system to WGS84 (Kaplan and Hegarty, 2009).

Following the calculation of the GNSS receiver coordinates, an additional transformation may be required to utilise the information in ITS or V2X applications. This can include conversion to the vehicle body coordinate frame, discussed in Section 3.3.3.

4.2.5 Augmentation systems

Various applications are hindered by the position accuracy and poor integrity of GNSS positioning, including aviation and maritime applications. This has led to the development of augmentation systems. These augmentation systems are used to enhance the performance of satellite-based positioning (Hofmann-Wellenhof et al., 2008), based on the RNP principles. Augmentation systems are separated from traditional differential services due to the greater focus on improving the position integrity. Differential services are discussed in Section 4.3.

As defined by their names, GNSS's cover the entire globe, yet there are systems that operate over small areas. These systems can be used to supplement the global systems, and are referred to as ground-based augmentation systems (GBAS) or space-based augmentation systems (SBAS) (Hofmann-Wellenhof et al., 2008).

The N-RTK receiver used throughout this thesis utilises SBAS information from EGNOS (European Geostationary Navigation Overlay Service). This is a major benefit of the GNSS positioning technique, as the integrity of the position solution is significantly improved.

4.2.5.1 Space-Based Augmentation Systems

SBAS use a network of GNSS monitoring stations to continuously observe GNSS signals. The measurements are collated at a processing centre, where correction parameters are generated to account for satellite orbits, satellite clocks, and the ionosphere (Hofmann-Wellenhof et al., 2008). The monitoring stations also perform integrity checks on the GNSS observations. This information is then relayed to SBAS satellites, to be re-broadcast to end-users. The SBAS satellites use L-band frequencies to broadcast the information, which makes the systems compatible with GNSS receivers. Generally, SBAS improves the positioning performance of GNSS receivers in three ways (Hofmann-Wellenhof et al., 2008):

- The position accuracy is improved by using the correction information;
- The SBAS signal provides an additional ranging solution; and
- The SBAS integrity message significantly improves the time-to-alert for GNSS malfunctions.

The most common SBAS are:

- The Wide-Area Augmentation System (WAAS), designed to cover the US;
- the European Geostationary Navigation Overlay Service (EGNOS), designed to cover all of Europe; and
- the Japanese Multifunction Transport Satellite (MTSAT) Space-Based Augmentation System (MSAS).

Each of these systems uses geostationary or geosynchronous satellites to augment the existing global systems. Various private SBAS systems are also in operation, primarily designed to provide commercial corrections services. Table 4.2 summarises the current SBAS.

Table 4.2 – Current Space Based Augmentation Systems (as of August 2015).

SBAS System		Satellite Type	Notes
Public	**Launched**		
EGNOS	2011	Inmarsat-3-F2/AOR-E	EDAS system to receive corrections via web instead of GEO satellites. The Artemis satellite serves Eastern Europe and Central/Southern Africa. SES-5 is also known as Sirius 5 and Astra 4B.
	2012	Inmarsat-4-F2	
	2012	Artemis	
	2012	SES-5	
GAGAN	2011	GSAT-8	India Space Rearch Organisation, two GEO satellites.
	2012	GSAT-10	
MSAS	2007	MTSAT-1R	Two GEO satellites, operated to serve Japan.
	2007	MTSAT-2	
QZSS	2010	QZS-1	Japanese SBAS for GPS. The full system will comprise of three satellites.
WAAS	2005	Intelsat Galaxy 15	Support for GLONASS (despite non-GLONASS base stations).
	2005	TeleSat Anik F1R	L1/L5 support from 2018.
	2008	Inmarsat-4-F3	-
SDCM	2011	Luch-5A	Russian SBAS.
	2012	Luch-5B	
Private	**Launched**	**Satellite Type**	**Notes**
Omnistar	2008	8 GEO satellites	Trimble, decimetre-level positioning.
Starfire	2002	6 GEO satellites	John Deere, agriculture market.
Trimble RTX	2013	-	Better than 50 centimetre accuracy positioning.
Terrastar	2012	-	Provide services through partners.

4.2.5.2 Ground-Based Augmentation Systems

GBAS use the same principles as SBAS, but the delivery of the information to the end-user is via terrestrial communications and the systems are typically more local (although ground-based regional augmentation systems (GRAS) are in operation). The most common systems are local-area augmentation systems (LAAS), which are used to provide additional information to aircraft approaching landing strips. The International Civil Aviation Organisation (ICAO) outlines the requirements and performance in various categories to define precision approach specifications (Hofmann-Wellenhof et al., 2008).

Other methods of delivering GBAS information include the use of pseudolites or low-frequency radio systems such as Loran.

4.3 GNSS positioning techniques

There are many methods of utilising GNSS signals to produce a position solution. Techniques to produce the most accurate solution through post processing are well established, but these methods are not useful for ITS applications. The demand from ITS applications is for real time positioning. GNSS positioning is generally split into four major techniques: Stand-alone; DGNSS; RTK; and PPP. Each technique can be used in real time as well as post processed, but each has different characteristics and prerequisites. Figure 4.5 describes the relationship between position accuracy, position availability, and data bandwidth required for GNSS positioning. Generally, higher accuracy GNSS positioning techniques have lower availability and require greater data bandwidth to operate.

Figure 4.6 illustrates the relative differences in positioning accuracy of the main GNSS positioning techniques - the relative sizes of the circles are to scale. The outer circle in the figure

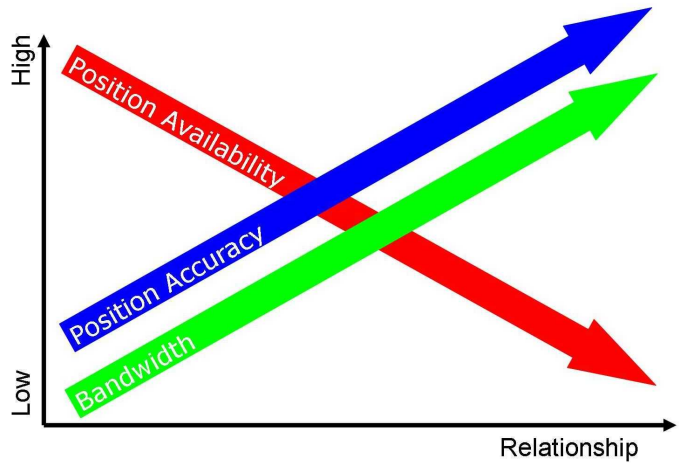


Figure 4.5 – The relationship between position accuracy, position availability, and data bandwidth of GNSS positioning techniques.

represents the theoretical positioning accuracy of stand-alone positioning, which is 13 metres. This can be improved to 5 metres by using multiple GNSS constellations, although this is not common. DGNSS positioning offers varying solutions delivering accuracy between approximately 2 metres down to 0.1 metres, and high precision techniques such as RTK and PPP will result in a positioning accuracy below 0.1 metres.

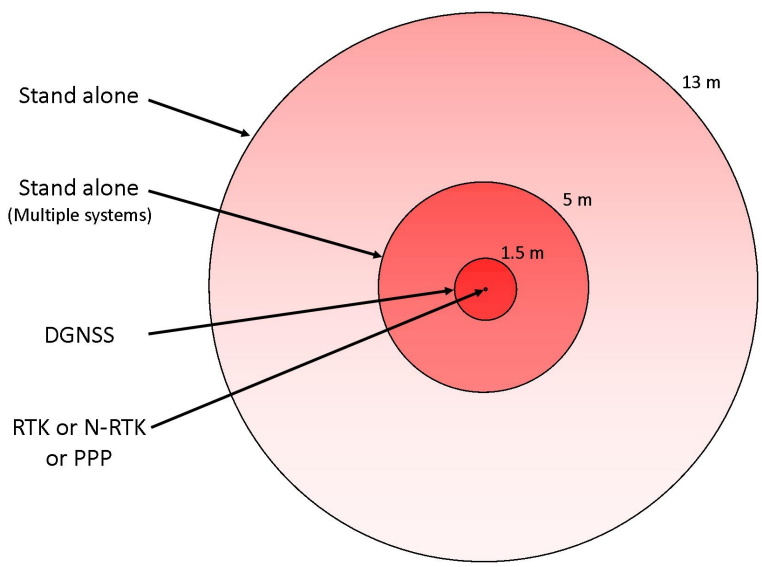


Figure 4.6 – The positioning accuracies of the main GNSS positioning techniques.

A number of GNSS positioning techniques have been developed to provide lower cost, better integrity, higher continuity, greater availability, or a mixture of all four. Table 4.3 highlights the main advantages and disadvantages of the most common techniques. The categories are coloured according to their perceived ability, with green as good, yellow as average, and red as poor. For example, stand-alone positioning provides poor accuracy but a good rating for cost, whereas RT-PPP provides good accuracy but a poor rating for cost. This trade-off is common amongst GNSS positioning techniques, and justifies the choice of different techniques for different applications.

Notably for this thesis, the average ratings achieved by N-RTK positioning for availability and continuity provide an opportunity for technique improvement. Chapter 5 and Chapter 6 explore this opportunity.

Table 4.3 – The ratings (poor, average, good) of the accuracy, cost, integrity, continuity, and availability of GNSS positioning techniques.

Technique	Accuracy		Cost	Integrity	Continuity	Availability
	Static	Moving				
Stand-alone	5 - 13	5 - 13	L	L	H	H
Differential GNSS	0.1 - 2	0.1 - 2	L	M	M	M
Real Time Kinematic	< 0.02	< 0.05	M	M	M	M
Network RTK	< 0.02	< 0.05	H	H	M	M
Precise Point Positioning	< 0.1	n/a	H	H	L	L
Wide Area RTK (WA-RTK)	n/a	n/a	M	M	M	M

Key	Poor	Average	Good

4.3.1 GNSS positioning technique categories

GNSS positioning techniques are generally distinguished along the following divides:

- Code or carrier-phase measurement;
- Absolute, relative, or precise point positioning;
- Static or kinematic modes; and
- Real time or post-processed solutions.

Code or carrier-phase measurement.
Making measurements using the navigation message on the carrier-wave, or by measuring the incoming phase of the carrier-wave and calculating the number of whole carrier cycles between the satellite and antenna (Kaplan and Hegarty, 2009).

Absolute, relative, or precise point positioning.
The position is either calculated in relation to the GNSS satellites only (absolute), calculated using measurements to known-location reference stations (relative), or using more precise GNSS information such as satellite clock and ephemeris data (precise) (Kaplan and Hegarty, 2009). Figure 4.7 shows the basic differences between the three classifications.

Static or kinematic modes.
The measurement algorithm either relies on the stationary nature of the receiver's antenna, or it can accommodate a moving antenna. Traditionally, static positioning techniques have resulted in significantly greater point accuracy, as multiple observations are made at the same location. By processing data collected over a long period, the errors and biases are minimised and the position achieves a greater confidence. The positioning algorithm could rely on the fact that the GNSS antenna did not change position from one epoch to the next in relation to the Earth. Whereas in a kinematic mode, the movement of the GNSS antenna introduces another set of unknowns between each epoch.

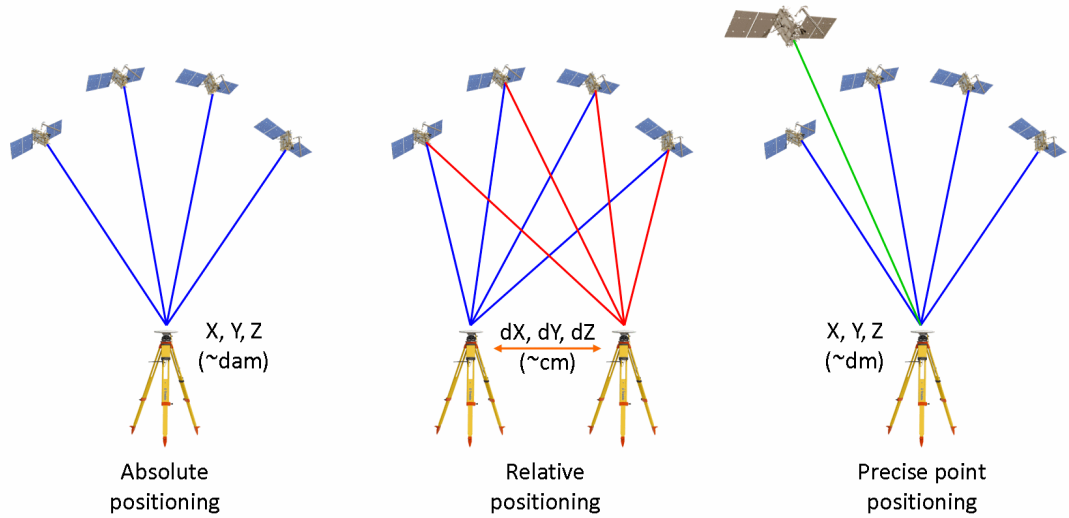


Figure 4.7 – GNSS techniques classification: Absolute, relative, and precise point positioning.

This difference in modes is less significant for code-based than carrier-phase-based measurement techniques. Code-based measurement techniques can provide a position using a single epoch of data (albeit with a set of prerequisites), whereas carrier-phase-based measurement techniques often rely on observations from a series of epochs (from a few seconds to several minutes) (Hofmann-Wellenhof et al., 2008).

Real time or post-processed solutions.
The position is calculated in real time (processing speed and data transmission delays notwithstanding), or the solution is calculated some time after the measurement is made (typically following the completion of a measurement campaign). Clearly, certain applications demand to know the position information near-instantaneously, such as for vehicle navigation, whereas land surveyors may sacrifice this ability in order to ensure position accuracy by utilising post-processing techniques.

There are a number of advantages of post-processed position solutions: Rogue data can be more easily identified and removed; a set of observation data can be processed as a batch; augmentation data can be used (such as precise ephemerides and GNSS reference stations); and the solution can be processed in a forwards or backwards direction (or both) (Hofmann-Wellenhof et al., 2008). Each of these advantages provides added solution integrity.

4.3.2 Correlation of GNSS errors

The process of measuring a range from the satellite to the receiver is a complex procedure that is hindered by the presence of various error sources. The signal is generated by a satellite, broadcast by an antenna, travels thousands of kilometres through a changing atmosphere, arrives in the local area of the GNSS receiver before reaching the GNSS antenna, and is finally passed through to the GNSS receiver. Each stage of this journey creates an opportunity for error. The minimisation of these errors is crucial to achieving an accurate position.

There are five categories of GNSS errors, namely:

Satellite and receiver clock errors.
The clock offsets translate directly into range and phase measurement errors. Although the GNSS satellites carry very accurate atomic clocks, there is a deviation between satellite vehicle time and GNSS time, which is only updated on the GNSS navigation message every 24 hours (approximately). At the update time, this deviation is equivalent to approximately 0.8 metres in

range, and shortly before it is updated the deviation can be up to 4 metres (Kaplan and Hegarty, 2009).

Ephemeris errors.
Accurate knowledge about the location and status of the satellites is required to reference the location of the GNSS receiver. Errors in the ephemeris data message create errors in the orbital positions of the satellite vehicles. In real time, the ephemeris is used to predict the location of the satellites over the short term, and is effectively updated every 12 minutes. However, if the solution is being post-processed, there are products available that provide a more accurate ephemeris based on the known movements of the satellites (Hofmann-Wellenhof et al., 2008).

The error in the orbital position of a satellite vehicle is in the region of 1 to 6 metres, although this translates into a range error of only 0.8 metres.

Tropospheric errors.
The troposphere is the lowest section of the atmosphere, and the location of all weather on Earth. The carrier component of the signal is delayed by the troposphere, but advanced by the ionosphere - this is a process known as ionospheric divergence (Kaplan and Hegarty, 2009). The delay caused by the troposphere is related to the local temperature, pressure and humidity. The propagation of the GNSS signals through the troposphere can be delayed by the equivalent of 2.4 metres at the zenith to approximately 25 metres close to the horizon. There are two components of tropospheric error, known as wet and dry. The dry component contributes to about 90% of the total tropospheric delay and can be accurately modelled. Greater detail can be found in Kaplan and Hegarty (2009) and Hofmann-Wellenhof et al. (2008).

Ionospheric errors.
The ionosphere is the section of atmosphere between 70 and 1000 kilometres above the Earth's surface. The typical delay signal caused by the atmosphere at the zenith is between 3 and 15 metres - mostly varying due to the time of day (night or day). A signal observed close to the horizon can be delayed by up to three times the delay at the zenith, with range errors of between 9 and 45 metres (Kaplan and Hegarty, 2009).

There are two main strategies to counter the ionospheric errors: Using ionospheric models to estimate the error; and utilising multiple signals using different frequencies from the same satellite (as there is a relationship between the signal frequency and the level of delay).

Receiver noise and multipath errors.
The reflections of the GNSS signal local to the GNSS receiver can add significant distance to the signal path, and various receiver internal error sources can be present, such as antenna phase offset error, thermal noise jitter, and local signal interference (Kaplan and Hegarty, 2009). The equivalent range error caused by receiver noise is typically less than 10 centimetres.

Multipath errors can vary greatly, depending on the local environment and the receiver design.

Prior to May 2000, Selective Availability on the GPS signal introduced an additional error source. Selective Availability was primarily achieved through the dithering of the satellite clock, although there was also the ability to manipulate the broadcast ephemeris message (Kaplan and Hegarty, 2009).

4.3.3 Stand-alone positioning

Stand-alone positioning (also known as *point*, *single point*, or *autonomous positioning*) determines the position using the carrier-signal code pseudoranges and navigation code message. Stand-alone positioning is an original method of position calculation. It uses the C/A code modulated on the carrier-phase of the electromagnetic GNSS signal, and can deliver a position accuracy of 13 metres (2-SD). This is a statistical measure of the user's position accuracy, and it will often be better or worse. GPS is maintained to provide a pseudorange with a 7.8 metre accuracy (95% confidence)

for any place on Earth - when this is combined for several pseudoranges, atmospheric effects, and receiver hardware performance, the stated 2D position accuracy for GPS is 13 metres.

GLONASS provides a similar positioning accuracy. If the receiver takes advantage of the modern signals or multiple constellations then it can deliver accuracy better than 5 metres (Hofmann-Wellenhof et al., 2008). These figures can be improved by smoothing - for instance, by using the phase ranges, or by adopting a Kalman filter (useful for dynamic applications).

The GNSS receiver operates autonomously in this technique, using only the received signals transmitted from the GNSS satellites. All of the information required by the receiver to calculate a position is included in the GNSS signals, such as the satellite ephemeris and almanac[3]. Equation 4.1 describes the calculation of the range from the user receiver to each satellite. As noted in Section 4.2, the range is known as a pseudorange as it requires a correction due to a time error or bias, introduced by the relatively inaccurate internal clock in the GNSS receiver.

4.3.4 Differential positioning

Differential techniques for positioning and navigation were originally developed to circumvent the Selective Availability degradation of the L1 frequency imposed by the US Department of Defense on the GPS signals (Hofmann-Wellenhof et al., 2008). Since Selective Availability was reduced to zero level in May 2000, these techniques have continued to be developed to enhance the performance of GNSS positioning. The principle of DGNSS is based on a system of a minimum of two receivers: One reference receiver that has a known position; and a rover receiver with an unknown position. The range from the known reference receiver position to the known satellite position can be calculated and compared to the measured range, using either pseudorange or carrier-phase measurements. This will result in a difference constituting three error sources: Satellite-specific biases; signal propagation errors; and receiver-specific biases (Hofmann-Wellenhof et al., 2008). Assuming that both receivers are measuring ranges to the same satellites and positioned locally, the satellite-specific biases and signal propagation errors can be effectively eliminated or reduced (essentially an interferometric technique). Spatial decorrelation causes the accuracy to degrade at a rate of approximately 1 centimetre per 1 kilometre (Hofmann-Wellenhof et al., 2008). The differential corrections can be used to post-process the positions of the rover receiver, but it is more typical to transmit them from the reference receiver to the rover receiver via a dedicated communication link such as ultra- or very-high frequency (UHF or VHF) radio.

In practice there are several DGNSS products available (Hofmann-Wellenhof et al., 2008):

- Free differential correction systems (marine use);
- Free space-based augmentation systems (aviation use);
- Commercial augmentation systems (agriculture/surveying);
- Commercial RTK systems (engineering surveying); and
- Assisted GNSS (mobile phone applications).

4.3.5 Carrier-phase relative positioning

GNSS satellites are in constant orbital motion; and the end-user is typically Earth fixed. This relationship means that the change in relative position from epoch to epoch is extremely significant. To account for this, the GNSS receiver must be capable of measuring the Doppler frequency of the GNSS signal very accurately. When dual frequency observations are made, the resulting integration of the Doppler frequencies can be used to make very precise phase measurements, providing centimetre-accurate position solutions.

The phase of the GNSS signal can be measured very accurately by a GNSS receiver, and the phase of the signal during transmission from the GNSS satellite can also be determined. However,

[3]The almanac is not relevant for dual frequency GNSS positioning. The almanac is used to model the ionospheric errors, but these errors can be removed by comparing the impact of the separate frequencies.

there remains a difficulty when determining the number of whole carrier-phase cycles between the satellite and receiver. This is known as the integer ambiguity, and it needs to be resolved (Kaplan and Hegarty, 2009).

Various techniques have been developed to resolve this integer ambiguity, but carrying out this resolution on a moving platform remains a difficult task. Initial techniques used the Ambiguity Function method to resolve the ambiguities, but this is not viable in dynamic, real time applications.

The most successful techniques take advantage of dual frequency observations; in particular, the combination of the two frequencies to create a sum wavelength and a difference wavelength. The difference wavelength (known as the wide lane) increases the efficiency of the integer ambiguity resolution as its wavelength is approximately four times greater than either of the original frequencies (Kaplan and Hegarty, 2009). The wavelength of the sum of the frequencies is 10.7 centimetres, and the wavelength of the difference is 86.25 centimetres. This does require the receiver to simultaneously track dual frequencies, and the noise level is much greater (the noise factor for the wide-lane increases six fold).

Once the integer ambiguity is resolved, the GNSS signals must be continuously tracked to maintain its relevance. An interruption in this tracking is called a cycle slip, and it requires the integer ambiguity resolution to re-start (Hofmann-Wellenhof et al., 2008). This is an important factor for the high precision GNSS positioning of road vehicles, as cycle slips are inevitable due to the dynamic nature of road vehicle environments. Thus, the desire is to achieve an instantaneous integer ambiguity resolution.

When the rover receiver is mobile and used to provide instant positions with a short occupation time, this system is known as RTK positioning. It is typically used in applications such as high precision surveying and machine control, but its applications in ITS are limited. This is mainly due to the restriction of baseline length, as the performance of the RTK positioning deteriorates because of increased spatial decorrelation (Hofmann-Wellenhof et al., 2008). This is one of the main reasons that the distance between the reference receiver and the rover receiver should be less than 20 kilometres for RTK positioning using a single reference station (Meng et al., 2008). The other major reason is the radio power constraint and line of sight requirement. In the UK the power used by UHF/VHF radios has to be less than 0.5 Watts. Pseudorange and carrier-phase observations are measured using dual frequency receivers at the reference and rover locations, and integer ambiguities are fixed at the reference station and calculated on-the-fly (OTF) at the rover receiver. The volume of data transmitted in this method is approximately sixteen times that transmitted in code based DGNSS (US Army Corps of Engineers, 2003).

4.3.5.1 Real time kinematic positioning

Although carrier-phase relative positioning can be performed as a post-processed solution, this would not suffice for most ITS and V2X applications. Therefore, the position solution must be determined in real time. This form of carrier-phase relative positioning is known as RTK positioning.

The calculation of the position using carrier-phase observables is defined in detail in Hofmann-Wellenhof et al. (2008) and Kaplan and Hegarty (2009). However, the undifferenced carrier-phase observable ($\varphi_k^p(t)$) is described in Equation 4.2 to provide context for the following sections (Hofmann-Wellenhof et al., 2008):

$$\varphi_k^p(t) = \varphi_k(t) - \varphi^p(t) + N_k^p(l) + I_{k,\varphi}^p(t) + \frac{f}{c}T_k^p(t) + d_{k,\varphi}(t) + d_{k,\varphi}^p(t) + d_\varphi^p(t) + t_\varphi \tag{4.2}$$

Where $\varphi_k(t)$ is the receiver phase at nominal time (of reception) t; $\varphi^p(t)$ is the phase of the signal at the satellite; and $N_k^p(l)$ is the initial integer ambiguity (referred to as the lane identifier), an arbitrary counter setting at the start of phase tracking. The errors in the range measurement are also included. $I_{k,\varphi}^p(t)$ is the error due to ionospheric effects (a negative value as the carrier-phase is advanced in the ionosphere); $T_k^p(t)$ is the correction for tropospheric effects (where $\frac{f}{c}$ is used to convert the units to cycles); $d_{k,\varphi}(t)$ is the hardware effect of the satellite; $d_{k,\varphi}^p(t)$ is the hardware effect of the receiver; $d_\varphi^p(t)$ is the multipath; and t_φ is the random carrier-phase measurement noise.

4.3.5.2 Integer ambiguity resolution

The ambiguity can be resolved in either the measurement, coordinate, or ambiguity domains, using a number of different techniques. By far the most common technique is the LAMBDA method (Least squares AMbiguity Decorrelation Algorithm), which operates in the ambiguity domain. This technique essentially contains four steps (Teunissen and Verhagen, 2004):

1. Least squares adjustment (float solution).
2. Integer estimation (integer least squares).
3. Acceptance test (ratio test).
4. Correct the float solution (fixed solution).

This robust technique has been adapted and improved upon by many researchers over the past two decades, and has proved very successful. However, even though it provides useful results when applied in an automotive context, the technique is not generally flexible or forgiving enough to deal with the continuously changing environment, such as the rapidly changing number of visible satellites, or the dynamic multipath. This is particularly the case with the validation step, number three. A ratio threshold is usually chosen as a fixed number, say 3.0, based on the underlying GNSS models. However, given the receiver's situation can change dramatically in the automotive environment, the ratio threshold is not similarly adjusted to suit.

Work by Teunissen and Verhagen (2004) suggests that instead of a fixed ratio threshold, a fixed failure rate is used, based on the probability of successful integer ambiguity resolution. The fixed failure rate, selected by the user (say 0.005), will adjust the ratio threshold based on the underlying GNSS model.

Figure 4.8 shows the results from post-processed GNSS observations recorded over one lap of the No.1 circuit at the MIRA proving ground. The results are processed epoch by epoch, in a method similar to RTK positioning. During the lap the vehicle passes under a bridge, at approximately 11:54:12, at which time the number of visible satellites drops too far to retain the fixed ambiguity solution. Note also that the ratio value varies throughout the test, but with the threshold is set to 2.0, the number of fixed ambiguity solutions is 53.1%. This data was processed using an Ordnance Survey base station located approximately 24 kilometres away, which is not ideal.

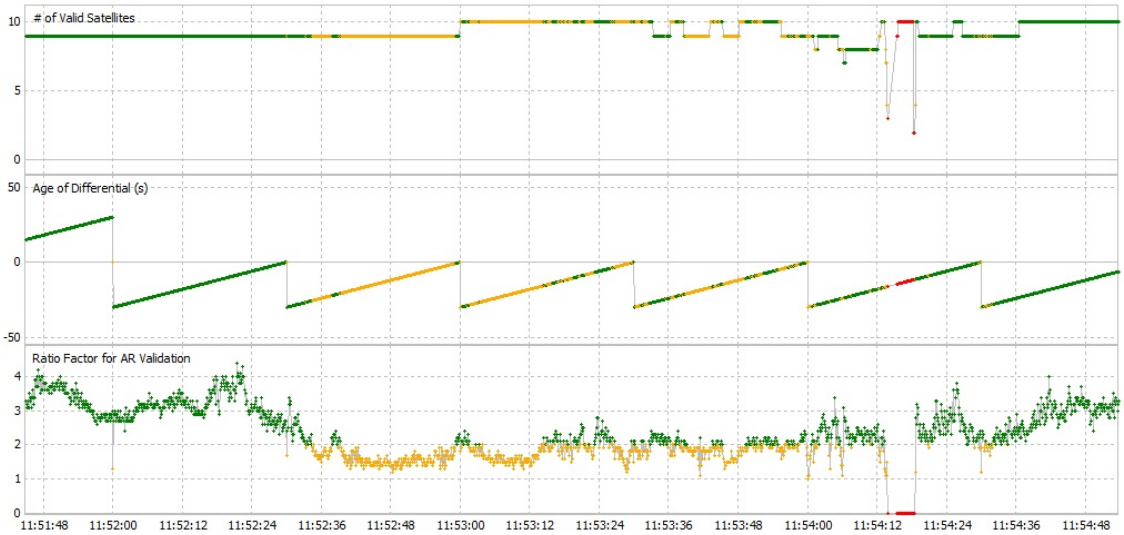


Figure 4.8 – The instantaneous ambiguity resolution results from one lap of the MIRA No.1 circuit.

Manipulation of the ratio threshold results in observations that can be up to 2.4 metres different, which in the automotive environment corresponds to a different lane location, generally due to the use of the float solution as the validation test is not passed.

The initial integer search and ambiguity resolution of an RTK GNSS receiver is relatively fast, typically within two minutes from a cold start, or fewer than twenty seconds from a hot start. Recent research has shown that it is possible to increase the speed of the ambiguity resolution, and customize the integrity controls, which would make the resolution process close to instantaneous in certain circumstances. However, this often requires reducing the integrity and including additional sources of external information.

In Figure 4.9 the fixed and float solutions are compared. The fixed solutions are those that pass the ratio threshold of 3.0, and the float solution was created using the same observation data but not allowing the integer ambiguity to be fixed.

The figure shows that the positions of the solutions vary from approximately 0.1 to 1.2 metres. The biggest variation occurs when the ratio value is low, suggesting that the selection of the fixed ambiguity is less certain. A simple interpolation of the chart shows that when the fixed ambiguity position is far from the float solution (in calculated position), the 'second best' fixed solution may also be a good candidate.

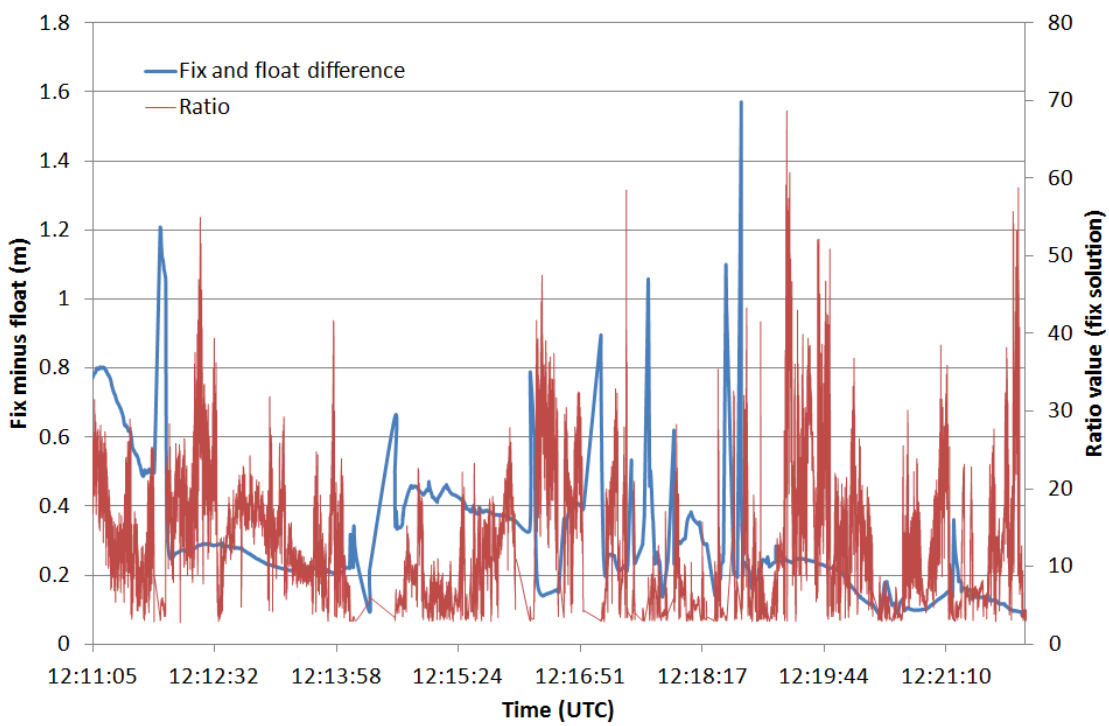


Figure 4.9 – The assessment of the ratio test in integer ambiguity resolution.

Ambiguity resolution in the automotive domain.

The determination of the carrier-phase ambiguities OTF is a key element of centimetre level precise positioning in real time (Kaplan and Hegarty, 2009). However, real time carrier-phase positioning is difficult in a dynamic environment such as would be experienced by a road vehicle; the availability of GNSS signals varies greatly over a short period of time, and if signals are lost the ambiguity resolution may need to be restarted. After initialisation, continuous lock must be kept on at least four satellite signals. In survey operations, this often requires pre-mission reconnaissance to ensure satellite visibility (Hofmann-Wellenhof et al., 2008).

Initialisation of OTF phase ambiguity resolution can be performed in less than two minutes (from a cold start), using dual frequency measurements and good pseudorange measurements. With low noise, the narrow correlator spacing technique can be used (Hofmann-Wellenhof et al., 2008).

A cycle slip or loss of signal lock causes the phase measurement to be re-initialised, and cycle counting must be re-started (Xu, 2007). A by-product of this process means that cycle slips are not a problem if the ambiguity is resolved epoch by epoch. The most widespread technique used to carry out the integer carrier-phase ambiguity resolution is the LAMBDA method.

4.3.6 Network-RTK positioning

To obtain the most accurate position for GNSS positioning, measurements are made of the number of carrier-phase cycles and the phase of the incoming GNSS signal. This carrier-phase GNSS positioning can be used to provide real time centimetre accuracy positioning, even in dynamic applications (dependent on satellite visibility, receiver and antenna design, and multipath mitigation).

4.3.6.1 Concept

RTK positioning can be used to provide a solution at an accuracy of better than 5 centimetres (horizontal) (Hofmann-Wellenhof et al., 2008), as well as a solution with high integrity, calculated in real time, and at a high output rate. This relies on the static reference receiver being located within 20 kilometres of the roving receiver, observing a good selection of common satellites with dual frequency receivers.

RTK positioning has proven to be successful at providing high accuracy position data for many end-users, but the requirement for a short reference-rover baseline is considered a significant limitation. When RTK positioning is used, the distance to the reference station has a bearing on the successfulness of the integer ambiguity resolution. A short baseline will benefit from a closer correlation of errors, due to the GNSS signals travelling through very similar parts of the atmosphere. Assuming each receiver is observing common satellites, this similarity will typically result in a higher success rate in the ratio test (using the common LAMBDA technique (Teunissen and Verhagen, 2004)). This is particularly important following a GNSS signal outage. This limitation is known as the spatial decorrelation of errors: As the distance between the reference and rover receivers increases, the correlation of the errors decreases, resulting in lower precision, more difficulty in correctly identifying the common integer ambiguity, and of observing common satellites (Rizos and Han, 2003; Leica Geosystems, 2011; Fotopoulos and Cannon, 2001; Wanninger, 2004).

N-RTK positioning has been designed to tackle this short baseline limitation. By removing this limitation, N-RTK positioning gives the end-user a wide mobility range, which is particularly important for automotive applications.

Figure 4.10 shows the main advantage of N-RTK positioning as compared to traditional RTK positioning. In the left-hand diagram, the individual RTK reference stations suffer from the spatial decorrelation of errors as the distance between reference and rover receivers increases. This is a major deterrent for vehicle positioning, as a wide range of mobility is required, which would require individually operating reference stations to be placed approximately 20 to 30 kilometres apart. However, a network of GNSS reference receivers (a CORS network) can be used to develop a model of differential corrections, as shown in the right-hand diagram, from which a rover receiver can interpret RTK correction information and utilise this during the computation of its position.

A minimum of four or five reference stations are needed for a successful network, depending on the network correction technique and the region size that one intends to cover (Rizos and Han, 2003; Leica Geosystems, 2011). The geometry of a CORS network allows two adjacent reference stations to be located up to 80-100km apart without degrading the accuracy (Fotopoulos and Cannon, 2001), although in practice most systems tend to locate them closer together than this. This is essentially a reduction from 30 reference stations per 10,000km^2 for conventional RTK, to 5-10 reference stations for N-RTK positioning, which is a very cost-effective approach that can deliver high precision services to virtually unlimited users (Wanninger, 2004).

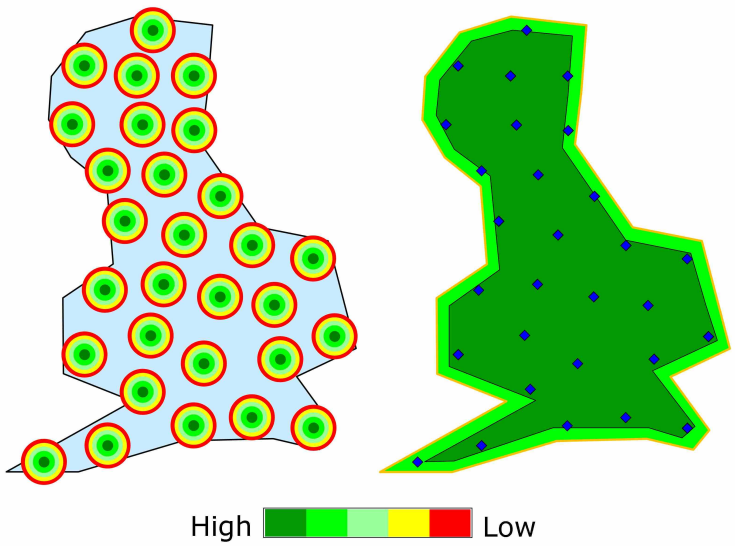


Figure 4.10 – The correlation of errors in RTK (left) and N-RTK (right).

The N-RTK positioning technique also provides other advantages. For instance, centralising the data collection and processing allows various techniques of differential correction calculation to be used, including those that consume the highest level of processing power (Wanninger, 2004). This means an N-RTK enabled receiver can be simpler and cheaper to manufacture. It also helps provide a robust and open quality control system as all the observation and correction data can be traced, and the process can be standardised and consistent between different users.

The transmission protocol of the N-RTK corrections is typically Radio Technical Commission for Maritime Services (RTCM) v3.0 or higher, and the composition of the correction information varies depending on the commercial service provider. The different N-RTK positioning concepts are discussed in Section 4.3.6.3.

Although there are other terrestrial-based positioning systems, the N-RTK positioning method using CORS networks is still the only reliable, real time, wide area coverage, and centimetre-level accuracy positioning technique available (Lorimer, 2010). It is expected that the CORS networks will become a critical part of a country's infrastructure, and countries like the UK are at the forefront. This makes N-RTK positioning one of the most promising positioning technologies for road vehicles and ITS applications. However, previous research has shown that N-RTK positioning of a road vehicle has two important limitations: The level of coverage of communication networks to deliver the important N-RTK correction messages; and the effect of GNSS signal obstruction and multipath. Finding effective solutions to these current barriers, which are preventing the wide adoption of N-RTK positioning, is seen as a key enabling step for ITS (Meng et al., 2008).

The proliferation of N-RTK positioning systems has increased dramatically over the last decade. Networks of CORS are liberally spread across Europe, North America, Australia, and East Asia. Networks vary in size from five or six reference stations serving as a positioning system for agriculture, to systems containing hundreds of CORS's that provide national or regional levels of service, primarily for various geosciences, environmental, and engineering applications. As an example, Figure 4.11 shows the location of the OS Net CORS run by Ordnance Survey in Great Britain.

4.3.6.2 N-RTK positioning availability

There are numerous commercial systems providing national correction information in Europe. Reference networks are either available or planned in most areas, with countries like Germany, France and the UK leading the way.

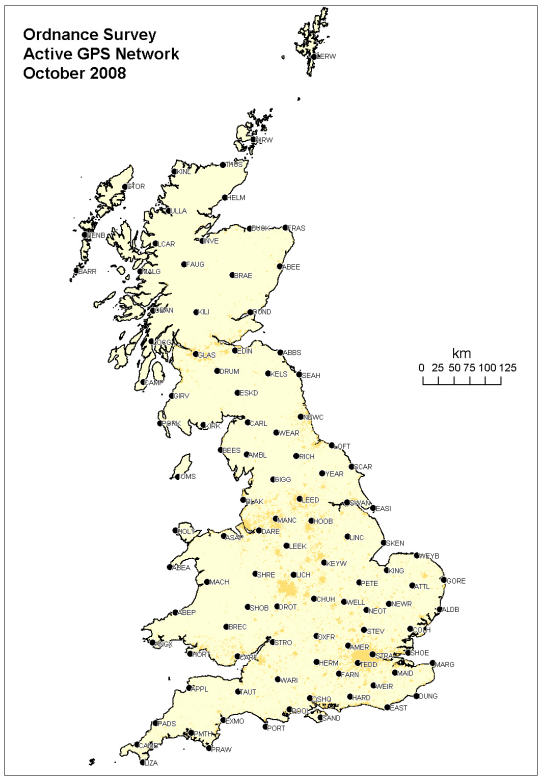


Figure 4.11 – OS Net reference station network in Great Britain, owned by Ordnance Survey.

The European Position Determination System (EUPOS) was set up in 2002 by constituents of central and eastern European countries to define and agree on the guidelines to N-RTK systems - specifically using the International EUPOS Steering Committee to give advice on network set up and financial guidance (EUPOS, 2011). The current estimate is that the combined total number of reference stations across the 18 member countries will be approximately 900. Guidelines are available for three levels of service: a DGNSS service with accuracy up to 50 centimetres; an RTK service offering an accuracy of up to 2 centimetres; and a geodetic service for post-processed accuracies of better than 1 centimetre.

In the UK there are five main national N-RTK commercial services. In 2015 they were:

- SmartNet from Leica-Geosystems;
- TopNET Live from Topcon;
- VRS Now from Trimble;
- FarmRTK from Axio-Net; and
- Essentials Net from Soil Essentials.

Each system utilises the Ordnance Survey's network of reference stations, called OS Net and totaling 108 CORS (as shown in Figure 4.11).

Leica Geosystems' SmartNet service has been operating since 2006, and has recently undergone an upgrade (Leica Geosystems, 2011). SmartNet combines a network of its own reference stations with those of OS Net to provide a corrections service to subscribers in RTCM standard, using Networked Transport of RTCM via Internet Protocol (NTRIP) over mobile or fixed internet. Leica-Geosystems also operate SmartNet in Ireland, Italy, Sweden, Norway, Lithuania, Slovakia, and parts

of Spain. In April 2009, Topcon partnered with Ordnance Survey to use OS Net in its TopNET subscription service (Topcon, 2011).

The Trimble VRS Now service bases its system on the VRS N-RTK concept (as described in Section 4.3.6.3). It is also available in the Czech Republic, Estonia, Germany, Ireland, and Spain (Trimble, 2011).

FarmRTK and Essentials Net are both designed for precision agriculture. Axio-Net offers a selection of services to European countries (Axio-Net, 2015). This includes European coverage of network corrections from 60 CORS providing sub-metre accuracy, with more accurate solutions available in Germany, Denmark, the Netherlands, and Great Britain using local CORS. The services are mainly aimed at commercial customers such as in agriculture and construction. The service offered in Great Britain also involves a partnership with Ordnance Survey to use OS Net.

In the US, the National Geodetic Society (NGS) runs a CORS network of over 1,450 reference stations, and provides an RTK support service and guidance using a subset of its stations (National Geodetic Survey, 2010). China has the ambition to establish a comprehensive CORS network that consists of more than 2,260 geodetic grade reference stations, covering the whole country.

4.3.6.3 N-RTK techniques

There are two main variations of N-RTK positioning: The Master Auxiliary Concept (MAC) and the Virtual Reference Station (VRS) concept. The VRS concept is the most prevalent in end-user devices, although the MAC concept is generally considered to provide the highest performance. The three concepts are described below. A detailed discussion can be found in Fotopoulos and Cannon (2001), Wanninger (2004), and Janssen (2009).

Master Auxiliary Concept.

The MAC concept is designed to allow the GNSS receiver at the end-user (rover) to perform the calculation of the differenced position. It is enabled by sending all relevant GNSS base station data to the rover receiver, which allows the rover receiver to perform a network adjustment (Euler et al., 2001). The volume of data that would need to be transmitted is large, but the MAC concept takes advantage of similarities in the GNSS information to make efficiencies. It assigns one reference station as the master, and calculates the correction differences and coordinate differences to all the other stations in the network (the auxiliary stations). It is this information that is transmitted to the rover receiver (Aponte et al., 2009).

The rover receiver may use the correction difference information to interpolate the error at its location, or reconstruct the observation information from all reference stations in its network, depending on processing power, and then perform double differencing to calculate its position.

Clearly, this concept relies on a two-way communication link between the end-user and the N-RTK processing centre, as the approximate location of the end-user is required to determine the correct information to broadcast. Although with a small network or separate services relating to pockets of reference stations, one-way communication would be viable as the selection of the master station is not important. This data link means that N-RTK positioning could be limited by availability of mobile data. Although the availability of a communication link is still an issue, the downlink data speed demands only 5.6 Kbps (Rubinov et al., 2011).

Correction information is transmitted at 1 Hertz, although the transmission frequency of tropospheric and orbit errors is only required every five seconds (0.2Hz). The dispersive and non-dispersive corrections are also broadcast separately (Janssen, 2009).

Virtual Reference Station.

It has long been established that a short baseline between reference and rover receivers leads to more accurate and successful relative GNSS positioning, as discussed later in Section 4.4.1. A short baseline can effectively deal with the satellite orbit and atmospheric errors, which become difficult to deal with as the baseline length grows, and is the reason why RTK positioning is typically limited to baselines of less than 20 kilometres (Hofmann-Wellenhof et al., 2008). A typical RTK baseline may be between one and ten kilometres, but it is still beneficial to reduce the baseline

further, particularly if there is a large difference in elevation. This is enabled by the VRS N-RTK technique. By using the observation data from several permanent reference stations that surround the rover location (for instance, using the OS Net reference stations shown in Figure 4.11), a virtual reference station is created close to the location of the rover, including virtual observation measurements and position. This VRS information is transmitted to the rover, and the rover receiver treats the information like that of a real reference station. This technique can deliver better than 5 centimetre accuracy up to 35 kilometres (Retscher, 2002).

The principle builds on the transfer of measurements made at the real reference stations to the virtual reference station. The carrier-phase measurement at the real reference station (Φ_r^s), shown in Equation 4.3, is made up of the geometric distance between the receiver and satellite ($\frac{1}{\lambda^s}\delta_r^s(t)$), the integer ambiguity (N_r^s), and the receiver and satellite clock bias ($f^s\Delta\delta_r^s(t)$). The key to the VRS technique is that the integer ambiguity and the receiver and satellite clock bias are not location dependent, so they can be transferred directly to the virtual reference station from the real reference station (Janssen, 2009).

$$\Phi_r^s = \frac{1}{\lambda^s}\delta_r^s(t) + N_r^s + f^s\Delta\delta_r^s(t) \tag{4.3}$$

By differencing the carrier-phase equation of the real and virtual reference stations ($\Phi_r^s(X_A,t)$ and $\Phi_r^s(X_V,t)$, respectively), the ambiguity and clock errors are cancelled. The result is shown in Equation 4.4.

$$\Phi_r^s(X_V,t) = \Phi_r^s(X_A,t) + \frac{1}{\lambda^s}\left[\delta_r^s(X_V,t) - \delta_r^s(X_A,t)\right] \tag{4.4}$$

By combining the carrier-phase measurement equations at the real and virtual reference stations, only two unknown terms remain. The first includes the coordinates of the virtual reference station ($\delta_r^s(X_V,t)$), which is in principle arbitrary and is typically the approximate location of the rover receiver. The second is the observable of the VRS ($\Phi_r^s(X_V,t)$), which can now be obtained without actually measuring it. In practice the technique is a little more complex, as satellite orbit and atmospheric errors and biases need to be modeled for the VRS position (Hofmann-Wellenhof et al., 2008). The VRS information can then be packaged using the RTCM standards and delivered to the rover receiver to enable N-RTK VRS positioning. The download data link demands a speed of at least 1.8 Kbps (Rubinov et al., 2011).

As described in Brown et al. (2005), the MAC concept exceeds the performance of the VRS concept in time-to-first-fix, reliability, ambiguity resolution, and accuracy. However, the VRS concept is more simple for the end-user and supports legacy GNSS receivers.

4.3.6.4 Communication standards

A protocol developed by the Federal Agency for Cartography and Geodesy of Germany (BKG), called NTRIP, enables the streaming of DGNSS or RTK correction data via the internet. NTRIP has three main components: The NTRIP server; the NTRIP caster; and the NTRIP client (Leica Geosystems, 2005). The components of an NTRIP system are shown in Figure 4.12. The NTRIP server runs a software package that communicates directly with one or more reference stations (known as the NTRIP source). For instance, Leica SpiderNet software connected to the Ordnance Survey's OS Net reference station network. The NTRIP server can perform additional tasks such as data processing and integrity checking, before passing on the DGNSS or RTK correction information to the NTRIP caster. The NTRIP caster acts as a gatekeeper between the end-user and the NTRIP server. It is a Hypertext Transfer Protocol (HTTP) server that receives data from one or more NTRIP servers, and passes it on to one or more NTRIP clients (the end-user). The NTRIP caster requires an authenticated username and password to access the correction information, and the whole operation is performed via an internet connection. The NTRIP client receives the correction data from the NTRIP caster, and can use it to calculate its own DGNSS or RTK position.

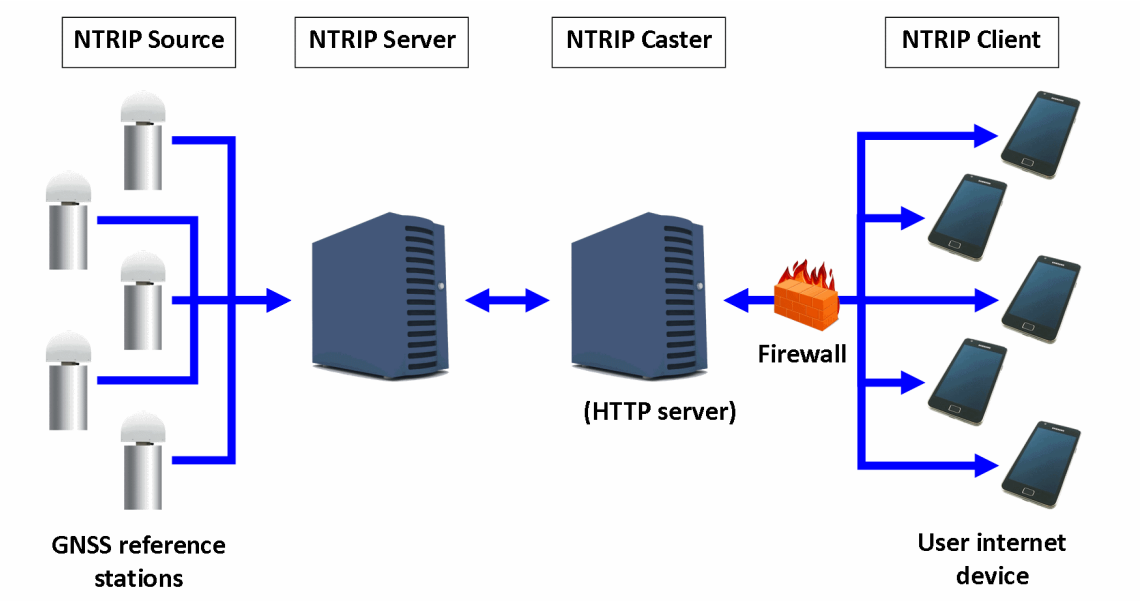


Figure 4.12 – The components of an NTRIP system.

4.3.6.5 Previous vehicle positioning research using N-RTK

As shown in previous research (Aponte et al., 2008), N-RTK positioning can deliver a vehicle positioning accuracy of better than 5 centimetres, and in real-world tests this level of accuracy had an availability of between 41% and 45% (depending on the environment). It was also found that the correction information was available via the GSM network for over 80% of the time. In these same tests the total time without any GNSS position solution (N-RTK, DGNSS, or stand-alone) was up to 16% in a motorway environment. The tests were carried out using the NGI's test vehicle, using post-processed GPS and IMU data, and digital map data, as ground truth. The results showed that N-RTK positioning was able to provide lane-level positioning accuracy, but the sensitivity of the technique to GNSS signal loss and coverage of the communication network had a significant effect on availability. GNSS outages could be caused simply by passing under a road bridge, and the N-RTK solution would be lost, although there would continue to be a DGNSS solution for a short period.

4.3.7 Precise Point Positioning

The PPP method builds on the stand-alone technique described earlier in this Chapter, but aims to use much more accurate satellite clock and ephemeris information. These are some of the most significant error sources in GNSS positioning, and have traditionally been difficult to estimate (Hofmann-Wellenhof et al., 2008). Post-processed PPP solutions have been shown to deliver better than decimetre accuracy (Lachapelle and Petovello, 2006). By using the precise satellite clock and ephemeris information, PPP can utilise carrier-phase measurements, including resolving the integer ambiguity. However, the resolution is typically time consuming and relies on power hungry processing algorithms, taking as long as 20 minutes to resolve the ambiguity - much too long for ITS applications.

The PPP products are created from observation data collected at GNSS reference stations. A relatively small number of reference stations are required to provide PPP coverage over large areas, which makes this technique especially useful for marine applications. As the GNSS antenna on a ship is likely to have a continuous clear sky view, the long initialisation time is not significant. Recent work has shown that near real time PPP solutions can be achieved, using modern PPP products generated from networks of CORS (Tobías et al., 2014).

PPP uses State Space Representation (SSR) products - which include precise clocks, orbits and ionospheric models - generated by public and private GNSS receiver tracking networks. The products are delivered to the receiver via the internet or communications satellites.

4.4 RTK positioning for road vehicles

RTK positioning is not used for mainstream vehicle positioning, other than for controlled activities such as agricultural applications. There are several factors that hinder the wider adoption of RTK positioning for road vehicles. These are detailed in the following Sections.

4.4.1 Length of base-rover baseline

The length of the straight line distance between the base and rover receivers is known as the baseline. Typically this distance is limited in RTK positioning, as the principle used in this technique relies on the correlation of the GNSS errors at the two sites. As the baseline length increases these errors become less correlated, often referred to as the spatial decorrelation of errors. Therefore, RTK positioning is limited to an operating range of approximately 10 to 15 kilometres from the base station. Beyond this range, the threshold value for the integer ambiguity resolution ratio test is difficult to reach.

This issue is particularly evident when the base station does not have accurately known coordinates - for instance, during the relative positioning of two road vehicles. Due to the lack of knowledge about GNSS errors provided by a base station with known coordinates, the ratio test is effectively easier to pass and the receivers are placed on a common ambiguity. As highlighted by Teunissen and Verhagen (2004), the ratio test is not an accurate measure of the successfulness of integer ambiguity resolution (using the LAMBDA method).

This limiting factor for RTK positioning for road vehicles is addressed in Chapter 6, by demonstrating how the V2X concept can be utilised in a new cooperative positioning technique.

Figure 4.13 shows how the accuracy of the relative baseline length decreases as the baseline length increases during a relative positioning trial using two vehicles. The figure only includes instances when the fixed ambiguity was resolved. During this test, the number of common satellites varies more frequently and the multipath environment is more dynamic. The fixed ambiguity resolution passes the ratio test successfully, but as the baseline length increases this becomes less reliable, to the point where a 1,200 metre baseline will be in error by approximately 0.5 metres.

4.4.2 Age of Correction

An important aspect of accurate and precise RTK positioning is the prompt and continuous delivery of the RTK correction message to the end-user. The metric used to measure this is called the Age of Correction (AoC), and its unit of measure is seconds. An RTK correction message is created either by a central server operated by a service provide or a user's own RTK base station. The correction message is delivered to the end-user via some communications medium, typically mobile internet, which is responsible for the majority of any delay or loss of message.

Figure 4.14 shows the effect of the AoC on RTK positioning accuracy. It shows that as the AoC increases, the corresponding position error also increases, with the worst position error occurring at an AoC of 25.8 seconds (43 millimetres). The trend line suggests that for each second of additional AoC, the position error increases by 1.1 millimetres (the trend line has an R^2 of 0.69). The results shown in the figure are only those producing a fixed integer ambiguity solution, and each epoch is treated independently from the last (the ambiguity resolution is not continuous). The data was generated using the fixed base station at the NGB, delivering RTK corrections once every 30 seconds (hence, the maximum AoC is 30 seconds). The rover receiver was located on the electric locomotive on the roof of the NGB as it completed one full lap of the circuit. The GNSS receiver was a Leica GS10 using a Leica AS10 antenna.

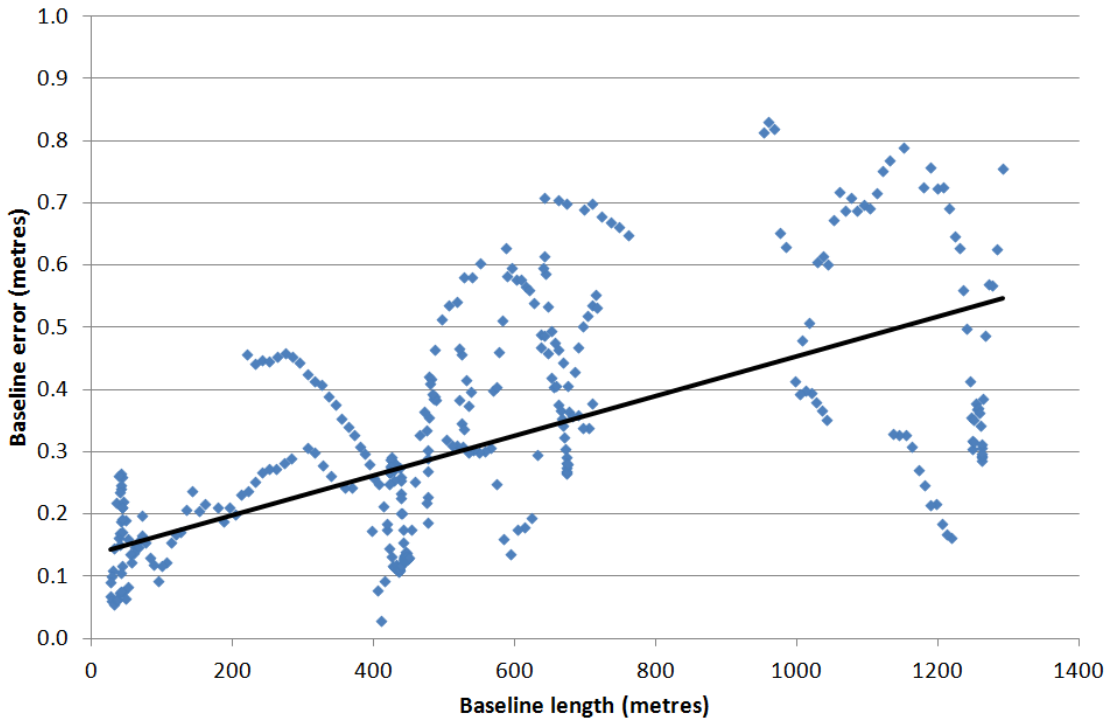


Figure 4.13 – The decrease in accuracy and precision of the RTK baseline length over increasing baseline length (fixed integer solutions).

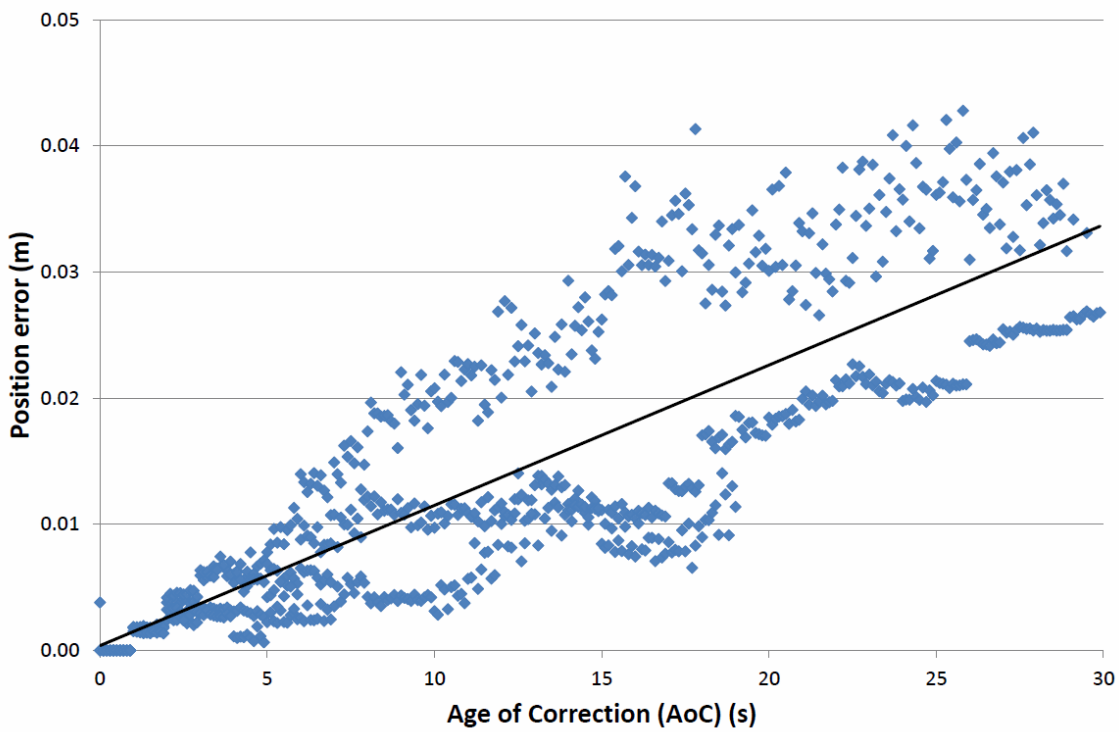


Figure 4.14 – The relationship between RTK positioning accuracy and the AoC message.

4.4.3 Number of satellite vehicles

As with all GNSS positioning techniques, RTK positioning requires a minimum of four satellite vehicles to be visible. In fact, RTK positioning needs the four satellites to be visible at both the base and rover receivers. Integer ambiguity resolution can be carried out using four satellite vehicles, although there is a significantly lower probability of doing so correctly. Figure 4.15 shows the effect of the number of satellites vehicles on the positioning performance of RTK positioning during a drive around the NGI loop in Nottingham (more details about the NGI loop are given in Section 5.7.2). Each of the figures represent the results of RTK positioning under different satellite vehicle visibility scenarios. The number of visible satellite vehicles is artificially limited. The chart in the top left of Figure 4.15 shows the results of RTK positioning when a maximum of four satellites are visible, with the successive charts to the right and then down on to the second row increasing this number by one, until the bottom right hand chart that shows the limitation of nine visible satellite vehicles. The solution types are: RTK fixed (green); RTK float (yellow); and stand-alone position (red). Note that there is no representation in the figures when no solution was provided by RTK positioning, other than a visible gap in the results.

The trial lasted for 29 minutes and 50 seconds (1,790 epochs at 1 Hertz), and includes 3 loops of the NGI circuit. The RTK positioning was performed on an epoch-by-epoch basis, independent from any previous calculation. The base station used was NGB2, located on the roof of the NGB (providing a short baseline). The number of visible satellite vehicles was limited by excluding satellites using their PRN code - the satellite providing the least availability during the trial was removed sequentially. Figure 4.16 shows the skyplot of the available satellites during the trial, for which satellites with PRN's G12, G22, G17, G09, and G27 were removed to produce an artificial satellite vehicle visibility limit.

Table 4.4 shows the numeric results of the driving trial. It shows that RTK positioning gives a good performance when up to nine satellite vehicles are visible, with only 3.6% of the time with no position solution and 82.3% of the time provided a position using a fixed integer ambiguity. When the limit of satellite vehicle visibility is set to four, the percentage of solutions providing an RTK fixed position drops to 30.3%, with 27.0% of epochs producing no solution. However, there is not a gradual change from one extreme to the other. As the table suggests, and as can be seen in Figure 4.17, there is a very gradual decrease in RTK positioning performance from nine to six visible satellite vehicles, after which a significant drop occurs at five satellites (61.9% RTK fixed) and at four satellites (30.3% RTK fixed).

Also of significant note is the mean ratio value at each satellite vehicle visibility limit. When the limit is nine satellites the mean ratio is 14.1 - a reasonably high figure that suggests a high confidence in successful integer ambiguity resolution. At a limit of eight visible satellites this mean ratio actually increases slightly to 14.4, which could be interpreted as an increased confidence in correct ambiguity resolution. As is noted by Teunissen and Verhagen (2004) however, the ratio value is not a direct indicator of the successfulness of integer ambiguity resolution using the LAMBDA method.

Table 4.4 – The influence of the number of visible satellite vehicles on the RTK positioning performance (metres) of road vehicles.

Satellite vehicle limit	Satellite vehicles (mean)	Mean ratio	RTK fix		RTK float		Stand-alone		None
			%	3D sd. (m)	%	3D sd. (m)	%	3D sd. (m)	%
9	6.5	14.1	82.3	0.021	7.0	3.413	7.0	38.538	3.6
8	6.3	14.4	82.0	0.023	6.9	3.585	7.1	38.547	4.0
7	6.0	14.0	82.0	0.024	6.4	3.526	7.4	38.171	4.2
6	5.3	12.2	80.9	0.026	6.3	3.919	8.0	37.481	4.7
5	4.5	6.1	61.9	0.030	16.2	3.497	11.6	35.943	10.3
4	3.7	2.8	30.3	0.019	25.3	1.929	17.4	34.331	27.0

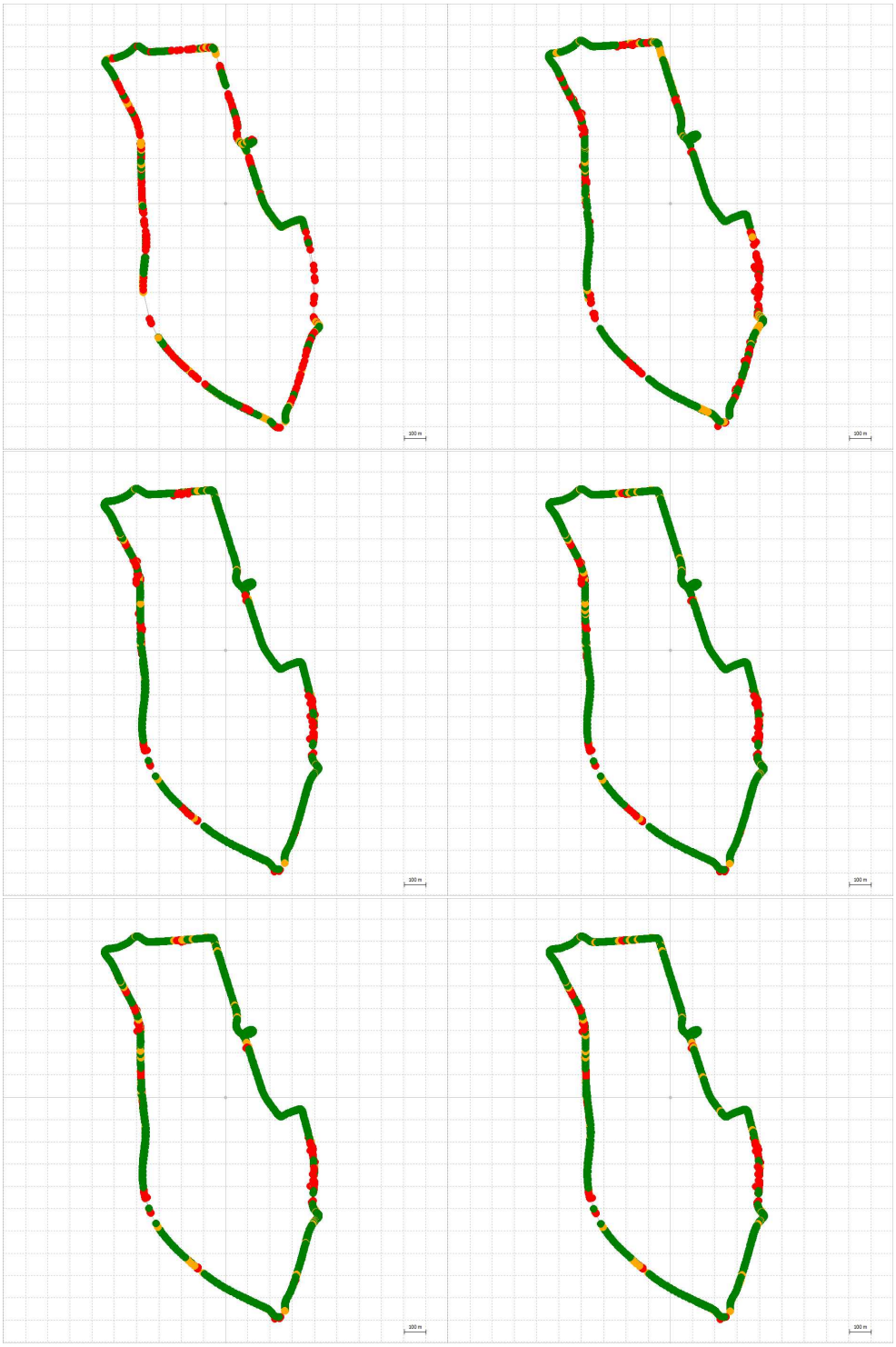


Figure 4.15 – The effect of the number of visible satellite vehicles on the performance of RTK positioning of a road vehicle. From 4 visible satellites in the top left to 9 visible satellites in the bottom right.

During periods of variation in the number of visible satellite vehicles, RTK positioning can become unstable and tends to resort to a float solution. This is a characteristic brought about

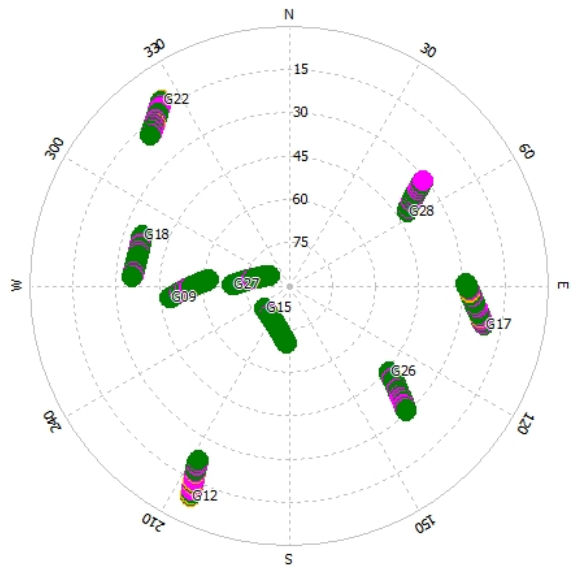


Figure 4.16 – Skyplot of the visible satellite vehicles during the satellite visibility driving trial.

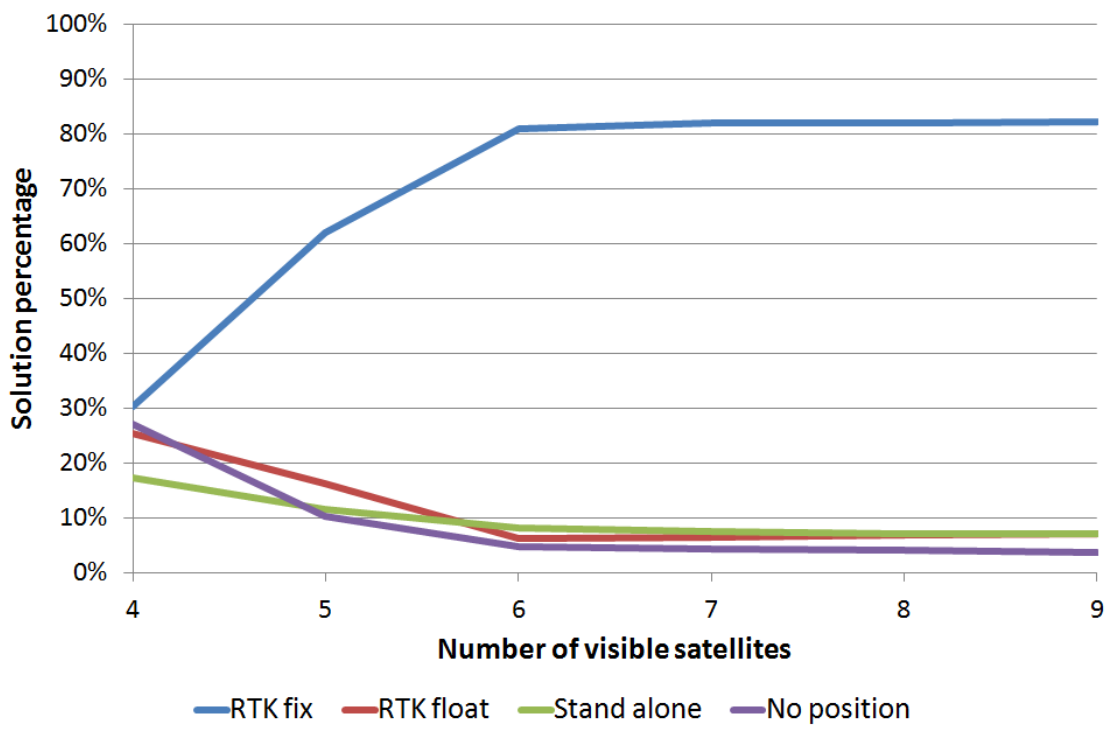


Figure 4.17 – How the number of visible satellite vehicles affects the solution type.

through the design of the GNSS hardware, as the demand of the typical end-user (engineering surveyor) is for high integrity of the fixed solutions. Hence, when using the GNSS hardware for vehicle positioning in a dynamic environment with a regular variation in visible satellite vehicles, the RTK position solution will tend to a float solution during periods when the number of satellite vehicles is changing. This includes periods when the number of visible satellites is increasing.

Figure 4.18 demonstrates this issue. During the same NGI circuit trials as above, a N-RTK receiver was used to calculate the vehicle position. In this figure, a solution type 4 is N-RTK fixed, and solution type 2 is N-RTK float. The change in the number of visible satellites from one epoch to the next is shown in blue. During periods of rapid satellite vehicle visibility changes, the solution tends to be N-RTK float, and periods of stable satellite vehicle visibility tend to produce a higher proportion of N-RTK fixed solutions.

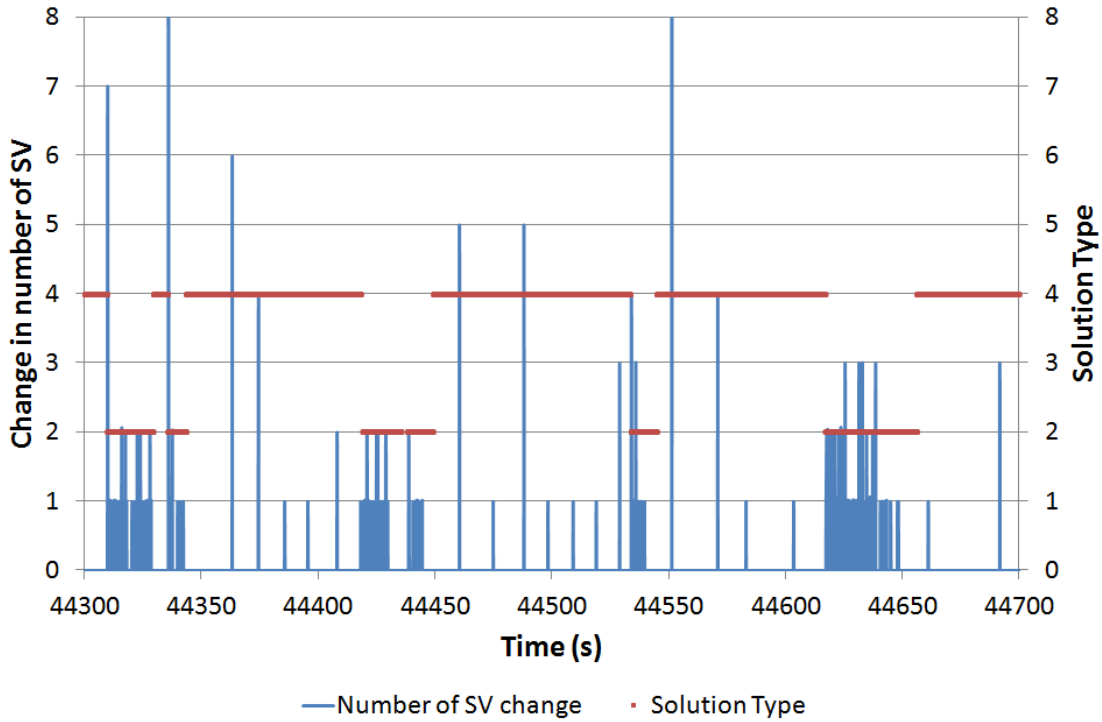


Figure 4.18 – The effect of a change in the number of visible satellites on the RTK solution type.

4.4.4 Type of integer ambiguity resolution

For dynamic vehicle positioning applications, there are three main forms of integer ambiguity resolution for RTK positioning:

- ***Instantaneous*** integer ambiguity resolution treats each epoch independently, thus the ambiguity is estimated and resolved on an epoch-by-epoch basis;
- ***Fix and hold*** integer ambiguity resolution operates in a similar way to continuous integer ambiguity resolution, but the ambiguity is more tightly constrained once fixed; and
- ***Continuous*** integer ambiguity resolution estimates and resolves the integer ambiguity over a continuous series of observation epochs, in a method similar to that of static applications, but by allowing for the dynamic movement of the vehicle.

Each of these methods has their own merits, and can prove advantageous in different driving conditions. However, they are all limited by the use of the fixed ratio threshold in the LAMBDA ambiguity resolution process. As shown in Table 4.5, the choice of ambiguity resolution method used can produce different results. Using the same data from the NGI circuit trial, the post-processed (forward only) results of the three methods show the instantaneous integer ambiguity resolution method produces 82.3% RTK fixed solutions, compared to 69.6% for fix and hold and 68.9% for continuous.

Table 4.5 – Comparison of integer ambiguity resolution methods.

Integer ambiguity resolution method	Solution type (%)			
	RTK fixed	RTK float	Stand-alone	None
Instantaneous	82.3	7.0	7.0	3.6
Fix and hold	69.6	19.7	7.0	3.6
Continuous	68.9	20.4	7.0	3.6

4.4.5 Integer ambiguity resolution ratio threshold

During integer ambiguity resolution using the LAMBDA method, the most probable solution is compared to the second most probable, resulting in a ratio. A ratio of 1 suggests that there is no difference in the probability of either of the solutions being correct based on the available information. To pass the ratio test, a threshold is chosen above which the first solution will allow the ambiguity to be fixed.

Typically, applications will use a ratio threshold of between 2 and 5, normally dependent on the preference of the operator setting the configuration or the manufacturer's default. Table 4.6 shows the effect of setting a different ratio threshold during the NGI circuit trial (using instantaneous integer ambiguity resolution). Clearly, a ratio threshold of 1.0 will result in 0.0% of the solutions being classified as RTK float, as where an integer ambiguity is available it will be set as fixed. After an initial steep decline, the percentage of RTK fixed solutions decreases steadily until 49.1% of the solutions are RTK fixed at a ratio threshold of 10.0. Figure 4.19 shows this trend graphically. The change in ratio threshold has no effect on the number of solutions that are stand-alone (7.0%) or not available (3.6%).

Table 4.6 – The effect of the ratio threshold on the solutions from RTK positioning.

Ratio threshold	Solution type							
	RTK fixed		RTK float		Stand-alone		None	
	%	3D sd	%	3D sd	%	3D sd	%	3D sd
10.0	49.1	0.015	40.3	2.951	7.0	38.538	3.6	-
8.0	56.8	0.016	32.5	3.175	7.0	38.538	3.6	-
6.0	65.0	0.018	24.4	3.113	7.0	38.538	3.6	-
4.0	72.1	0.019	17.2	3.292	7.0	38.538	3.6	-
2.0	82.3	0.021	7.0	3.386	7.0	38.538	3.6	-
1.8	83.1	0.021	6.2	3.489	7.0	38.538	3.6	-
1.6	83.7	0.021	5.6	3.596	7.0	38.538	3.6	-
1.4	84.7	0.021	4.6	3.439	7.0	38.538	3.6	-
1.2	85.8	0.022	3.5	2.843	7.0	38.538	3.6	-
1.0	89.3	0.022	0.0	-	7.0	38.538	3.6	-

The accuracy of the solution does not vary significantly. The 3D standard deviation (taken from the estimated covariance matrix in the observation equations) shows that the position accuracy slightly improves as the ratio threshold increases. At a ratio threshold of 1.0 the 3D standard deviation is 0.022 metres, and at a ratio threshold of 10.0 the 3D standard deviation is 0.015 metres (for the RTK fixed solutions).

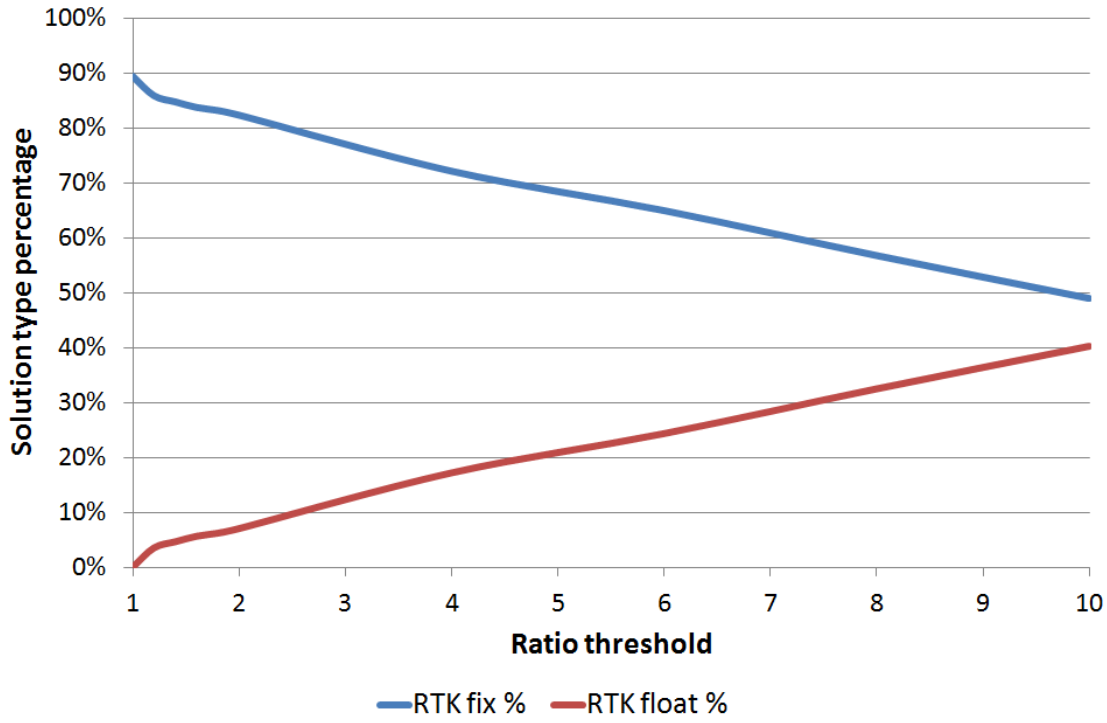


Figure 4.19 – Comparison of ratio thresholds on solution types for RTK positioning.

4.5 Future development of GNSS

When fully operational, the four GNSS services and affiliated SBAS and GBAS will offer the user a constellation of over 120 MEO satellite vehicles, and 20 GEO satellite vehicles (Brigadier General Haywood, 2010; Revnivykh, 2010; Oosterlinch, 2010). There will be extensive ground networks providing highly detailed models, precise orbits, and robust integrity. The systems will most likely develop other positioning techniques or methods.

The developments will offer systems with increased power, improved interoperability, built-in integrity, more accurate clocks, longer codes to improve multipath mitigation, and improved satellite geometry. In practice this will lead to reduced (or better modelled) multipath, increased visibility and availability, faster acquisition, better atmospheric modelling, and the extension of GNSS positioning to further applications.

These improvements will further enable GNSS positioning for ITS and V2X applications. In particular, the availability of a high precision solution will be significantly increased in areas currently vulnerable to signal obstruction - such as urban canyons - as more satellites will be visible in the reduced sky view. There will also be an increased likelihood that nearby vehicles are able to view common satellites; an important factor when performing relative GNSS positioning between two vehicles.

4.5.1 Interference, jamming, and spoofing

GNSS signals are electromagnetic waves, which by their nature are affected by signal attenuation, refraction, reflection, and interference from other signals of similar wavelengths. These characteristics create errors in the GNSS observations made by GNSS receivers, and are mitigated by using various hardware and software developments, and various positioning techniques. However, in recent years, there has been increasing concern about the fragility of GNSS positioning to intentional or unintentional interference, jamming, and spoofing (Inside GNSS, 2010).

This concern is brought about through a combination of increasing reliance on GNSS positioning, the ubiquity of its use, the crowding of the electromagnetic spectrum, and real-world examples of near-miss incidents. GNSS is commonly considered critical infrastructure, and many industries rely on the technology for accurate and reliable positioning and timing information.

Researchers are now investigating methods of avoiding such GNSS fragility, and developing back-up systems. This has led to the resurgence of Loran and its modern adaptation enhanced-Loran (eLoran), the development of the Electronic Chart Display and Information System (ECDIS) marine navigation device, and the further investigation of terrestrial pseudolites. Modern GNSS signals are designed with better anti-spoofing capability (such as the GPS M code), and the variety of available signals from the four GNSS providers and various other regional systems provides its own inherent protection.

Scintillation has traditionally been a big problem, but the science is well established. The problem is greater in equatorial regions, and not considered significant in UK. However, the Met Office is now providing real time space weather reports and updates to mitigate some of the issues.

4.5.2 Regional Satellite Navigation Systems

Regional Navigation Satellite Systems (RNSS) provide a navigation service to regions of the Earth, but do not provide global coverage. Generally this is through the use of GEO and IGSO satellites.

The Indian Regional Navigation Satellite System (IRNSS) is operated by the Indian Space Research Organisation (part of the Department of Space), and will eventually consist of 3 GEO satellites and 4 IGSO satellites. The first satellite was launched in July 2013, and began transmitting test signals shortly after (Indian Space Research Organisation, 2014).

4.5.3 Proposed constellations and dates

By the year 2020, the total number of satellite vehicles will be 110 based on the minimum requirement for each full GNSS system. Although in reality it will be closer to 125 with the spare and redundant satellites of each constellation. This estimate is made up of the proposals from the four GNSS service providers, and is shown in Figure 4.20. The GPS and GLONASS constellations are at FOC, and should remain there through individual satellite replacement schemes. The Galileo system should achieve IOC by 2016, and FOC by 2019. The BeiDou system is anticipated to have its full constellation of 35 satellite vehicles by 2020. The specific dates for satellite launches are unknown.

Major investment in GNSS services by their respective operators is currently being undertaken. GPS is operated by the US Department of Defense, and has a full system of more than 24 satellite vehicles in orbit, with additional satellite vehicles in reserve and under test. By 2016, it is expected that there will be 24 satellite vehicles in orbit broadcasting the new L2C frequency, by 2019 there will be 24 satellite vehicles broadcasting the L5 frequency, and by 2021 there will be 24 satellite vehicles broadcasting the L1C frequency signals (Gruber, 2010). Both of these frequencies will have higher signal strengths, with the L5 frequency in particular offering lower noise and better multipath protection, and will not be encrypted like the current L2 frequency. This will allow manufacturers to develop significantly cheaper dual or triple frequency receivers (GPS World (Editorial), 2009).

Over the next decade, both Galileo and GLONASS will approach their FOC, China's BeiDou will start the deployment of its final MEO satellites, and L2C and L5 signals of modernised GPS will be available for demanding applications in precise positioning, navigation and tracking. Furthermore, services offered by GBAS and SBAS, such as WAAS, EGNOS, and QZSS, and next generation wireless communications will be widely available to support the daily operation of ITS.

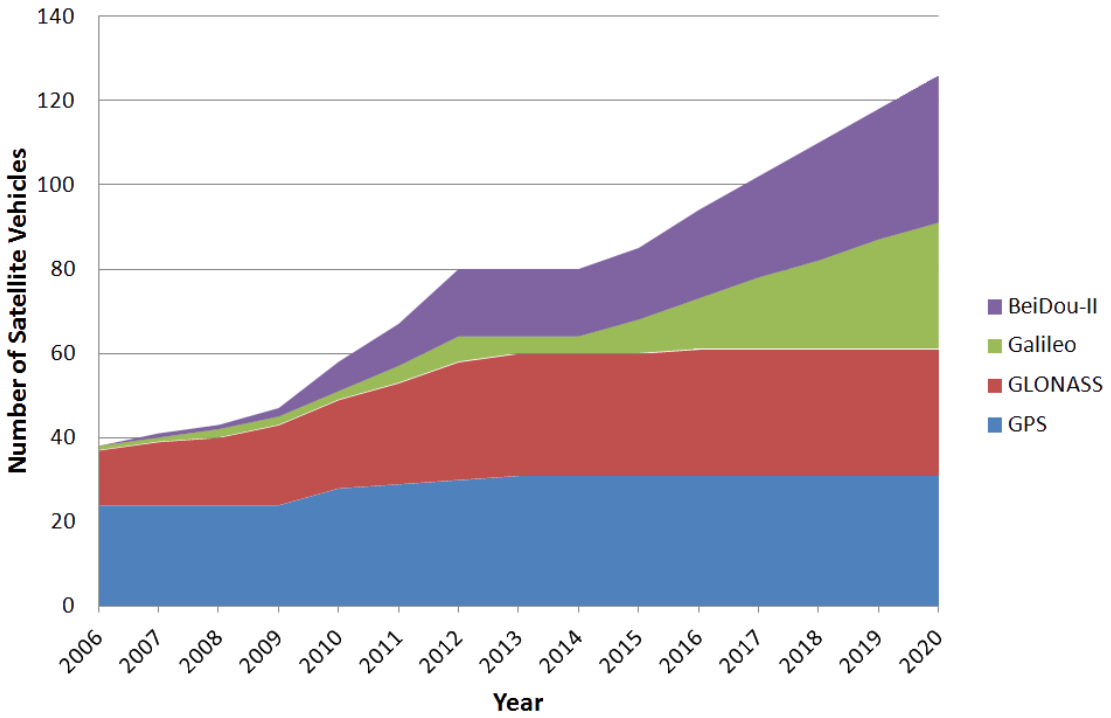


Figure 4.20 – Current and future GNSS constellations.

4.6 Integration of GNSS with other sensors for vehicle positioning

A GNSS receiver is the overwhelming choice of positioning sensor for vehicle navigation and positioning. GNSS receiver chips are now very low-cost, and the civilian service from GNSS providers is free to the end-user. The coverage is global, and for the desired applications the availability is generally very good. However, GNSS positioning does have limitations, and for certain applications alternative positioning systems and devices exist and are in use. Alternatives include technologies that utilise the electromagnetic spectrum, inertial and dead reckoning measurements, and less commonly, magnetism.

4.6.1 Non-GNSS sensors for vehicle positioning

According to Özgüner et al. (2011), sensors are fundamentally transducers that convert one physical property or state into another property or state. The output generated from a sensor can be used directly, converted further, or combined with other sensory information to generate vehicle position information. This can be anything from low-precision heading information, to complete situational awareness. The most popular and favourable non-GNSS sensors for vehicle positioning are visual cameras and laser scanners. The most advanced autonomous vehicles make liberal use of such technology for positioning and navigation. Typically, these sensors are used to build up the situational awareness of the vehicle, and allow it to navigate through the real world based on predefined rules. These systems rely heavily on the perception of the world through such sensors, and can be susceptible to false negatives and false positives.

In these systems, GNSS positioning plays a very minor role, although the type of GNSS hardware used does not deliver the full potential of GNSS positioning. Various other sensors are available to provide position information. These include: Inertial sensors to measure acceleration and orientation; magnetic sensors to observe the heading (compass); various vehicle-borne sensors to

detect the motion of the vehicle itself; and cooperative infrastructure in place to guide the vehicle. Generally, the sensors available to create position information for vehicles can be classified into the following categories:

- Visual navigation;
- Terrestrial ranging;
- Inertial measurement;
- Magnetic compass observation;
- Vehicle-borne sensors; and
- Cooperative infrastructure.

Positioning opportunities also exist through the use of barometric and nuclear magnetic resonance (NMR) gyroscopes (Groves et al., 2014), and by utilising map matching algorithms. The following Sections provide more detail about the above categories. Section 5.3 discusses the integration of such sensors with GNSS positioning for vehicle positioning, and Section 5.4 highlights some of the most successful approaches to such vehicle positioning.

4.6.1.1 Visual navigation

Visual navigation systems have made significant progress due to the increased availability of low-cost cameras and computer processing performance. Relatively simple image processing software can interpret images to produce reasonably accurate navigation information from low-cost digital cameras - even simple webcams and cameras on mobile phones. Driven by the low-cost and prevalence of cameras on personal devices with generous processing power (such as smartphones), visual navigation has developed into one of the primary off-the-shelf navigation sensors for researchers.

Typically, visual navigation is performed in one of three ways (Özgüner et al., 2011):

1. **Comparison of the image with stored images**
   This determines the camera's viewpoint, based on the known location of the image stored previously. The process can be made more efficient by comparing feature descriptors.

2. **Identification of features within images**
   The identification of features within an image allows the camera's location and orientation to be calculated by analysing several features and their location within the captured images.

3. **Visual Odometry**
   The motion of the camera can be calculated by comparing successive images. This is a form of dead reckoning.

Camera-based systems are the most common hardware solution for Lane Departure Warning (LDW) systems. The methods of identifying the lane markings within an image are advanced and cost-effective. For instance, the large contrast between the brightly coloured lane marking and the dark coloured road material are easily identified by thresholding and edge detection. With a well calibrated system, the lane position can be estimated to an accuracy of 0.059 metres (Bevly and Cobb, 2010). However, a major limitation of visual navigation is that they are almost exclusively passive systems, which must cope with various environmental conditions (Özgüner et al., 2011).

4.6.1.2 Terrestrial ranging

Terrestrial ranging encompasses all ground-based measurement systems using waves in the electromagnetic spectrum, involving an active transmission of the wave at some point. These mainly include radio and light waves, although limited use of sound waves (vibration through a medium) is used in low speed vehicle navigation. As is the case with GNSS positioning, the use of electromagnetic waves is hindered by signal obstruction, attenuation, reflection, and jamming or interference (Groves et al., 2014).

Radio waves.

Radio waves are classified as having a frequency of between 3 kilohertz and 300 Gigahertz, or as having a wavelength between 100 kilometres and 1 millimetre. GNSS signals are a radio wave more commonly classified as microwaves. GPS L1 and L2 signals operate at a frequency of 1.575 Gigahertz and 1.227 Gigahertz, and with wavelengths of 19 centimetres and 24 centimetres, respectively.

Radar[4] was developed in the 1940s as an object-detection system. Radio waves are transmitted or pulsed from an antenna, the waves bounce off an object, and a small part of the original wave is returned to a receiving antenna or dish (typically in the same location as the original transmitting antenna). Radar systems are now commonly used in collision avoidance systems for road vehicles (Özgüner et al., 2011).

Radar can be used to detect road obstacles both near and far, although there is a general trade-off between the field of view and the range. Many vehicles therefore carry different radar sensors for different applications (for instance, parking sensors and ACC). The systems are generally robust mechanically, and can operate under a wide range of environmental conditions - different lighting, rain and snow, and dust or haze generally cause no issues. Vehicle applications tend to use radar at frequencies of 24 Gigahertz and 77 Gigahertz, although some short range sensors use 5.8 Gigahertz or 10.5 Gigahertz (Özgüner et al., 2011).

Radar systems prove particularly useful as they generate a number of valid measurements. Not only are range measurements made, but the azimuth of the range, and the rate at which the range changes can also be accurately determined. Radar systems vary in their approach to the measurements, but they are generally based on either the Doppler shift of the waves or use continuous range modulations.

eLoran is the modern version of the long established LOng RAnge Navigation system that was developed during the Second World War. Using terrestrial radio transmitters, the low frequency (100 kilohertz) and long wavelength signal is used by eLoran receivers to trilaterate the position. The system is popular with marine users, as the propagation of radio waves over large bodies of water is more stable, and the resulting positioning accuracy (approximately 10 metres) is suitable for marine applications (Hofmann-Wellenhof et al., 2008). Due to the high power and long wavelength, the transmitters can cover a large area. eLoran positioning is currently not a strong candidate for high precision, high accuracy vehicle positioning.

Pseudolites (or pseudosatellites) are ground-based low power transmitters that act like a GNSS satellite. During the initial testing phase of GPS, pseudolites were used on the ground to test the system. They broadcast the L1 frequency signal, and utilise the five PRN codes 33 to 37 (specifically reserved for pseudolites) (Kaplan and Hegarty, 2009). Ambiguity resolution can be sped up by using pseudolites for vehicle navigation, due to the rapid change in geometry as the vehicle moves past the pseudolite. This makes pseudolites particularly useful for the approach of aircraft to landing strips. However, due to this inherent geometry, the location of the antenna on the vehicle must allow it to view signals arriving at very low horizontal angles (or from below if aircraft navigation is the goal).

GNSS receivers can distinguish between signals of the same frequency from different satellites partly due to the signal strength, as the relative satellite-receiver distance changes very slowly this strength also changes slowly (Bevly and Cobb, 2010). These low signal strengths mean that pseudolites cannot use the same frequencies as they will be much too powerful and drown out the GNSS signals. Pseudolite systems use different techniques to get around this problem, including pulse transmissions and utilising different frequencies. Various configurations of GNSS receivers and pseudolites can be used, although the aim is to ensure that a common time is synchronised.

Signals of Opportunity (SoOP) include a variety of radio signals that propagate through the local environment of populated areas and close to transport infrastructure. As described above, radio waves can be exploited for positioning purposes. These include Bluetooth, Wi-Fi, FM radio, and DAB. Positioning measurements can be made from such signals given a little extra information,

[4]Radar is an acronym for RAdio Detection And Ranging. The word radar is now considered a common noun, and is therefore no longer capitalised.

such as the location of the transmitters or a signal strength map. Other less common SoOP include UWB and satellite communication systems such as Iridium (by using Doppler measurements).

Presently, such SoOP systems do not offer a significant advantage to high precision vehicle positioning, although there is a clear target market in dense urban areas, tunnels, and underground or multi-storey car parks - those areas where GNSS positioning is at its most fragile.

Cellular communications have long been used for positioning, relying on the proximity of the device to the transmitting tower and triangulation. Cellular devices typically utilise the signal strength of cellular signals to aid positioning, as the approximate location of cell towers are well known and readily available. This is part of the system known as A-GNSS, which effectively turns the process of GNSS positioning into a hot fix, rather than a much longer cold fix (the direct upload of the GNSS ephemeris message is also a key part of this system).

Light waves.

Lidar, a portmanteau of the words *light* and *radar*, uses the optical amplification and stimulation of emitted light in laser form to measure distances. The reflection of a laser from an object is interrogated to extract the travel time of the laser to and from an object, from which distance is calculated.

Specifically, lidar systems measure the time difference between the transmission and reception of a pulsing light wave (Bevly and Cobb, 2010). Lidar can also provide reflectivity measurements (known as echo width), which can be used to classify objects (for example, lane markings), and works irrespective of the lighting conditions. In testing, lidar-based positioning has been shown to be accurate to 0.044 metres in ideal conditions (Bevly and Cobb, 2010). The major limiting factor of its adoption in mainstream ITS applications is the high relative cost of the sensors, and the previous lack of research and development.

The complexity of a driving environment, and the scattering nature of a lidar device, requires that artificial boundaries are placed when searching lidar scans for features. For instance, outside the bounds of a highway, the echo width measurements become very noisy. Within the bounds of a highway, lidar is a popular sensor for object detection (Özgüner et al., 2011).

Modern lidar devices utilise advanced laser measurement techniques, such as measuring the time of flight of a laser reflection at multiple azimuth angles, taking multiple distance measurements per laser pulse, and multiple scans in multiple planes. These techniques help to minimise the limitations of lidar: Namely the poor accuracy, atmospheric interference, and the production of 3D measurements.

Ultrasonic.

Ultrasonic measurements use ultrasound pressure waves for ranging, in a similar way to that used by sonar[5], which uses the propagation of sound waves to make ranging measurements under water. Ultrasound waves are at the limit of the human hearing range.

An ultrasonic pulse is emitted is a controlled direction, and any objects in the path of the sound wave will reflect part of the wave back towards the transmitter. The time difference between transmission and reception is measured to produce a range to the object (Özgüner et al., 2011).

Ultrasonic measurements are commonly used to measure distances to close objects in automotive applications. The most common example is its use for parking sensors (often referred to as proximity sensors). Fundamentally, ultrasonic sensors are limited by the requirement to target the ultrasound transmissions, as the measurement of transmission and reception angle is not possible. For this reason, multiple ultrasonic sensors are typically used on a vehicle, each facing a different direction.

4.6.1.3 Inertial measurement

Inertial sensors measure a combination of acceleration and rotation, and are occasionally paired with magnetic sensors. This allows the determination of velocity and orientation. The best performing inertial sensors are mechanical, although they can be bulky and expensive. MEMS sensors offer a low-cost inertial solution, and typically offer good navigation performance when combined with

[5]Sonar was originally an acronym for SOund Navigation And Ranging, but is now a common noun.

other sensors. Promising current research is exploring the use of cold-atom technology and de Broglie wave interference, which appears to enable low-cost, robust, and high accuracy inertial navigation (Kasevich, 2007).

Inertial sensors translate the movement of a body into electronic signals, independent from external systems (Bevly and Cobb, 2010). They have been used for decades in aviation and missile guidance systems, and are typically split into two categories (Grewal et al., 2001):

1. ***Accelerometers.*** These devices measure the force along an axis and output a strength related electrical signal.

2. ***Gyroscopes.*** These devices measure the rate of turn around an axis, and output a signal based on the rate.

The key to inertial sensors is that they output a reading at a known interval. This allows a first integration of the measurements to provide a velocity, and a second integration to provide the distance.

Inertial sensors suffer from three sources of error that need to be handled, namely; noise, bias, and scale factor. Any errors or biases in the initial reading will propagate through subsequent integrations (Bevly and Cobb, 2010). To an extent, the propagation or scale factor errors can be calibrated or estimated out, but the stochastic element of the noise makes it very difficult to predict. In this respect, any noise in the inertial measurements is typically treated as Gaussian distributed, allowing simple filtering (Bevly and Cobb, 2010).

The most inexpensive IMU's are MEMS sensors, which are both light and small in size. However, they are also characterised by poor performance compared to high end inertial sensors - the gyroscope quality is the main cost and performance factor in an IMU (Angrisano et al., 2010). MEMS IMU's are useful as they can be placed almost anywhere on a vehicle, and they can provide good angular measurements at a high rate (Björkholm et al., 2010).

The prevalent choice of technology for an IMU or gyroscope is to use MEMS sensors. Consumer grade applications such as smartphones, some simple automotive systems, and video game controllers, take advantage of their low cost and small physical size. When the application is more demanding, the IMU will utilise fibre optic gyroscopes, which are more expensive, but offer significantly better performance. Hence, industrial and tactical grade applications such as weapons guidance, precision agriculture, and autonomous vehicles will utilise these devices.

Inertial Navigation Systems (INS) are a combination of IMU's that output a navigation solution. For instance, an INS may incorporate three gyroscopes and three accelerometers set on three axes.

Before carrying out any measurement or navigation tasks it is generally necessary to carry out a short calibration exercise (Kellar et al., 2008), although some systems can carry out calibration during operation. When integrating inertial sensors with other devices it is important to filter the data - to introduce constraints and assign the appropriate weighting to the measurements. This is covered in more detail in Section 4.6.2.

The most difficult aspect of choosing the correct device is comparing the performance parameters, and deciding which are the most important for any given application. A method of evaluating gyroscopes and IMU's based on five key performance factors has been suggested in a White Paper from KVH Industries (KVH Industries, 2014). They are:

1. **Noise or Angle Random Walk (ARW)**. This is the average error that occurs as a result of high frequency white noise.

2. **Bias offset error**. A stationary gyroscope can often incorrectly register some rotation, and this is called the bias offset error. Its deviation from zero is typically given at 25°C for an ideal environment - for instance, no temperature change, vibration, shock, or magnetic field is applied.

3. **Bias instability**. This is the instability of the bias offset at any constant temperature in an ideal environment.

4. **Temperature sensitivity**. The bias offset and absolute scale factor of a gyroscope will vary slightly with temperature changes, although this can be improved through calibration.

5. **Shock and vibration sensitivity**. Shock and vibration can be modelled as noise and bias offset in the gyroscope output, but this can cause large inaccuracies. These inaccuracies are not easily improved through calibration.

In addition, it has been suggested that mounting misalignment (or cross-axis sensitivity) is an often overlooked performance factor, as it is a dominant source of error in many applications (especially when a major change of direction is included or significant periods of IMU-only navigation are required) (Farrell et al., 1999). This is the situation when the gyroscope axes of roll, pitch, and yaw are not in perfect perpendicular alignment.

4.6.1.4 Magnetic compass observation

A magnetic compass, or magnetometer, can be used to determine the absolute heading (or yaw angle) of a vehicle. By sensing the magnetic field of the Earth, the direction of travel can be compared to that of magnetic North[6]. Most commonly this is achieved by using three magnetic sensors, arranged orthogonally (Özgüner et al., 2011), as this helps to interpret the magnetometer readings and determine the orientation of the sensor (in relation to the surface of the magnetic effect). Often a tilt sensor is integrated with the magnetometer to assist with this orientation.

The Earth's magnetic field is weak however, and there is a lot of background noise in the measurements. To account for the background noise, calibration of the sensor is required, which typically involves rotating the compass through complete circles. Magnetic interference is also an issue, with major sources including computers, radio receivers, power electronics, and combustion engines - all common in road vehicles.

These limitations make the use of magnetometers for road vehicle positioning difficult, and the accuracy of the measurements is low. The roll and pitch of a vehicle can also be detrimental, as the frequency of the variation can be beyond that which can be measured by the sensors (Özgüner et al., 2011).

4.6.1.5 Vehicle-borne sensors

Fundamentally, vehicle navigation is constrained by the limited range of movement and the linear nature of roads. For instance, longitudinal movement is limited to the maximum acceleration and deceleration characteristics of the vehicle, and the lateral movement is limited by the extents of the road and lane boundaries. Clearly there are examples when these constraints can be broken, but generally the likelihood is low. More information is provided in Section 3.2.

For these reasons, dead reckoning is a powerful tool in vehicle positioning and navigation. Basic dead reckoning sensors on a vehicle include wheel odometers and steering angle sensors, in order to crudely determine the velocity and direction of travel. Many built-in Sat Nav devices in road vehicles make use of these sensors to bridge minor GNSS signal outages (such as through tunnels), in combination with map matching algorithms.

Modern road vehicles now include a multitude of vehicle sensors that help to carry out many of the vehicle's operations. Even the most inexpensive vehicles now include wheel speed sensors (odometer) to assist with ABS. This information is accessible from the industry standardised On-Board Diagnostics (OBD-II), typically via a Controller Area Network (CAN). More complex vehicles will have data sets containing hundreds of readings, which are output at high rates (up to 100 Hertz).

As the sensors are not designed primarily for vehicle positioning and navigation, the sensor accuracy is generally limited to that required for its main task, with the specification determined by the OEM (Özgüner et al., 2011). The outputs from these sensors can easily be captured via the vehicle's internal CAN bus.

Wheel odometer.

The most common vehicle sensor to integrate with a navigation device is an odometer sensor. This measures the relative speed between the tyre and the road surface, and the measurements can

[6]Note that magnetic North is not the same as true North, and this must be accounted for when calculating geographical location.

be particularly useful for dead reckoning (Bevly and Cobb, 2010). There are two main odometer sensor types:

1. ***Active sensor.*** This sensor uses transducers, which are useful for measuring low speeds.
2. ***Passive sensor.*** This sensor uses a toothed gear to generate a signal, but requires sufficient speed to activate it.

Care needs to be taken with the odometer readings, as the measurements are taken inside the frame of the wheel, which may or may not be coincident with the frame of the vehicle (Bevly and Cobb, 2010). The sensor readings can also suffer from wheel slip and wheel radius error (scale factor errors), and can be insensitive at low speeds. Although these issues are often accounted for in the navigation filter (Wang et al., 2005).

The wheel odometer typically consists of a rotary encoder or Hall effect sensor (where frequency is proportional to speed) (Özgüner et al., 2011). The odometer output can be differentiated to provide a speed measurement (Bevly and Cobb, 2010), although this can produce a noisy output due to the nature of the differentiated quantised signal.

The differentiated encoded noise can be considered Gaussian, especially when the encoder resolution is high (Bevly and Cobb, 2010). Changes in the wheel size (radius) or wheel slip (longitudinal movement) can corrupt the speed measurement (Bevly and Cobb, 2010) - these effects are particularly significant in off-road environments. Typical measurement models will assume that the wheel radius will remain constant, and an amount of wheel slip will be expected.

The relationship between the wheel odometer reading and the dashboard speedometer is determined (calibrated) by the vehicle manufacturer. Typically, the real speed of the vehicle is slightly lower than that indicated on the dashboard speedometer, in order to take account of possible inaccuracies in the measurement - for instance, due to tyre size or pressure. The legislation regarding speedometers differs between countries, but generally the speedometer must never indicate a vehicle speed lower than the actual speed, and in the UK the indicated speed must be within 110% + 6>25 mph (The Secretary of State for the Environment Transport and the Regions, 2001)[7].

Steering angle sensors.

The angle of the steering wheel is traditionally controlled by the driver, although vehicle models are now available with self-park features that include an actuator on the steering wheel to control low speed manoeuvres. This is possible through the development of steer-by-wire systems, which rely more on electronic systems and less on mechanical systems. The position of the steering wheel can be measured by taking the output (or input) from these actuators (Özgüner et al., 2011).

As the steering wheel is one of the primary controls of the vehicle, the movements of the wheel made by the driver can be used to monitor driving performance. This is particularly useful for predicting the intentions of drivers and monitoring the driver's attention.

Vehicle dynamic state.

The vehicle dynamic state is typically related to the yaw angle and rate, and the lateral and longitudinal accelerations (Özgüner et al., 2011). These measurements can be provided by a variety of sensors, including ABS and traction control, wheel speeds, and steering angle. Many modern vehicles also include low-cost GNSS receivers (either as part of the in-built navigation system, or as part of the sensor timing system) that can be used to measure vehicle heading (Jewell, 2011).

Actuation sensors / driver inputs.

There is a wealth of information created by the vehicle when actions are performed that can contribute to the vehicle positioning and navigation solution. This includes vehicle movement related information generated from sensors placed on the steering wheel, and the throttle and brake pedals, but also contextual information provided by sensors and actuators controlling other

[7] This legislation does not cover the indication of speed provided by Sat Nav devices as they are not designated devices for determining the speed of the vehicle. No discriminatory calibration is required, hence the speed indicated by the Sat Nav device is typically 5-10% lower than that of the vehicle's dashboard speedometer.

vehicle actions. These can include turn indicators (signals), traction control sensors, windscreen wipers and headlights. Crude information can be gathered on the vehicles general location based on weather and road surface condition when matched with other data sources, and the anticipated direction of travel can be predicted from the driver's notification of their intention to make a turn.

Mechanical sensors can also provide useful information about the state of the vehicle and its motion. These include transmission gear selection, the state of the differential, brake pressure at the master cylinder, and engine variables such as coolant temperature, O_2 and NO_x levels, engine revolutions per minute (RPM) measurements, and spark plug firings.

Lane departure systems.
Lane departure systems (LDS) are increasingly common on passenger road vehicles. Although the technical design of the systems differs slightly from one manufacturer to the next (albeit many manufacturers share the same parent company or OEM suppliers), each is based on the accurate identification of the lane markings. Most commonly, this is done using cameras and image recognition (Özgüner et al., 2011).

Parking sensors.
Ultrasound measurements using ultrasonic sensors is discussed in Section 4.6.1.2.

Blind spot sensors and cruise control systems.
Theses systems typically use radar. Radar systems used for terrestrial ranging is discussed in Section 4.6.1.2. The repeated measurement or scanning of the blind spot region is a simple safety feature that can reduce the probability of a dangerous lane change manoeuvre. Cruise control systems can be enhanced with the use of radar sensors to measure the range to the vehicle in front. Such ACC systems will automatically adjust the cruising speed to maintain a pre-defined vehicle headway. Radar allows a very high measurement rate, often above 100 Hertz, which introduces high redundancy, and allows the automated speed control to be gradual and comfortable for the driver.

4.6.1.6 Cooperative infrastructure

The concept of vehicle positioning using cooperative infrastructure was traditionally based on the addition of extra components to the highway (California PATH, 1997). In previous research projects, these components have included magnets, radar reflective strips (sensing the scattered energy from a frequency selective surface), and radio-frequency identification tags (RFID). In more recent research the exploitation of new road infrastructure components such as wireless transmissions from traffic lights, road maintenance equipment, and pedestrian crossings, has been performed for vehicle positioning (Özgüner et al., 2011). This type of positioning is commonly classified under the V2I concept.

4.6.2 Integration of GNSS and inertial sensors

The integration of GNSS and inertial sensors is an accepted and heavily researched thesis. By their nature, the two methods of navigation are complimentary: The precision and accuracy of GNSS sensors is good over the long term, but poor over the short term; whereas, inertial sensors perform well over the short term, but poorly over the long term (Bevly and Cobb, 2010; Angrisano et al., 2010). In this case, short term is typically a maximum of a few minutes.

Given the correct antenna, a GPS chipset costing £3 can perform as well as a £15,000 receiver in certain environments (van Diggelen, 2010). The evidence for this research was based on the typical environment in which a mobile phone works, such as a heavily urbanised zone. This is an indication that GPS-only systems are reaching a positioning plateau, and that the next decade will be characterised by GNSS plus other sensor systems: For instance, MEMS, Wi-Fi, and the combination of multiple GNSS and RNSS constellations.

Most research has combined inertial and GNSS sensors with some form of Kalman filter. Research into Kalman filtering is very advanced, and is often the basis of an INS. Put simply, a Kalman filter mixes several measurement inputs and weights them in order to reduce certain deficiencies and enhance certain strengths, to provide the best statistical navigation output (Bevly and Cobb, 2010). One of the key aims is to minimise the variance. For this reason, the Kalman filter is often referred to as an unbiased, minimum variance estimator (Bevly and Cobb, 2010).

To allow the Kalman filter to operate successfully, regular position and velocity updates are required to limit the propagation of the covariance caused by the inertial measurements. The covariance is used to statistically weight the corrections to the state of the device (for instance, the corrections to the position solution). This weighting is known as the Kalman gain. Clearly, this process is continuous and needs to be repeated at a high rate.

From the perspective of the GNSS receiver, this combination of GNSS and inertial measurements can be performed in three ways (Bevly and Cobb, 2010):

- Loose coupling;
- Close coupling; and
- Tight coupling.

Loose coupling combines the inertial measurements with position and velocity measurements calculated by the GNSS receiver. Feedback is sent to the inertial processor to remove biases, scale factors, and misalignment. The main benefit of loose coupling is that the measurement vector remains small and a constant size, reducing the complexity and keeping the computational burden low. Loose coupling is also easily adaptable to partial IMU integration. However, the measurement quality depends heavily on the GNSS receiver, which is known to have limitations in the vehicle environment (for instance, a minimum of four satellites must be in view).

Close coupling combines the inertial measurements with the GNSS satellite-receiver range measurements. This combination occurs before the GNSS receiver calculates the position. In close coupling, feedback to the inertial processor is maintained, but there is no feedback to the GNSS receiver. The main benefit of close coupling is that range measurements are processed individually, so they can be weighted or even removed. This also allows the system to continue with fewer visible satellites than required for loose coupling. However, the measurement vector still relies heavily on the number of range measurements, which can make the computational burden quite large.

Tight coupling takes another step up the GNSS measurement process, by feeding back into the tracking loops of the GNSS receiver. This process is more complex, and is often referred to as deep integration. The main benefit of this type of coupling is that the tracking performance of the GNSS receiver can be improved - an important aspect when considering vehicle positioning is typically performed in a dynamic environment.

4.6.3 Popular integrated positioning solutions

The following sections discuss the application of integrated positioning solutions. The subject is separated into two categories: Research carried out into autonomous vehicles and fundamental vehicle positioning research.

4.6.3.1 Vehicle autonomy research

Autonomous vehicle research has undergone a recent surge in development activity, driven primarily by private companies such as vehicle manufacturers and technology companies. Traditionally, such research has been completed by research institutions, making this shift to private enterprise a strong indicator of the credibility of vehicle autonomy.

A major prerequisite for vehicle autonomy is the ability of the vehicle to position itself, and navigate through its environment. Generally, this has shifted from absolute positioning with navigation based on existing mapping data, towards a simultaneous location and mapping (SLAM) approach. The best known example of this is the Google Self-Driving Car Project. The project

originated from the technology and expertise developed by the Stanford Artificial Intelligence Laboratory (Stanford University, California) and the Stanley robotic vehicle from the 2005 DARPA Grand Challenge (Fagnant and Kockelman, 2014).

The Google Self-Driving Car Project favours electric or hybrid powered vehicles, originally using a Toyota Prius as the base vehicle, and more recently a Lexus RX450h (both hybrid power vehicles). In May 2014, Google announced the development of a custom-built, fully autonomous vehicle with no driver controls. With all vehicles, the primary sensor is a Velodyne 64-beam lidar (Velodyne, 2015), specifically designed for the navigation of autonomous ground vehicles and marine vessels. This allows the software to build an accurate 3D map of the environment, which is compared to a known high-resolution map of the area. Other positioning sensors on the vehicle support the lidar system, including a GPS receiver for general positioning, a wheel encoder to accurately measure vehicle speed, inertial sensors for orientation, and radar and ultrasonic sensors to determine range to other objects or vehicles. Stereo or mono-cameras are also used for object detection, and to recognise road features such as traffic lights and signs (Özgüner et al., 2011).

A public transit system in Minnesota uses a VRS GPS-based positioning system to guide buses along a narrow hard shoulder (Shankwitz, 2010). The lane is only a little wider than the bus, so the position accuracy needs to be high. The driver retains control of the vehicle, and is advised by the on-board system as to adjustments that need to be made. When the GPS signal is lost, an augmentation system takes over. This includes: Using the dynamics of the vehicle just before the GPS signal was lost; up-to-date mapping information; a 2D velocity sensor to measure vehicle wheel slip; additional yaw rate sensors; and lidar scanners for collision detection. The system is accurate to 5 to 8 centimetres, and updated at 10 Hertz.

Table 4.7 – A summary of autonomous research vehicles.

Institution	Country	Primary vehicle	Reference
Stanford University	United States	Audi TT (Shelly)	(Brown, 2010)
VisLab and University of Parma	Italy	VIAC Challenge	(Bertozzi et al., 2013)
IFSTTAR	France	Quasper	(Guizzo, 2012)
Freie Universität, Berlin	Germany	Spirit of Berlin and MadeInGermany	(Göhring, 2012)
Oxford University	United Kingdom	Bowler Wildcat, Nissan Leaf	(Mobile Robotics Group (MRG), 2012)
The National University of Defense Technology	China	Hongqi HQ3	(Murray, 2011)
Volvo	Sweden	Volvo road train	(SARTRE, 2009)
Princeton University, Princeton Autonomous Vehicle Engineering	United States	PAVE	(Buehler et al., 2007)
BMW	Germany	BMW ConnectedDrive	(Juskalian, 2012)

A number of institutions have developed autonomous research vehicles that utilise GNSS sensors. These are summarised in Table 4.7. The Audi TT (affectionately known as Shelly) developed by Stanford University is a popular example of vehicle autonomy that relies heavily on GNSS-based positioning. The development of Shelly stems from previous research vehicles named Stanley and

Junior (entrants to the DARPA Grand and Urban Challenges, respectively). Similarly, although with a smaller budget, Princeton University entered vehicles in the DARPA Challenges. The Princeton Autonomous Vehicle Engineering (PAVE) team is primarily composed of undergraduate students. Their autonomous vehicles make use of terrestrial sensors, inertial sensors, and high precision GNSS-based positioning.

The Quasper autonomous vehicle developed by IFSTTAR[8] in France, primarily utilises RTK positioning and an iXSea IMU for positioning. Visual cameras are used to identify road markings and other objects in the surroundings, and lidar is used to detect objects. This is contrasted by the VisLab autonomous vehicle from Italy (VisLab is a spin-out company from the University of Parma), which relies less on the GNSS receiver and its inertial sensors, and more on the seven visual cameras and four laser scanners. Four VisLab autonomous vehicles successfully travelled from Parma, Italy to Shanghai, China in 2010 – a journey of approximately 9,900 miles.

The Spirit of Berlin and MadeInGermany autonomous vehicles approached a different scenario by successfully demonstrating autonomous vehicle navigation on the streets of Berlin. Run by the Freie Universität in Berlin, the vehicles used a combination of differential GNSS-based positioning, laser scanners and visual cameras.

Generally however, there has been a gradual shift away from GNSS-based positioning technology to situational-awareness technology such as lidar scanners.

The Bowler Wildcat and Nissan Leaf autonomous vehicles developed by the Mobile Robotics Group at Oxford University in the UK make a large effort not to use GNSS-based positioning at all. The approach is to navigate through the local environment rather than with the use of any global reference system. Their vehicles primarily use cameras, radar sensors, and laser scanners, and wherever possible the lowest cost option is used. Likewise in China, the National University of Defense Technology equipped a standard Hongqi HQ3 passenger car with various terrestrial sensors, but no GNSS-based positioning equipment. The vehicle drove autonomously between Changsha in the Hunan province to Wuhan in the Hubei province – a 154 mile journey along a major highway.

The ConnectedDrive autonomous vehicle developed by BMW also demonstrated autonomous highway driving during a trial on the Autobahn. Sensors on board the vehicle included radar, cameras, ultrasonic sensors, and laser scanners, but again no GNSS-based positioning. The BMW system is designed using sensors and systems readily available in production vehicles (for example, in applications such as lane keeping assist and ACC).

Table 4.8 – Sensors used by major vehicle manufacturers for vehicle autonomy (semi or fully).

OEM	Lidar	Radar	Camera	Ultrasonic	Laser
Audi		✓	✓	✓	✓
BMW		✓	✓	✓	✓
General Motors		✓	✓	✓	✓
Google	✓	✓	✓	✓	
Mercedes-Benz		✓	✓	✓	✓
Volkswagen	✓	✓	✓	✓	✓
Volvo	✓	✓	✓	✓	

Table 4.8 shows the sensors used by major vehicle manufacturers in their commercially available passenger vehicles or in development for forthcoming fully-autonomous applications. Radar systems have been available for many years - for instance, to provide information for ACC - but the sensors are increasingly used to gather ranging information from other directions. Ultrasonic and camera sensors are commonly used to provide assistance for slow speed manoeuvres such as parking. Light-based sensors such as laser and lidar systems are typically more advanced, and are mostly used to gather large volumes of data in order to create situational awareness in the local vicinity.

[8] IFSTTAR is the acronym for the Institut français des sciences et technologies des transports, de l'aménagement et des réseaux, which translated into English is the French institute of science and technology for transport, spatial planning, development and networks.

4.6.3.2 Fundamental vehicle positioning research

Vehicle-based positioning systems are dominated by GNSS receivers for absolute positioning, and terrestrial sensors (primarily ultrasonic and radar) for relative positioning - essentially short distance ranging.

Each sensor or system invariably has a fundamental limitation, which leads to an integrated sensor approach (to balance the strengths and weaknesses of each sensor). For instance, GNSS receivers are typically paired with vehicle borne dead reckoning sensors (for example, wheel odometers or steering angle sensors), or low-cost MEMS inertial sensors. This enables the system to provide continuous navigation information - even during short term GNSS signal outages. These low-cost, off-the-shelf integrated systems do not offer the availability and continuity of a high accuracy position solution, but the desire to achieve such a system has led researchers to develop innovative solutions.

GNSS-based positioning is often dismissed as low accuracy and prone to the loss of a solution when GNSS signals are obscured. However, this is based on the stand-alone positioning capability and the various anecdotal stories of poor navigation provided by Sat Nav devices. Although increasing the availability of GNSS-based positioning is very difficult (fundamentally weak GNSS signals and the continued increase in signal obscuration from infrastructure), there remains a large opportunity to adopt modern GNSS-based positioning techniques for vehicle navigation. This includes the adoption of established GNSS positioning techniques such as DGNSS positioning and RTK positioning, as well as state-of-the-art techniques such as N-RTK positioning and PPP.

GNSS-based positioning can provide heading information using a single antenna, although this requires the vehicle to move. If two antenna are mounted on the vehicle, and the relative orientation with the vehicle is known, the direction of travel can be calculated. In addition, a dual antenna GNSS-based positioning system can be used to improve the carrier-phase based positioning performance. A fixed baseline between the two antennas allows an additional constraint to be included in the ambiguity resolution equations.

In Kuylen et al. (2006), two multiple antenna systems were tested: A single frequency receiver with three antennas; and a dual frequency receiver with two antennas. The tests showed that the baseline length is inversely proportional to the accuracy of the attitude calculation, and that during a city driving test the availability of a fixed ambiguity attitude measurement was 79% for the dual frequency receiver and 70% for the single frequency receiver. The authors also noted that the TTFF for both systems was approximately the same, given a baseline rigidity constraint.

In Bevly et al. (2006), a multiple antenna GPS receiver was shown to measure the attitude of a vehicle with an accuracy of 0.4 degrees (1 metre baseline). The system was configured with one GPS antenna to measure the vehicle velocity vector heading and the yaw rate bias, and two antennas to calculate the vehicle heading and roll.

As discussed in Section 4.6.2, GNSS receivers pair well with inertial sensors - their positioning characteristics are complementary. Inertial sensors can be used to provide dead reckoning information - the provision of a vehicle's heading and velocity, but other devices such as wheel speed and steering angle sensors can also provide this information. The combination of GNSS receivers with sensors that provide this dead reckoning information is a powerful tool for road vehicle positioning.

Before Selective Availability was switched off, researchers in Abbott and Powell (1999) identified the importance of GPS receivers and gyroscopes for land vehicle navigation. They also emphasised the benefit of map matching techniques for both the accuracy of navigation and the calibration of dead reckoning sensors.

In Angrisano et al. (2010), the researchers expanded on previous integrated navigation research by introducing GLONASS observations to the traditional GPS plus INS system. Using a reference system consisting of a DGNSS receiver and a tactical grade IMU, the researchers carried out field tests with a road vehicle in Italy. They found that in open sky areas, the GPS plus INS solutions were dominated by the GPS measurements, and that the introduction of GLONASS measurements was detrimental to the position accuracy. However, in urban areas with reduced satellite visibility, the solution is strongly influenced by the prevalence of severe multipath and the addition of GLONASS measurements increased the accuracy. Although this appears to be of great

significance, the increase in accuracy provided by the GLONASS satellites in urban areas still leaves the level of accuracy well below that in the rural areas with a clear view of the sky.

Work carried out for Jiang et al. (2005) demonstrated an integrated GPS plus INS system suitable for non-safety critical autonomous vehicle applications. Combining a DGPS receiver and an inexpensive dynamic tuning gyroscope IMU together with a real time loosely coupled Kalman filter, the test vehicle covered a distance of 320 metres. The test included an artificial loss and regain of the GPS signals, and showed a maximum position error of 8 metres with a heading deflection of 1.4 degrees.

Applications in Büsing et al. (2010) were identified as requiring accuracy to the lane level, but would also require a measure of confidence. These include ACC, merge and exit assistance, and black spot warning. The focus of their research was to determine how far the GNSS positioning system can be degraded whilst still offering a reliable solution. Their investigations into using vehicle sensors during reduced GNSS performance showed that: Steering angle sensors worked well on straight roads but poorly on curved sections; rear axis odometers performed well for dead reckoning; and linear accelerometers are useful to correct model errors when the road has significant camber.

In Gao et al. (2008a), a GPS and low-cost sensor were tested in a tightly coupled system. A steering angle sensor and low-cost MEMS IMU was paired with a centimetre-accurate GPS receiver. The researchers found that the steering angle sensor increases the horizontal positioning accuracy following a GPS outage by between 30% and 53% (depending on the environment). However this still signifies an error of 15 metres after 40 seconds.

The approach to sensor integration in Taylor et al. (2006) was to use the wheel odometer as the primary positioning device, and to use a low-cost GPS receiver as a calibration device. This paper looked at the improvement in vehicle positioning in an urban environment when using a poor GPS receiver and antenna. The system predominantly positions the vehicle using the odometer (ratio 7:3) - as the GPS position is unavailable or provides poor accuracy - but uses the GPS receiver when available to calibrate the odometer. To further assist the positioning ability, the data was combined with digital map data and map matching algorithms. The existing map matching algorithm is integrated with odometer observations to determine the precision of the GPS system, which in turn calibrates the odometer. The average error of the system was found to be 17.8 metres (100% confidence) and 10.1 metres (95% confidence), which is greatly improved over GPS only at 55.6 metres. Although these position accuracies are poor, and not suitable for high precision ITS and V2X applications, it does show that the combination of multiple sensors and model constraints can deliver significant improvements in positioning performance.

The research in Toledo-moreo et al. (2009) also addressed the integration of digital map data with GNSS and dead reckoning. The dead reckoning sensors were an odometer and gyroscope, and the GNSS receiver included EGNOS corrections. The goal was to provide lane-level accuracy positioning for navigation. The paper shows that the data fusion copes with a GNSS outage for 110 seconds, but notes that determining the accuracy of a map matching system is itself determined by the accuracy of the underlying map data. Hence, in this system the filter will constrain the position within certain bounds of the map segment. The system without the digital map observations provides accuracy measurements of 2.13 metres (2.35 metres, 1 SD), but with the digital map observations the accuracy was 0.57 metres (0.67 metres, 1 SD). This is adequate for lane-level navigation.

The research carried out in Rezaei and Sengupta (2007) paired DGPS (using a local base station, providing a position accuracy of between 0.3 and 1.0 metres) with vehicle sensors (wheel speed sensors, steering angle encoder, and fibre optic gyroscope). The aim was to achieve the accuracy required for cooperative collision warning (CCW) applications (rated at 0.5 metres lateral accuracy, speed accurate to 2 m/s, and a heading error of less than 5 degrees). The system designed in the paper almost meets the CCW requirements, but struggles if the GPS solution has been lost for longer than 10 seconds or the vehicle travels around a fast corner.

In Wang and Gao (2004), the navigation solution was created by coupling a GPS device (code measurements) with a gyroscope-free INS, and then processing the data through an artificial neural network using constraints (based on the vehicle dynamics). They found that the drift of the system

after a GPS outage was 31.85 metres (after 60 seconds), 24.20 metres (after 45 seconds), and 15.58 metres (after 30 seconds). For a low-cost system this performance is admirable, but not satisfactory for many of the advanced ITS and V2X applications.

The work carried out in Cui and Ge (2003) also introduced vehicle model constraints to the navigation solution, but the approach was used to improve the positioning performance of the GNSS receiver in urban canyon environments. By using vehicle movement constraints (for instance, the vehicle can only move along known lines), the researchers found that in some cases the minimum number of required satellites is reduced from four to two. Tests were simulated using previously recorded data, but show that positioning errors are typically less than 5 metres, even when the number of satellites drops to one. It also shows that the divergence of the error is slower than using the typical Extended Kalman filter (EKF) approach.

For the research carried out in Wang et al. (2005), the navigation solution combined a GPS receiver, an INS, and Vision Based Lane Recognition (VBLR). Although highlighting the fact that map matching techniques may become obsolete as positioning technology eventually provides a high accuracy solution on its own, the research introduces map data as an additional sensor in the traditional Kalman filter. The results were encouraging, although large inaccuracies did appear during tests, mostly caused by inaccurate map data. The IMU heading error also proves difficult to distinguish from the acceleration errors – it is suggested that a multi-antenna attitude system is employed. These discrepancies were identified by the integrity monitoring, which was essentially a cross checking mechanism of the various sensors.

The research carried out in Alves et al. (2010) used GNSS sensors, on-board OEM vehicle sensors, and additional vehicle inertial sensors. The paper introduced the Which Road, Which Lane, and Where in Lane positioning accuracy characteristics, and looked at the benefit of sharing positioning information between vehicles. The work compared two methods of transferring positioning information: The first method transfers the calculated position coordinates between vehicles and the second transfers all of the raw data to allow the vehicle to calculate the position of the other vehicle. Each vehicle was also equipped with four different grades of receiver. The main conclusion was that transferring the raw data overcomes the problem of receiver incompatibility when each vehicle is using a different type of GNSS receiver (for instance, where one vehicle uses a much worse or much better receiver than the other).

Chapter 5

Network RTK for vehicle positioning

5.1 Overview

Stand-alone Sat Nav devices can not meet the accuracy requirements of many current and rapidly emerging ITS applications in which instant and precise knowledge of vehicle position is essential. ITS applications using GNSS, such as mobile mapping, lane departure warning, autonomous driving, lane-based traffic or fleet management, and collision avoidance, have been limited to controlled environments where single reference station-based conventional RTK positioning is utilised. In 2009, N-RTK positioning technology was voted as one of the five technologies to watch by GPS World (Gakstatter, 2009). N-RTK positioning overcomes many of the drawbacks of conventional RTK positioning, such as short reference-rover baselines, and low robustness. It can significantly improve the overall GNSS positioning performance (such as accuracy, integrity, availability, and continuity) through accurately modelling the distance dependent errors using the raw measurements of an array of CORS surrounding a rover site. In the past few years many N-RTK positioning commercial services have been established around the world but are mainly used for surveying and mapping.

This Chapter assesses the two major causes of the lack of performance of a N-RTK receiver for road vehicle positioning: Deterioration in the communication system and GNSS signal outages.

As the mobile communications networks evolve in the UK and other countries, the performance of the N-RTK receiver also improves. In this research it is found that once the received signal strength indicator (RSSI) drops to approximately -100 dBm, the correction messages suffer from either message loss or message delay, which causes the receiver to under perform. The performance of the communication link during a cell tower handover has shown that there is no deterioration in the performance linked to the handover, although cell tower handovers generally occur at the limits of a cell tower's coverage, and hence at low signal strengths.

The resolution of the fixed integer ambiguity is crucial for the high accuracy solution available to a N-RTK receiver. The integer ambiguity resolution is relatively fast, typically within two minutes from a cold start or fewer than twenty seconds from a hot start. During tests on the M1 motorway, passing under an overhead obstruction caused a maximum total GNSS outage of 4.65 seconds, and a maximum time until the integer ambiguity was resolved of 52.10 seconds. On average, the GNSS outage was 1.14 seconds with an average re-fix time of 13.13 seconds. Until the ambiguity is resolved, the receiver can continue with a DGNSS solution delivering lane-level accuracy.

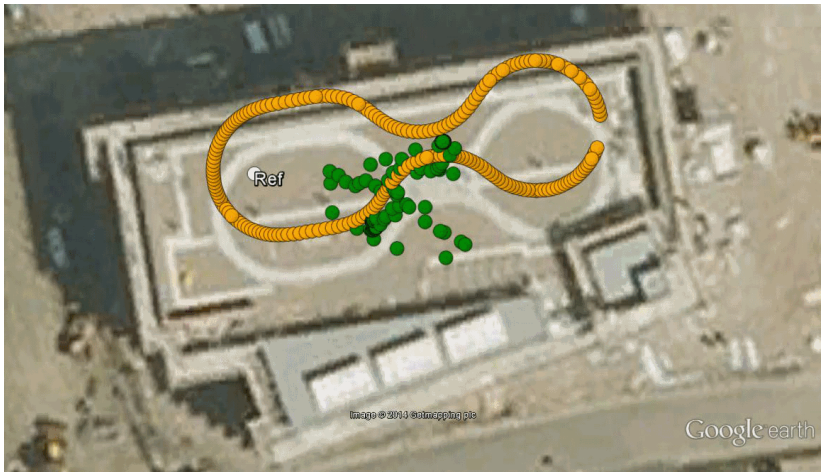
5.2 Initial tests of GNSS vehicle positioning

5.2.1 N-RTK positioning compared to a typical Sat Nav device

N-RTK positioning can provide sub-decimeter positioning accuracy during kinematic operations. A static receiver with a clear sky view and continuous connection to the corrections service will provide positioning accuracy better than 5 centimetres - on an epoch-by-epoch basis. Static measurement

over several minutes can produce sub-centimetre accuracy. However, as with any other GNSS positioning technique, the positioning accuracy of a N-RTK receiver on a moving vehicle will degrade slightly.

During initial trials using a N-RTK receiver on a moving platform, the positioning performance was compared to that of a standard, low-cost PND - a Samsung Galaxy S2 smartphone (with a SiRFstarIV GPS chipset). Figure 5.1a) shows the positioning results when both devices were placed on top of the electric locomotive on the roof of the NGB. The orange dots represent the positioning output from the N-RTK receiver, and the green dots represent the output from the smartphone (note that the Google Earth background image is of unknown accuracy, hence the offset of the position results from the track location). Clearly, as the electric locomotive travels along the track, the N-RTK receiver is producing a precise output (accuracy is not determined here), but the output from the smartphone does not appear to follow the train's movements at all.



a). RTK (orange) vs. smartphone (green).

b). N-RTK (green) vs. smartphone (white).

Figure 5.1 – Comparison of N-RTK and typical PND positioning performance.

In Figure 5.1b) both devices were carried by a road vehicle. In this test, the antenna for the N-RTK receiver was placed on the roof of the vehicle (rear and right side), whereas the smartphone was held in a cradle attached to the front windscreen. The output from the N-RTK receiver is shown in green dots, and the smartphone is represented by white dots. The smartphone performs better in this scenario than the previous scenario, although it is still offset from the N-RTK positions and the underlying Google Earth image.

These tests both demonstrate the dramatic improvement in positioning accuracy from N-RTK positioning over low-cost L1-only devices, and the goal of the positioning engine in low-cost personal navigation devices. The positioning performance of the smartphone is heavily assisted by other positioning information. In particular, SoOP and map matching in these two scenarios. In Figure 5.1a), the positioning solutions from the smartphone appear to be clustered in the centre of the building - a characteristic that suggests matching the position to the location of a known Wi-Fi access point. In Figure 5.1b), the smartphone tracks the vehicle with a good approximation of the road geometry - this suggests assistance from map matching (constraining the dynamic movement of the receiver) and increased positioning bias from Doppler measurements.

The results from these initial trials do not quantify the performance of either solution. A thorough comparison of the main GNSS positioning techniques for road vehicle positioning is given in Section 1.3.

5.2.2 Initial trials of N-RTK positioning of a vehicle

To assess the performance of N-RTK positioning for road vehicles, and to help determine future trials and development, a series of initial tests were carried out at the MIRA proving ground. As described in Section 1.4.4, the proving ground has several driving circuits, of which No.1 circuit and No.2 circuit are the longest. An N-RTK receiver was placed on board the MIRA test vehicle (shown in Figure 1.10) and driven around the test tracks.

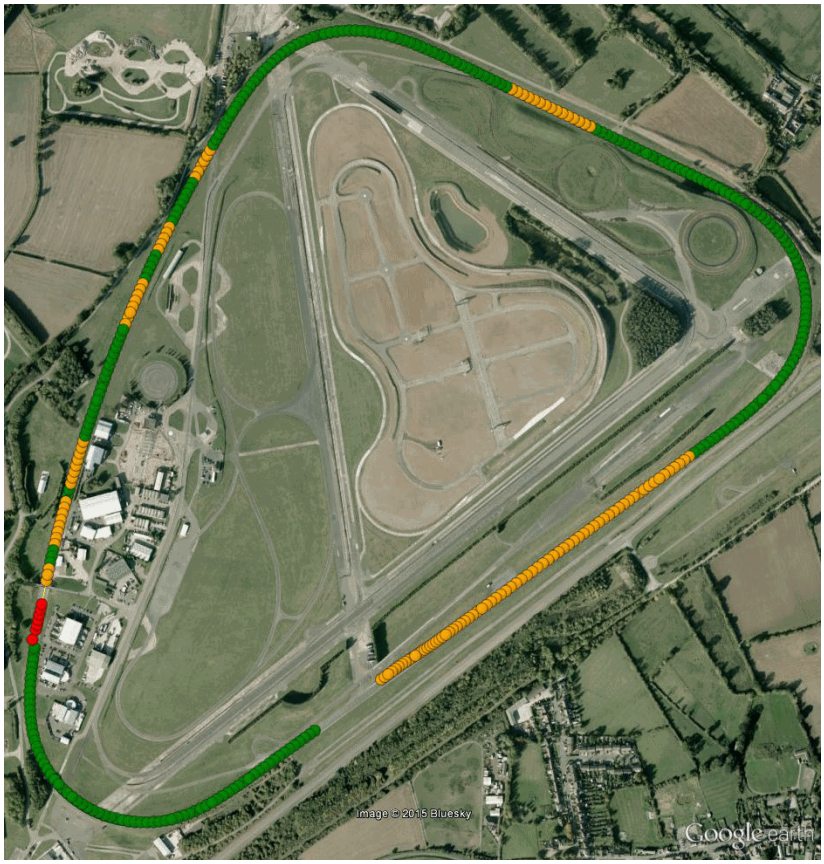


Figure 5.2 – Initial N-RTK positioning trials at MIRA proving ground - No.2 circuit.

The result from a single lap of the No.2 circuit is shown in Figure 5.2. The green dots represent a fixed position (65.1%); the yellow dots represent a float position (33.2%); and the red dots represent a stand-alone position (1.8%). As can be seen in more detail in Figure 5.3, an overbridge causes a short period of solution outage (1.4 seconds), followed by a short period of low accuracy stand-alone

solutions before regaining the fixed solution (3.4 seconds). There is also a small number of short periods of solution degradation from fixed to float, each less than 10 seconds.

These initial trials highlight the potential vehicle positioning performance of N-RTK positioning. It is important to stress that a float solution is also beneficial for vehicle positioning, as it can generally provide a positioning accuracy that meets the *Which lane* positioning category. This means that N-RTK positioning has demonstrated that a good positioning performance is achievable if a strong communication link to the corrections service and a good sky view are available. However, N-RTK vehicle positioning needs additional performance quantification, with particular attention to these two limitations.

Figure 5.3 – N-RTK GNSS signal outage at MIRA proving ground - No.2 circuit.

5.3 N-RTK for vehicle positioning: Performance analysis

Following the initial trials of N-RTK vehicle positioning, and the evidence from previous research, it was determined that further analysis of the positioning performance was required. In particular, this was measured using the principles of the RNP. In ITS and V2X applications the position must be highly accurate, with strong integrity, high continuity, and high availability. More details about the RNP can be found in Section 3.5.2.

5.3.1 Accuracy of N-RTK for road vehicle positioning

As shown in previous research (Aponte et al., 2008), and highlighted in new data collected for this thesis in Table 5.1, N-RTK positioning can deliver a highly accurate and precise solution in an ideal observation environment.

During kinematic tests using the NGI electric locomotive, over 99% of the observations lie within 2 centimetres of the truth solution (1 standard deviation of the 2D measurement is 13 millimetres), with a very small number of anomalous results of up to 15 centimetres (2D). The ground truth was provided by a tightly coupled post-processed solution, from the NGI's Applanix POS/RS INS. This consists of a NovAtel OEM4 dual-frequency GPS receiver combined with a navigation-grade Honeywell Consumer-IMU (Taha et al., 2009).

Table 5.1 – Comparison of the tightly coupled (GPS and IMU) solution with the N-RTK solution.

Tightly coupled solution minus N-RTK solution (metres)				
	Easting	Northing	Height	2D
SD	0.009	0.010	0.009	0.013
Max	0.150	0.150	0.150	0.150
Min	0.007	-0.009	-0.009	-0.009

5.3.2 Integrity of N-RTK for road vehicle positioning

Relative GNSS positioning has intrinsically high integrity, and there are various parameters to help estimate it (Hofmann-Wellenhof et al., 2008; Kaplan and Hegarty, 2009):

- During the calculation of the GNSS position, a variance-covariance matrix is used to minimise the errors (in a least-squares approach). This matrix can be used to provide a reasonably good estimate of the position precision;
- The geometry of the visible satellites is measured using a parameter called dilution of precision (DOP), which can also contribute to the estimate of position precision;
- The ephemeris contained within the GNSS navigation message or delivered externally to the GNSS receiver via communications networks will highlight any unhealthy satellite vehicles; and
- N-RTK positioning uses the LAMBDA method to resolve the integer ambiguity (a least squares calculation). The final stage of this process is to compare the best solution with the second best - a test that includes a threshold relating to how much better the best solution is compared to the second best. This threshold can be set by the user to increase the probability that the best solution is chosen, or reduced to increase the probability of a fixed ambiguity solution.

5.3.3 Continuity of N-RTK for road vehicle positioning

The continuity of N-RTK positioning will vary depending on the local environment and the access to the corrections service. For instance, a static receiver with a good sky view and a strong communications link will operate with a high continuity rate (the solution will satisfy the accuracy and integrity parameters over 99% of the time). Clearly if the satellite signals are obscured or the communications link is unavailable, the continuity will be very poor. These issues are discussed in Section 5.6 and Section 5.7. Figure 5.4 shows the effect of tree coverage on N-RTK positioning. This single carriageway road in Nottingham is tree lined, and during a brief trial drive the N-RTK solution was found to degrade to a float solution as the density of tree coverage increased.

As N-RTK positioning uses carrier-phase observations, GNSS outages and cycle slips significantly affect the performance of the receiver.As will be shown in Section 5.6, the re-initialisation of the fixed integer ambiguity resolution following a GNSS outage (such as that caused by an overbridge) can be relatively fast. However, from a cold start the ambiguity resolution can take up to two minutes. This may limit the widespread adoption of the technology for vehicle positioning.

Figure 5.4 – Example of scenario leading to poor N-RTK solution continuity.

5.3.4 Availability of N-RTK for road vehicle positioning

The availability is a measure of the percentage of time that the solution meets the accuracy, integrity, and continuity requirements. The availability is heavily dependent on the operational environment and the fundamental nature of GNSS positioning. As the GNSS signal coverage is not fixed and the signals may become unavailable for a variety of reasons, the availability is difficult to measure. For instance, as shown in previous research (Aponte et al., 2008) and the results from motorway trials in Section 5.7.2.2, the availability of a N-RTK fixed solution can vary greatly.

5.4 The limitations of N-RTK positioning in the vehicle domain

Previous research (Aponte et al., 2008, 2009) and the initial N-RTK positioning trials in Section 5.2 and Section 5.3 highlighted two major limitations for the implementation of N-RTK positioning for automotive applications. These are:

- GNSS signal outages; and
- GNSS correction message outages.

The following paragraphs introduce these limitations, and Section 5.6 and Section 5.7 explore these limitations in more detail.

GNSS signal outage.
This is the fundamental flaw of GNSS positioning. Due to astonishingly weak GNSS signals and the laws of physics that govern electromagnetic waves, the receiver's antenna needs to have an unobstructed view of the satellite in order to provide a high accuracy solution. It is clear that the majority of the transport infrastructure is outdoors and has a good view of the sky, particularly away from heavily urbanised areas. However, the receiver gets no warning of impending signal obstruction, so that even momentary obstructions such as an overhead gantry on the motorway can cause significant loss of positioning accuracy, and often causes a receiver to output no solution at all, as shown in Figure 5.5. Here the vehicle is travelling in a northern direction in lane one and passes underneath an overhead steel frame gantry. This causes both a GNSS outage and deteriorated position accuracy, to the extent that the vehicle is positioned a distance of three lanes from its actual location (note that the underlying map image is of unknown accuracy).

A GNSS outage can be caused in several ways: The obstruction of the GNSS signals can lead to a loss of signal lock; a momentary obstruction or partial obstruction can cause cycle slips to occur (during carrier-phase positioning); if the visible satellites at the rover receiver are not the

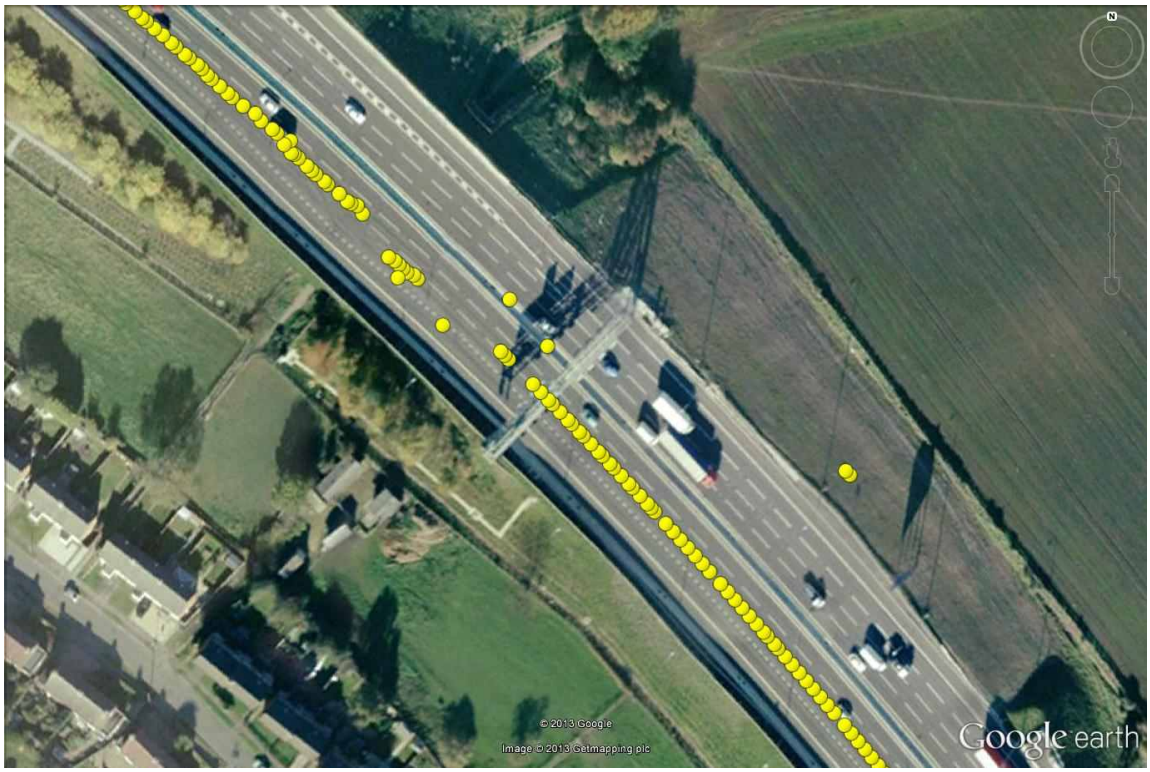


Figure 5.5 – The typical effect of overhead obstructions on GNSS positioning of a road vehicle.

same as at the reference receiver then the ambiguity cannot be resolved; there may be intentional or unintentional signal jamming or interference; and if the receiver assessed the integrity of the signals to be poor then it may not provide a solution.

GNSS correction message outage.
A fundamental aspect of N-RTK positioning is the delivery of reference station data used in the processing of the receiver's position (Wanninger, 2004). Although there are various methods used to deliver this data, the most secure and reliable method involves transmitting raw reference station observations, so that the receiver may perform the calculation of the position with all of the possible data. This is shown to provide the highest integrity (Janssen, 2009). The vulnerability here is not the algorithmic method used to transmit the data, but is in fact the characteristics of the communication system. This is due to three reasons:

- There is no connection between reference and rover receivers;
- There is data loss from the connection; or
- There is an inadequate delay in the transmission of the data.

5.5 N-RTK limitations tests: Test equipment

In order to gather evidential data regarding the limitations of N-RTK positioning for automotive applications, the NGI's testing equipment was used. The road test vehicle (an internal image is shown in Figure 5.6) was equipped with a Leica GS10 receiver with AS10 antenna (Figure 5.7). The real time correction information was provided through the Leica SmartNet service, using a GSM/GPRS connection on the Vodafone network. The signal strength was measured in real time using the Android application RF Signal Tracker (Hunt, 2012), operating on an Android-based mobile phone (also shown in Figure 5.7).

Figure 5.6 – The inside of the NGI road test vehicle (Mercedes Vito van).

The data recorded included:

- GNSS raw data;
- N-RTK positioning real time output; and
- GSM signal strength.

Figure 5.7 – The RF Signal Tracker Android application and smartphone used to record the GSM signal strength (left), and the Leica Geosystems GS10 receiver (right).

As the experiments were not intended for the analysis of the accuracy of the GNSS receiver, there was no requirement to utilise the ground truth system on board the NGI test vehicle.

5.6 GNSS signal outage

A GNSS receiver requires GNSS signals in order to calculate a position. A minimum of four signals are required to calculate the four unknowns: The three position unknowns (x, y, z) and the time correction. This issue is even more acute for carrier-phase relative positioning, as the probability of successfully fixing a solution and its inherent robustness is directly related to the number of visible satellites. As shown in Section 4.4.3, six satellites is the minimum number required to keep the position availability high.

5.6.1 Examples of GNSS outages on the M1 motorway

To assess the GNSS signal outages limitation, the test vehicle was driven along the M1 motorway for a distance of approximately 100 kilometres. The M1 is a major road transport artery linking London in the south to Leeds in the north of England, typically with three or four lanes in each

direction. The test route passed under 214 overhead obstructions (northbound and southbound directions), of known classification (footbridge, road bridge, and gantry). This scenario was chosen as the environment is quite rigid, allowing repeatable tests, and it is the area in which future ITS technology is most likely to be adopted first (Silberg and Wallace, 2012).

An example of a GNSS signal outage is shown in Figure 5.8. As the vehicle approaches a road overbridge, the number of visible satellite vehicles decreases resulting in a total signal outage. As the vehicle passes the bridge the number of visible satellite vehicles then begins to increase. Correspondingly, the N-RTK solution degrades from a fixed solution (4) to a float solution (2) before the overbridge; no solution (0) is output during the signal outage; and following the reacquisition of the GNSS signals the solution recovers to a float solution, and then to a fixed solution.

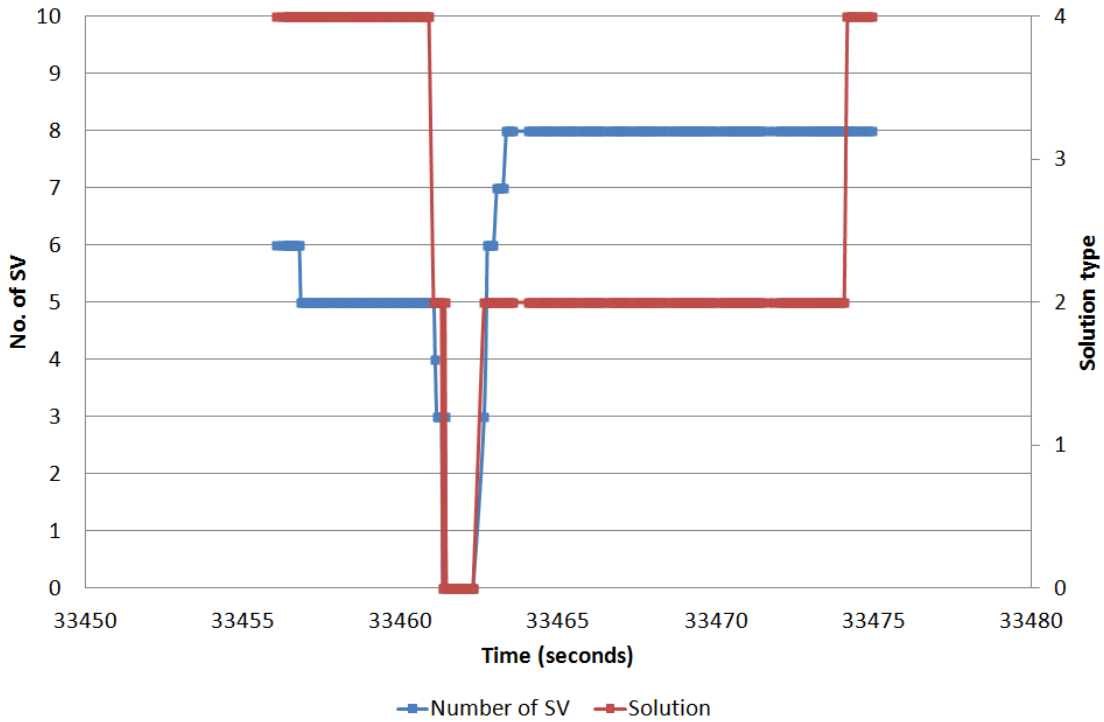


Figure 5.8 – A GNSS signal outage. The number of visible satellite vehicles and the resulting N-RTK solution.

During the GNSS outages tests, the vehicle travelled at a constant speed of 60 mph, primarily in lane 1 of the motorway. Table 5.2 shows the statistical breakdown of the GNSS signal outages and the resulting reacquisition of the fixed ambiguity in the N-RTK solution.

The longest total GNSS outage caused by an overhead obstruction was 4.65 seconds, when passing under a road bridge. At 60 mph this translates into a distance of almost 130 metres without any GNSS solution, which is much further than the width of the overhead object. Once the GNSS signal is reacquired, there is a short period during which the fixed integer ambiguity is resolved, in order to achieve the 5 centimetre-level accuracy. The longest duration between the start of a GNSS outage and the reacquisition of the fixed ambiguity for the N-RTK solution is 52.10 seconds, or approximately 1,450 metres. Although during this period, a DGNSS solution is available as soon as the satellites are reacquired.

5.6.2 GNSS signal availability and ambiguity resolution

As described in Section 4.4.3, the number of satellite vehicles required to fix the integer ambiguity is greater than the theory predicts. Four common satellites are required to be visible between the

Table 5.2 – Statistical breakdown of GNSS outages caused by overhead objects.

Obstacle		Outage		Re-fix	
		(s)	(m)	(s)	(m)
Footbridge	Mean	0.79	21.9	9.78	273.0
	Max	1.75	48.8	19.75	551.0
	Min	0.00	0.0	6.90	192.5
Road bridge	Mean	1.40	39.1	13.80	385.0
	Max	4.65	129.7	52.10	1453.6
	Min	0.15	4.2	5.10	142.3
Gantry	Mean	0.28	7.8	15.77	440.0
	Max	1.05	29.3	27.55	768.6
	Min	0.00	0.0	8.70	242.7

base and rover receivers, and although a fixed solution was possible for a small portion of the test (30.3%), this is significantly lower than what is possible with at least six visible satellite vehicles (80.9%).

When the number of visible satellite vehicles is low, the relative geometry between the satellites and the receiver provides a higher DoP. This results in the best and second best candidates for the fixed integer ambiguity to provide a similar level of measurement residuals, leading to more failures during the ratio test (the threshold is not met).

As described by Angrisano et al. (2010), the additional use of the GLONASS satellites with GPS satellites can improve the availability of a position solution when the number of visible satellites is low, but does not improve the accuracy of a position solution when the availability of GPS satellites is high. This is partly due to the poor compatibility of the two constellations when performing integer ambiguity resolution.

5.6.3 GNSS signal multipath

The Leica GS10 receiver with AS10 antenna has mechanisms in place to deal with GNSS signal multipath, although low-level multipath still appears in the N-RTK observations. As shown in Figure 5.9, the clustering of static observations over a five minute period is denser at a location in a low multipath environment (A04, a point on the railway track that is away from highly reflective facility boxes) than at a location considered to have a worse multipath environment (A11, a point close to the facility boxes). Each location had the same number of visible satellites and horizontal DoP. For simplicity the graphs show the 2D position, although the third dimension (height) displays a similar difference. Each location included four receivers (with separate antennas) set up in close proximity, labeled P1 to P4. It is important to note however, that the precision of the observations in location A11 is still better than 5 centimetres, suitable for many ITS and V2X applications. Also shown in Figure 5.9 is the variation of height observed over a five minute period, which displays a sinusoidal variation typical of the effect of signal multipath.

The distribution of the observed points in the 2D spread of observations at location A11 also demonstrates the impact of satellite geometry on GNSS positioning accuracy: There is a bias perpendicular to the direction of travel of the satellites (on their inclined 55 degree orbits).

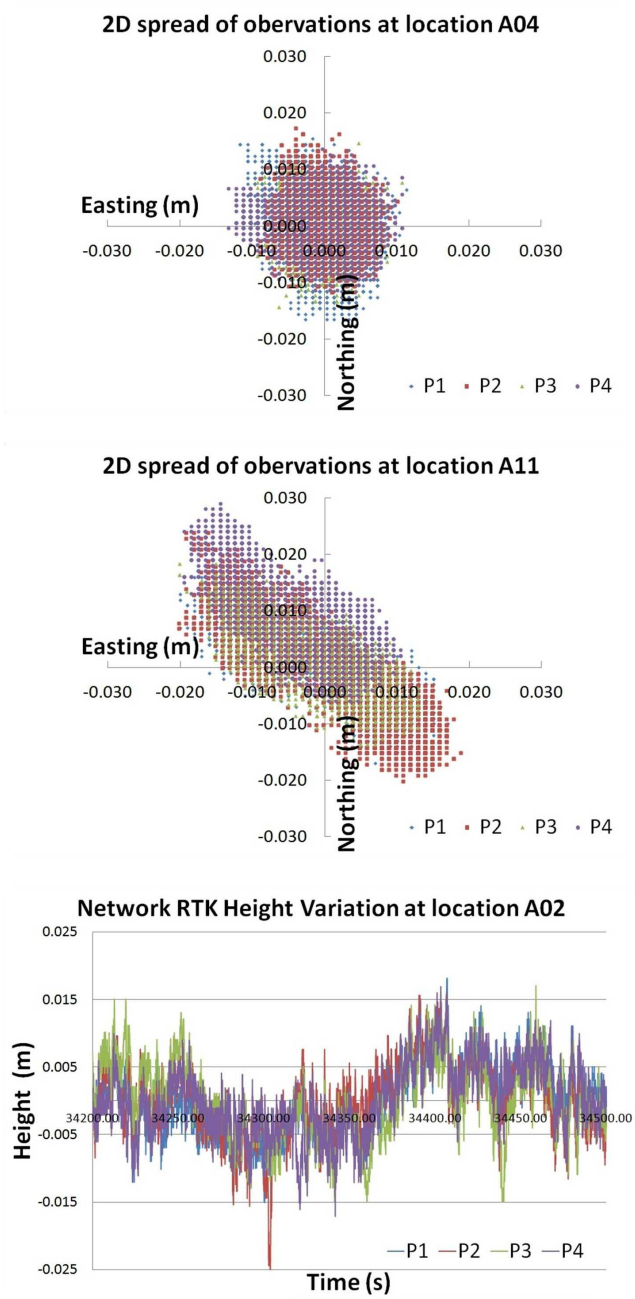


Figure 5.9 – The effect of signal multipath on the N-RTK position solution.

5.7 GNSS correction message outage

For high precision N-RTK positioning, a continuous connection to the corrections service is required. The position calculation is designed to handle minor breaks in connection or partly missing data sets, but data older than 10 seconds is generally considered too old to perform reliably. As shown in Section 4.4.2, RTK positioning relies heavily on prompt delivery of correction information for accurate position calculation.

5.7.1 Cellular communications

First generation (1G) cellular systems used analogue technology to allocate different frequency channels to users in the same cell (FDMA multiplexing). Second generation (2G) cellular systems (namely GSM[1] and US-Time Division Multiple Access (US-TDMA)) are digital, including both signalling and voice channels. GSM is the most popular standard in the world, accounting for around 80% of handsets (GSM World, 2009). These systems use a combination of FDMA and a technique where different users were allocated different time slots but on the same channel, known as TDMA. However, the second generation design had very little scope for data traffic (Poole, 2006).

This led to the creation of the 2.5G cellular systems in 1997. This combined the General Packet Radio Service (GPRS) with GSM, wherein individual packets of data are routed to the user rather than dedicating a specific circuit. This allowed dead periods in another cell to be used productively and made the whole system more efficient. (Note: The Enhanced Data rates for GSM Evolution (EDGE) development carries out a similar process but with a different modulation).

5.7.1.1 Cellular implementation

A cellular network allows mobile phones to connect to it by searching for nearby cellular antennas, representing the centre of a cell. There are five sizes of cells: Macro; micro; pico; femto; and umbrella cells, which are used to cover smaller cells and fill in the gaps. The size of the cell is set by the height of the antenna and its range. The longest practical range is 35 kilometres. Picocells can be found indoors (such as in shopping centres) where high usage might be anticipated (Poole, 2006).

Modulation used on the waves is Gaussian minimum shift keying (GMSK), a continuous-phase frequency shift keying. There are generally four main GSM frequency bands operating around the world:

- 900 MHz and 1800 MHz in Africa, Europe, the Middle East, and Asia; and
- 850 MHz and 1900 MHz in North America (the other bands were unavailable at allocation).

South American countries use a variety of the above frequencies in different combinations. There is also the rare use of the 400 MHz and 450 MHz frequency bands, although with no current commercial use.

As an example, the GSM 900 frequency band uses 124 channels spaced at 200 kilohertz (duplex spacing at 45 MHz). Guard bands of 100 kilohertz are at either end of the channel. In contrast, the third generation (3G) frequency band is 2100 MHz in Europe and will utilise the 2600 MHz band in the future (Poole, 2006).

The frequency is divided into time slots for the cellular devices to use, which allows 8 full-rate or 16 half-rate speech channels per frequency band. Half-rate channels use alternate frames.

GSM uses the Subscriber Identity Module (SIM) card system to identify devices in the network and correctly route voice and data information. GSM authenticates the user to the network using this SIM, but the process does not work in reverse. This means that algorithms are used in ciphers for security of voice calls, but they are generally weak and considered insecure. Other security threats come in the form of Trojans or malware embedded on the device.

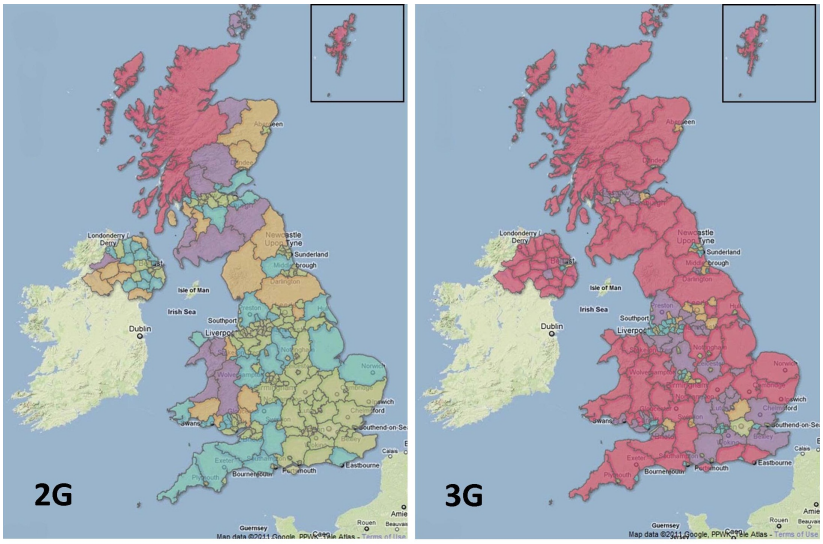
Due to the longevity of GSM, some aspects of its implementation are becoming open source as the patents are expiring (Poole, 2006).

5.7.1.2 Cellular coverage in the UK

The preferable communication system is to use mobile internet over the GSM/GPRS cell network, which is already well established (Wegener and Wanninger, 2005). The major network operators claim over 99% coverage of the population in the UK, but this does not take into account

[1] GSM stands for Global System for Mobile Communication, although the acronym originated from Groupe Special Mobile.

physical and local conditions such as land and building obstructions, atmospheric conditions, and interference from vegetation and other radio signals.



Colour					
Coverage	>90%	70-90%	50-70%	25-50%	<25%

Figure 5.10 – 2G (left) and 3G (right) coverage by geographic area in the UK.

A BBC survey carried out in 2011 in the UK, found that when users had a mobile phone data connection, it was only a 3G standard 75% of the time (2G otherwise), and that there are significant notspots that include major rail and road networks (BBC, 2011). A similar ongoing study by OpenSignalMaps has found that a 3G service is only available 58% of the time (OpenSignalMaps, 2011). The UK government published a report in 2011 (Ofcom, 2011), detailing the extent of 2G and 3G services, and part of the result is shown in Figure 5.10. As can be seen, there were areas of the UK in 2011 with poor data communication coverage (below 50%), and this would be a significant problem when using N-RTK positioning for road vehicles.

A report published in 2014 by OpenSignal showed that the UK's 68 major roads have no signal available for 5% of the time (OpenSignal, 2014). The crowd-sourced data also shows that 3G services are available for 75% of the time, and fourth generation (4G) services are available for under 50% of the time. Results for smaller roads are worse, where 3G coverage is available for only 66% of the time.

However, the situation is continually evolving, and more and more areas of the UK are achieving a strong and robust data communications signal. This is driven by significant growth in the demand for over-the-air entertainment services.

5.7.1.3 Cellular data loss

In earlier research carried out by Aponte et al. (2009), continuity tests show that when using GSM/GPRS mobile communications to transfer the N-RTK corrections, the availability was approximately 88% and the connection could be lost after a few hours of continuous use. This can be caused either by SIM cards that use dynamic Internet Protocol (IP) addresses creating interruptions when renewing the addresses, or where voice data was prioritised on the network. Other research carried out by the NGI has shown that a typical mobile internet connection (a combination of wired public internet and GPRS) suffers from approximately 20% data loss (Yang et al., 2009a).

When the receiver passes from one cell to the next in a cellular network, this is known as a cell handover. This process is managed by the cell network, and not the cellular modem. This handover

process is assessed later in Section 5.7.2, to discover whether there is deterioration in the cellular network connection during this time.

5.7.1.4 Cellular data message delay

During N-RTK positioning, the receiver considers messages older than 10 seconds unusable for a fixed integer N-RTK solution, although messages younger than 60 seconds can be used to give an accurate DGNSS solution (Aponte et al., 2008). Messages older than 60 seconds will restrict the receiver to only output a stand-alone position, by which time the accuracy will decay beyond vehicle positioning requirements. Previous research found that the typical mobile internet connection suffers from an average delay of 0.85 seconds (Yang et al., 2009a).

5.7.2 Real-world cellular coverage tests

In order to test the variation of GSM signal strength in real-world conditions, a small circuit was chosen close to the NGI (shown in Figure 5.11), which incorporates a variety of environments from open sky to bridge underpasses, and dense tree coverage. Using a repeatable path allows the identification of issues that are attributed to problems with the communications link as opposed to other issues (such as hardware problems and GNSS signal outages), and despite the short distance, the loop also provides a wide range of GSM signal strengths. During the experiments to follow, the data was measured during three consecutive laps of the circuit.

5.7.2.1 NGI circuit

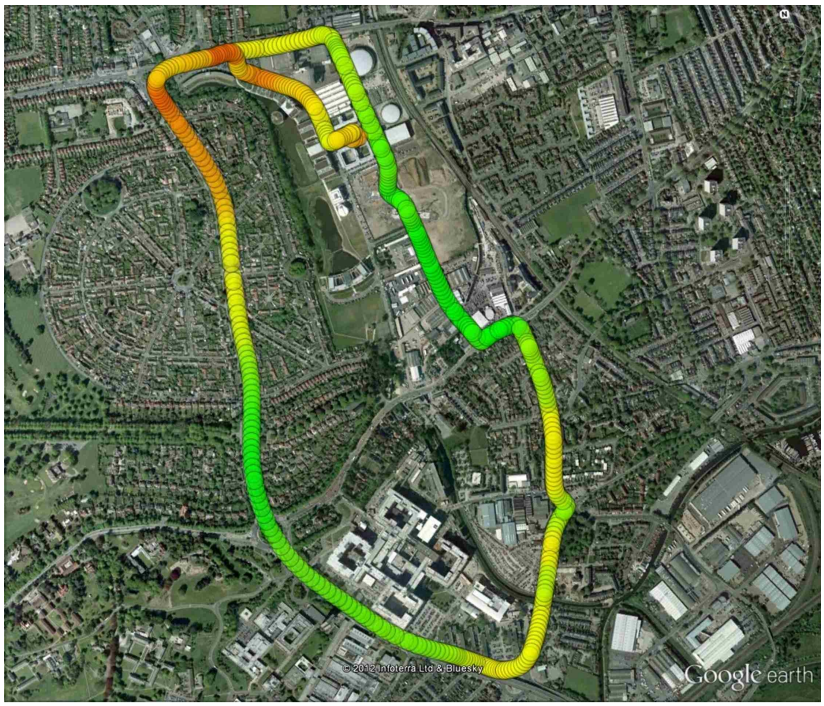
The NGI circuit in Nottingham is shown in Figure 5.11. The variation in colour along the route is an indication of the RSSI. In this area the RSSI varies between -50 dBm and -105 dBm, which are the typical maximum and minimum strengths of a cellular network. This is despite the assessment from the network provider that this entire area delivers 'High Speed' internet and email. Figure 5.11 also shows the subjective rating and expected performance of the RSSI.

Table 5.3 details the RSSI observations measured during the signal strength trials around the NGI circuit. The range of values shows the typical maximum and minimum RSSI values experienced by a mobile phone user (other than no signal being received). The signal strength is recorded every 5 metres, in order to achieve a good geographic spread across the area (as opposed to biasing the results with observations recorded whilst the vehicle is stationary). The RSSI observations do not correspond to a typical Gaussian distribution, suggesting that there are external influences on the strength of the signal and the handover between one cell tower and the next.

As shown in Figure 5.12, there is an increase in the AoC of the messages following a drop in signal strength (RSSI) to approximately -100 dBm. This is visible from the peaks in the AoC message to over 8 seconds. The graph shows three laps of the NGI circuit, noticeable by the repeated pattern of signal strength. The increase in the AoC occurs at approximately the same geographic location on each lap – an area in the north west of the circuit that suffers from weak signal strength (as seen in Figure 5.11). As described by Flood (1996), the received signal strength is the sum of the direct and indirect (or reflected) waves, varying with distance between a series of maximum and minimum values. On a moving vehicle, the RSSI will vary with time as it moves between these maximum and minimum values, and is especially complicated in urban areas where there may be no direct waves at all and waves are propagated by a series of reflections. A moving receiver also suffers from a Doppler shift in the frequency of received signal.

As described in Section 5.7.1.4, the N-RTK receiver considers messages older than 10 seconds out of date. So in this scenario, there is a brief occasion during the loop in which the loss of the N-RTK solution is attributed to the weak GSM signal strength.

A close inspection of Figure 5.12 highlights a slight delay between the drop in RSSI to -100 dBm and the increase in the AoC. This delay needs further analysis, but is assumed to relate to the slower update rate of the ionospheric and tropospheric corrections (10 seconds and 60 seconds respectively). There are also periods of increased AoC that are uncorrelated with a drop in RSSI,



RSSI (dBm)	Rating
> -51	Excellent
-51 to -74	Excellent
-75 to -84	Good
-85 to -94	Average (workable)
-95 to -113	Poor (marginal)
< -113	Very Poor

Figure 5.11 – The GSM signal strength (RSSI) around the NGI circuit in Nottingham, with the subjective RSSI ratings.

Table 5.3 – The spread of RSSI observations recorded during the trials around the NGI circuit.

RSSI (dBm)		No. observations	% observations
-50		79	5.9
-55		75	5.6
-60		23	1.7
-65		171	12.7
-70		103	7.7
-75		210	15.6
-80		134	10.0
-85		186	13.9
-90		116	8.6
-95		201	15.0
-100		44	3.3
-105		0	0.0
-110		0	0.0

for which there is no clear explanation, although none of these occasions results in a loss of the fixed ambiguity N-RTK solution.

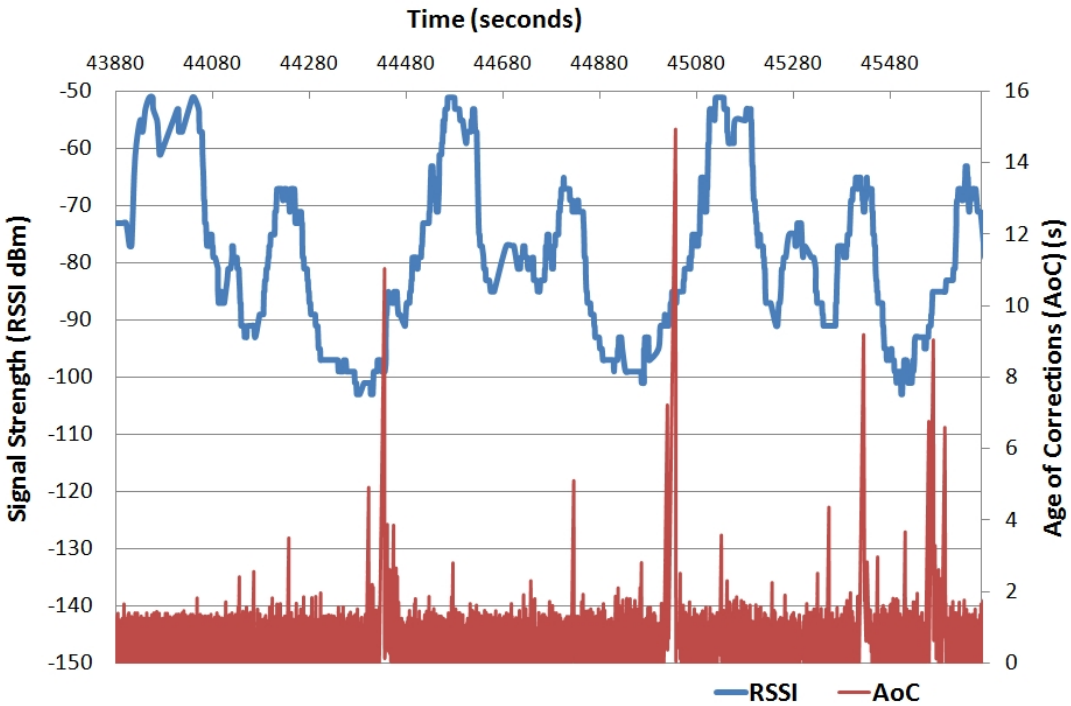


Figure 5.12 – The relationship between GSM RSSI and the AoC.

There were 80 cell handovers recorded during the trials. This is considered higher than average, although there are many valid reasons for the high number. Firstly, the number of physical cell towers is high due to the large volume of cellular traffic (there is a university, a large hospital, and major roads, as well as general housing and business properties in the vicinity). Secondly, modern cellular systems take advantage of dynamic cell indentifiers, allowing the device to switch between 2G, 3G, and 4G. These switches can count towards the number of cell handovers.

In any event, the cell handovers showed an average improvement of +1.2 dBm from just before the handover until just after. The maximum improvement is +22 dBm, although there are occasions when the RSSI gets worse - the biggest fall in received signal strength being -12 dBm. Figure 5.13 displays the frequency distribution of the change in RSSI during a cell handover. Note that the resolution of the RSSI measurements is 2 dBm.

Cell handovers occur at a range of RSSI, not just low signal strength. This suggests that cell handovers are managed by the network operator in a way that does not disrupt the data connection. There appears to be no correlation between a cell handover and a problem with the correction message delivery.

Although this experiment was not a test of the receiver performance, during the NGI circuit trial 63.1% of the receiver observations were N-RTK fixed, and 33.0% of the observations were DGNSS observations. Therefore, 3.9% of the possible epochs had no observations, partly due to passing under bridges. The largest GNSS outage during the NGI circuit trials was 4.85 seconds. These values show an improvement over previous research, particularly as this is considered a difficult GNSS positioning environment.

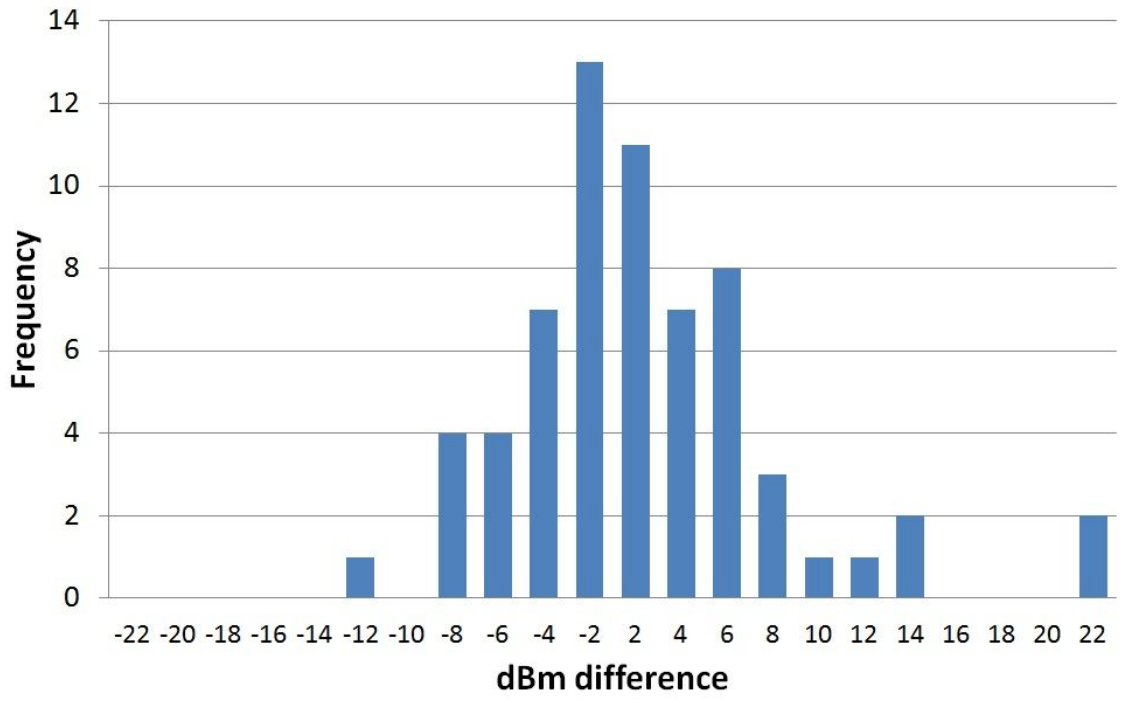


Figure 5.13 – Frequency histogram of the RSSI change during a cell handover (2 dBm bins).

5.7.2.2 M1 motorway

Major motorways in the UK connect large urban areas. This means that the largest percentage of their length is geographically located in non-urban areas. As the cellular network is designed to cover areas of high population (such as towns and cities), coverage for transport infrastructure such as motorways and railways can be poor. There are fewer cell towers, and their antennas are not directed towards transport infrastructure. This tends to mean that the RSSI of cellular signals is low. This issue is shown in Figure 5.14. The location of the cell towers are denoted by white hexagons, and their antenna direction by the blue circle segments. During a driving test to determine the RSSI, data was gathered along the M1 motorway (running through the centre of the image, in the north-south direction). A good RSSI is shown as green, and poor RSSI is red. The figure shows that close to urban areas such as Hucknall, the cellular coverage is good, but as the vehicle moves north into a more rural area, the cellular coverage becomes poor. Note that only the cell towers that were connected to the device are plotted in the figure.

To assess the issue of poor RSSI on inter urban area routes, a trial was carried out along a 100 kilometre stretch of the M1 motorway (from Leeds to Nottingham). A Leica Geosystems GS10 receiver with AS10 antenna was used to calculate the position of the test vehicle, using corrections delivered through the cellular connection of a smartphone. An application on the smartphone simultaneously recorded the RSSI of the cellular connection. The equipment set up is described in more detail in Section 5.5.

During the trial the mean RSSI was -85.1 dBm. To compare the effect of RSSI on N-RTK position solution availability, the trial data was divided into three scenarios:

- Scenario 1 was the section of motorway between Junctions 41 and 34.
- Scenario 2 was the section of motorway between Junctions 34 and 28.
- Scenario 3 was the section of motorway between Junctions 28 and 26.

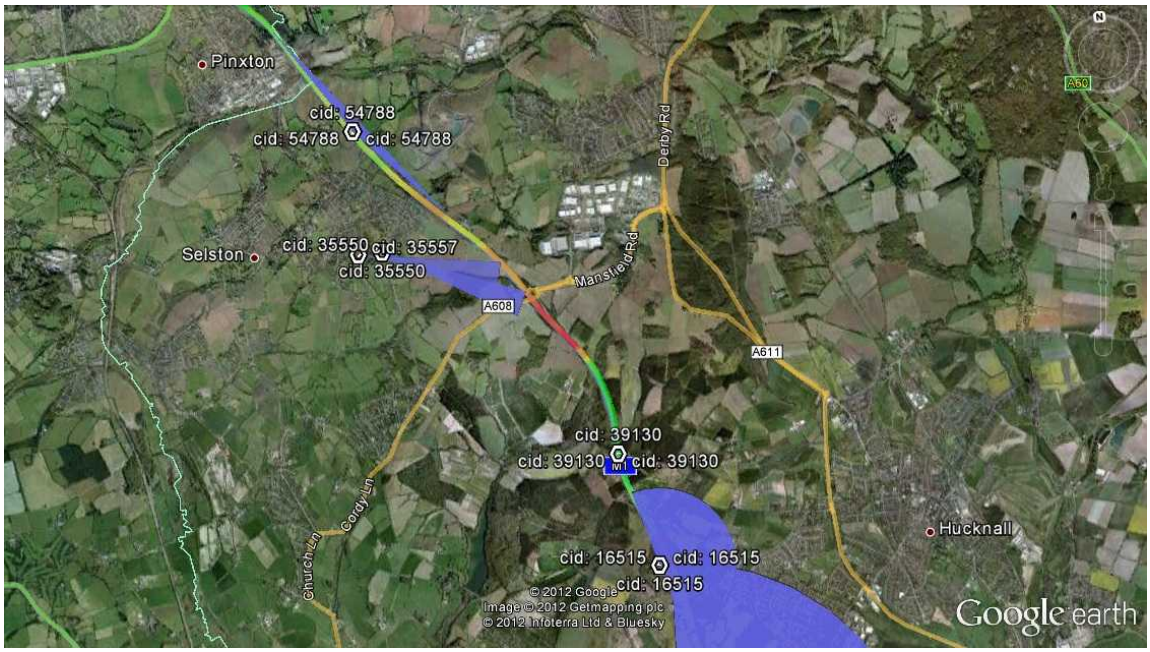


Figure 5.14 – RSSI signal strength and cell tower coverage on the M1.

Scenario 1 and scenario 2 are considered to have similar infrastructure. For instance, the number of overbridges and other characteristics of the road are similar. Scenario 3 is a modern section of motorway, which includes a greater number of overhead structures. These are primarily gantries to support the ITS infrastructure that enables the Managed Motorway system (for instance, additional signs and enforcement cameras).

Table 5.4 – The effect of GSM/GPRS RSSI signal strength on N-RTK solution type.

Scenario	Mean RSSI (dBm)	Solution Type (%)				Description	Cell changes (adjusted)
		Non	Stand alone	DGNSS	N-RTK		
1	-83.3	3	6	33	58	M1 Jct 41 > Jct 34	32
2	-92.6	3	5	47	45	M1 Jct 34 > Jct 28	47
3	-78.5	3	0	55	43	M1 Jct 28 > Jct 26	49

The results of the trial are shown in Figure 5.16 and Table 5.4. Scenario 1 had a stronger mean cellular signal strength (-83.3 dBm) compared to scenario 2 (-92.6 dBm), and also provided a higher percentage of N-RTK position solutions (58% versus 45%).

The RSSI was stronger during scenario 3 (-78.5 dBm) than both scenario 1 and scenario 2, but the availability of the N-RTK position solution was lower (43%). However, during scenario 3 there was a greater percentage of DGNSS solutions and a lower percentage of stand-alone solutions, suggesting that a data connection was available for a larger proportion of the test.

Figure 5.15 shows the distribution of RSSI during the three scenarios. The Gaussian distribution is not strong for any of the scenarios, with multiple peaks in each. Scenario 3 for instance, has a higher frequency of both strong and weak RSSI than scenario 1.

As was discussed in Section 5.7.2.1, cell handovers do not have an effect on the availability of the N-RTK position solution, but are included in Table 5.4 for reference[2].

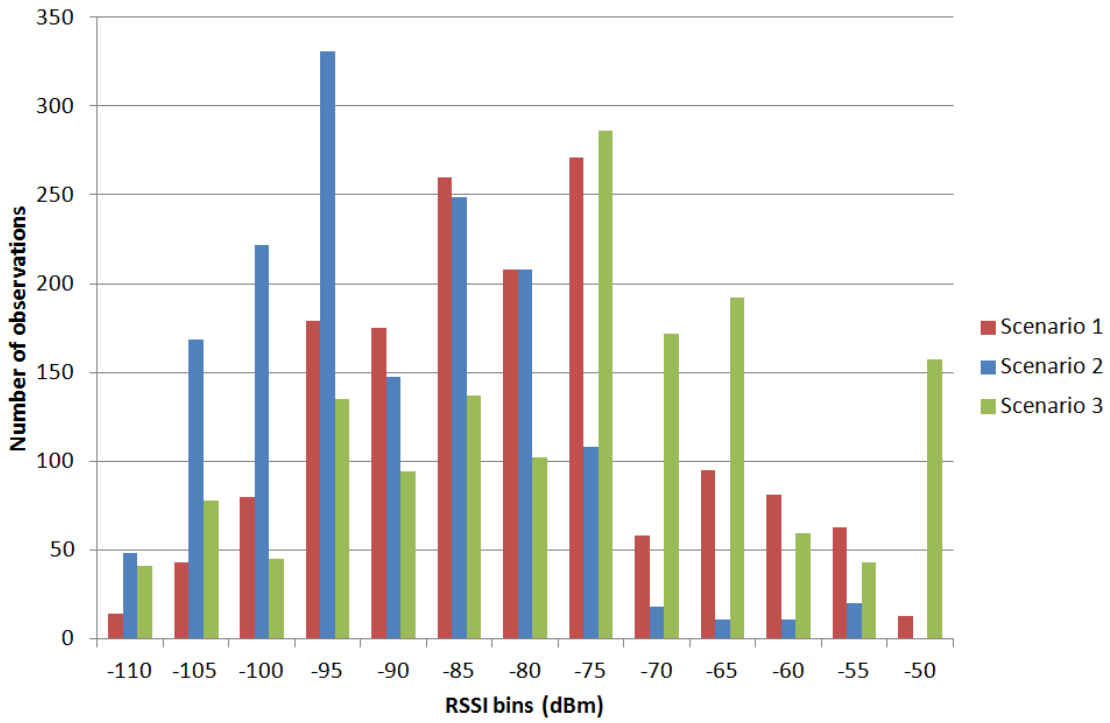
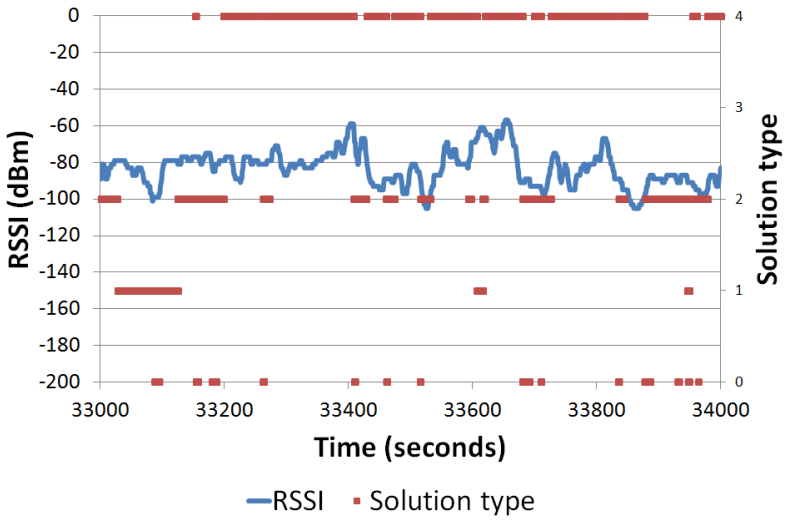
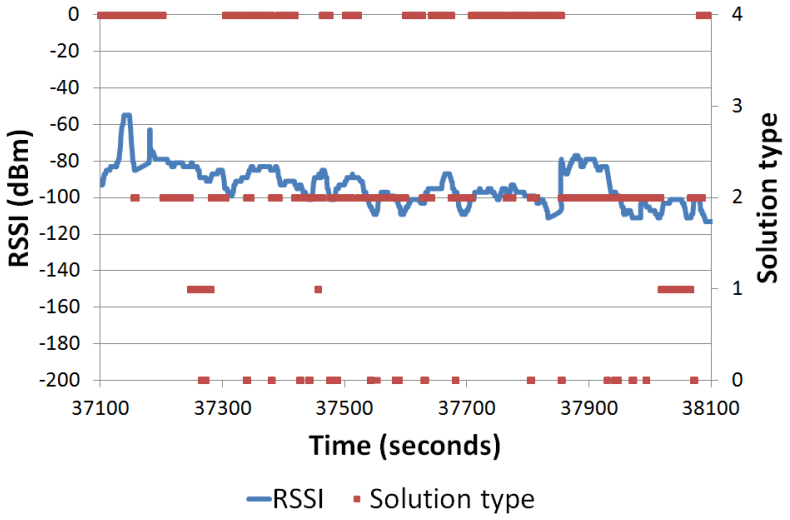


Figure 5.15 – RSSI histogram for M1 motorway scenarios.

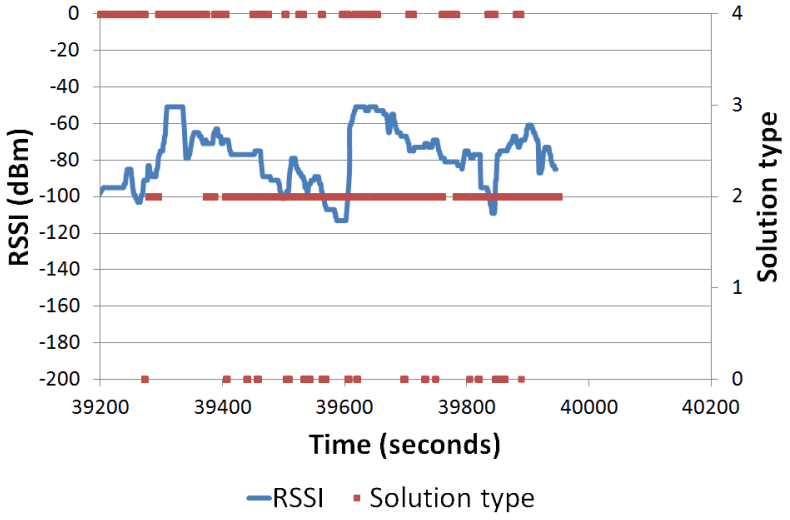
[2]The values in the table are amended to enable the comparison of the three scenarios, as the length of each scenario was different. The original values were: 32 in scenario 1; 31 in scenario 2; and 24 in scenario 3.



a). Scenario 1.



b). Scenario 2.



c). Scenario 3.

Figure 5.16 – The effect of GSM/GPRS RSSI signal strength on N-RTK solution type.

5.7.3 Alternative communications options

The nationwide adoption of mobile internet services by mobile phone users has provided a useful communication system for positioning systems. However, the network providers do not guarantee the type of communication service demanded by advanced ITS and V2X applications. The quality of service is too easily disrupted by passing into an area with weak signal strength, or when there are many users congesting the bandwidth.

Future generations of mobile networks, such as 4G, will significantly increase the available bandwidth and increase download speeds, but there is an unknown increase in the demand of the system from non-critical mobile phone users. The issues in the existing system can be minimised slightly through improvements at the user end, such as using stronger gain antennas or accessing multiple networks with different SIM registrations. The nature of cellular networks also lead to a decrease in signal strength occurring prior to the cell handover. which could cause delays in the message delivery. Therefore the management of this process could be improved. Future testing of the GSM network can be carried out at the new innovITS ADVANCE test facility at MIRA in the UK, as shown in Figure 5.17. Here the private network can be controlled and manipulated as desired. There are three GSM/GPRS antenna towers, at the locations marked by blue squares in the figure.

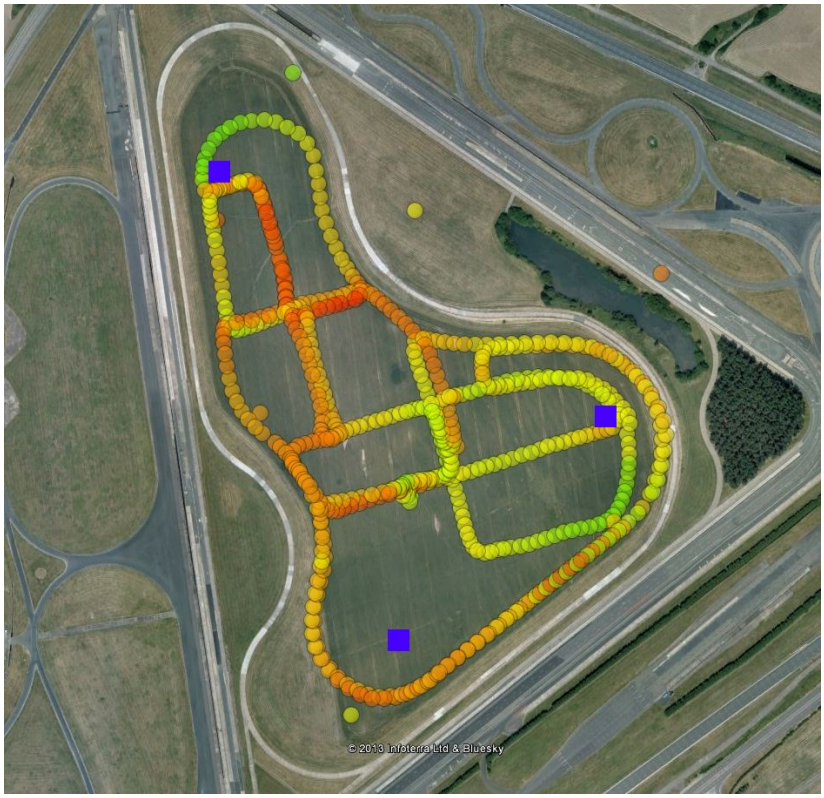


Figure 5.17 – GSM/GPRS RSSI at the innovITS ADVANCE test track.

An alternative communication method, that has the same wide area coverage of a cell network, is satellite communication. In tests carried out by the University of Nottingham (Yang et al., 2010), observation of static positions showed 98% of messages were received correctly at a latency of less than 10 seconds. This compares with the High-Speed Download Packet Access (HSDPA) cell network figures of 99.8% and 1.2 seconds. When in a kinematic mode, the satellite communications fared less well. Testing three separate satellite communication systems, problems were encountered with signal reacquisition, long latency, and static initialisation. The results showed that at best

70% of correct messages were received, with a latency of 4.2 seconds, although this is often over 20 seconds.

DAB is capable of being used as a future communication method for N-RTK positioning. Compared to traditional VHF and UHF radio communication, it uses the frequency more efficiently and is more robust to degradation (C. Gandy, 2003).

The design of the Leica GS10 receiver is aimed at delivering a very reliable and highly accurate solution. It was not intended for use on vehicles and in dynamic environments. The receiver deals well with multipath, rejecting low strength GNSS signals and allowing the resolution of the integer ambiguity. However, this means that within city environments it may provide fewer solutions than a modern smartphone, albeit with a much higher accuracy when it does. Recent research has shown that it is possible to increase the speed of the ambiguity resolution, and customize the integrity controls, which would make the resolution process close to instantaneous in certain circumstances (Odijk and Teunissen, 2010).

Chapter 6

Cooperative Vehicle GNSS Positioning

6.1 Overview

The positioning of GNSS receivers relative to one another is a common application in transportation; for instance, during the aerial refueling of an airborne fighter jet by another airplane. In this case, it is important to know accurately the relative position of the two airplanes, but not necessarily their absolute position.

Relative positioning of road vehicles is more complex. By their nature, road vehicles are almost always close to other vehicles or road infrastructure, and there are many separate agents in each scenario. Vehicles can also travel large distances, and in terms of GNSS positioning, this may mean vastly different atmospheric conditions. Hence, relative positioning in road transport is useful if all GNSS receivers relate to the same datum, which in most cases is effectively absolute positioning.

The advancement of the V2X concept in recent years signals a path to real time vehicle-to-vehicle communication. If this can be paired with the latest high precision GNSS positioning techniques, this would create a useful tool in the cooperative positioning and driving applications that have been discussed in ITS research for decades.

As discussed in this chapter, cooperative GNSS positioning theory has been outlined and tested by other researchers. The success of cooperative GNSS positioning is hindered by poor data sharing efficiency, the incompatibility of GNSS receiver equipment, a lack of data trust, and loss or delay of data over the communication medium.

This chapter outlines the variety of communications options available, and the standards that are available for sharing GNSS information. Cooperative positioning techniques are discussed before a new technique is introduced, called Pseudo-VRS. This technique borrows the VRS positioning technique from N-RTK positioning, and applies the principles to cooperative position for road vehicles. Real-world tests are carried out at the NGI to assess the performance of the new technique. Pseudo-VRS is found to make an important contribution to the fundamental limitations of high precision GNSS - through the availability of corrections information, and the rapid resolution of the integer ambiguity resolution in RTK positioning.

6.2 Connectivity and communication technology

Modern passenger vehicles are equipped with a variety of communication technology. This varies from cellular communications to operate services in the infotainment systems, to wired CAN-bus systems to carry data between the vehicle sensors and on-board computer. The following sections describe the main technologies used to transfer information between systems on a vehicle, and to transfer information between vehicles.

6.2.1 Intra-vehicle connectivity

Traditionally the communication systems in vehicles have been wired. This robust approach provides the reliability required to manage the limited number of sensors, actuators, and on-board computing power. However, modern vehicles are becoming increasingly complex, and this puts an additional burden on the wired system and even on the available space inside cable channels. As the number of devices increases, the prospect of using wireless communication systems becomes more attractive.

6.2.1.1 Wired

The Controller Area Network (CAN) was developed in the 1980s to replace increasingly unwieldy point-to-point wiring systems. CAN is a serial bus system, and it quickly emerged as the standard in intra-vehicle communications (ISO 11898 in 1993) (Voss, 2005).

All devices on the network have a CAN controller chip, which allows them to see all messages on the network, and decide whether they are relevant or not. This allows the CAN to be modified without significant impact. Different physical layers are used for high and low speed data, and mechanisms are in place to control the priority of information across the bus.

The FlexRay consortium was organised to develop a standard for intra-vehicle communications that would be faster and more reliable than CAN. The results of the development were two standards, and the system is now used in a selection of passenger vehicles (Paret, 2012).

Data rates are up to 10 Mbps, with two independent channels available to provide increased robustness to faults. The bus is separated into two parts- a static segment and a dynamic segment. The static segment is divided into time allocations, which provides a better real time data connection than CAN. The dynamic segment operates in a similar manner to CAN.

Ethernet is not widely used in intra-vehicle communications. However, given the development of low-cost unshielded twisted single pair (UTSP) cables allowing data speeds of 100 Mbps based on widespread internet communications protocols, Ethernet communications are viewed as a valid option (Matheus, 2012).

It must be noted however, that even the 100 Mbps data rate may not be sufficient for future ITS or V2X applications.

6.2.1.2 Wireless

The typical passenger vehicle in 2020 is expected to contain around 200 sensors (Pinelis, 2013), and connecting these to the vehicle's electronic control unit (ECU) could add significant weight to the vehicle - according to Qu et al. (2010), today's cars can carry around 50 kg of additional weight. Hence, wireless technologies may be a sensible method in reducing the complexity, weight, and cost of installing additional vehicle-borne sensors.

Wireless communications systems that are widely available were developed relatively independently. This means that there is limited ability to move seamlessly from one medium to the next - for instance, from 3G to Wi-Fi. Coverage of each system also varies, and this is particularly evident indoors: Cellular communications are inherently prone to poor coverage indoors as the majority of cellular antenna masts are located outdoors. Some systems are limited by their range and power consumption, and all systems are fighting over a limited frequency spectrum (Wang et al., 2014).

Bluetooth.

Bluetooth is highly commercialised for communication between portable devices. Such devices are very common, particularly in the automotive environment (Bisdikian, 2002), and can transmit data at rates up to 3 Mbps. Current devices demand a high power level for the transmission of the short-range radio frequency (RF) signals, although a new standard has been developed for low power Bluetooth.

Bluetooth technology has a relatively poor scalability, as a small network can only contain eight devices - seven slaves and one master (Ye et al., 2004).

ZigBee.
This low-cost and low-power technology, which can provide data transmission rates of up to 250 Kbps, is considered a promising solution for intra-vehicle wireless communication by the ZigBee Alliance (Zigbee Alliance, 2014). Based on personal area networks that are simpler and less expensive than Bluetooth or Wi-Fi, ZigBee protocols have been tested for use in intra-vehicle applications. However, the results found that the technology is susceptible to interference from engine noise and other nearby RF devices (Tsai et al., 2007).

Ultra-Wideband.
UWB technology can support short-range data transmission at up to 480 Mbps, using very low energy over a large bandwidth availability (7.5 Gigahertz) (Qu et al., 2010). UWB systems have previously been shown to offer resistance to wireless channel fading and shadowing. They also provide a high-level time resolution that allows for inter-vehicle positioning applications, they are relatively low-cost, and require simple processing procedures (Oppermann et al., 2004). Extensive research into the use of UWB for intra-vehicle communication has been summarised by Lu et al. (2014).

Millimeter Wave.
Recent research shows that millimeter Wave (mmWave) technology is a promising solution for intra-vehicle multimedia communications (Lu et al., 2014). mmWave can support over 1 Gbps data transmission over a short range. The technology is primarily concerned with managing the transmission of infotainment type data, such as high definition video.

6.2.2 Inter-vehicle connectivity

Road vehicles, the road infrastructure, and drivers operate with very little inter-communication. Drivers may provide small indications of their driving intentions (such as communication via vehicle lights or the horn), vehicles may relay their position to tracking centres, or induction loops imbedded in the road surface may monitor the presence of vehicles, but overall the network operates through individual decision making.

A collective approach to vehicle movement is starting to become a reality. Some inter-vehicle communication services have been developed to improve road safety, reduce congestion, and shorten journey times. These include the near-real time notification of congestion ahead on the route, or variable message signs on roadsides that are starting to provide more up-to-date information to the driver.

The current situation still offers significant scope for improvement through inter-vehicle communication. Demonstration projects such as Demo '97 and SARTRE have proven the benefits that can be realised from vehicles working in unison.

6.2.2.1 VANET

The VANET was introduced in Section 2.4.3. The ability to communicate with surrounding vehicles in an ad-hoc nature is considered a key enabling characteristic of V2X applications. As opposed to the typical MANET, the VANET poses significant challenges. These include (Lu et al., 2014): The network topology changes rapidly, as vehicles move around the vicinity; due to this dynamic topology and limited range of communication media, frequent network partitioning can occur; and nearby obstacles can cause blocked or dropped communication links.

However, there are benefits that the VANET has over the traditional MANET. These include (Lu et al., 2014): Map matching allows a degree of predictability of the movement of vehicles; there are no significant power or computing restrictions of on-board systems; and GNSS positioning systems can be used to locate vehicles independently (where a solution is available).

6.2.2.2 Wi-Fi

Wi-Fi connectivity is hampered severely by its limited communication range. A single Wi-Fi access point may have a range of 500 metres LoS (line of sight), but this means that a vehicle travelling at 100 kph will have a maximum connection period of 18 seconds. Given the protracted nature of Wi-Fi handshaking protocols, and the possibility of signal obstruction or interference, this connection time is expected to be further limited.

However, due to the prolific nature of Wi-Fi access point installation (especially in cities), the road vehicle is often well within range of a Wi-Fi connection. Some cities even provide city-wide Wi-Fi coverage and access (such as in Mountain View, California, the home of Google Inc.).

A summary of the research performed using Wi-Fi for vehicle communication is given by Lu et al. (2014).

6.2.2.3 DSRC and WAVE

DSRC is considered a key enabling technology for V2X applications (Lu et al., 2014). The three major ITS research regions have dedicated parts of their radio frequency spectrum for DSRC:

- The US Federal Communication Commission (FCC) has allocated 75 Megahertz of bandwidth at 5.9 Gigahertz;
- The EU has allocated 10 Megahertz of bandwidth at a frequency of 5.8 Gigahertz for DSRC use; and
- Japan had used technologies considered DSRC at a frequency of 5.8 Gigahertz.

The specifications for DSRC are contained in the IEEE Standard for WAVE. Most of the prominent research by academia and industry utilise these standards and protocols.

6.2.2.4 Cellular communications

Attempts to bring cellular communications into the vehicle - in particular, internet connectivity - either focus on built-in or brought-in connectivity (Lu et al., 2014). For instance, the vehicle is equipped with a cellular modem, or can tether to a cellular device (such as a hand-held mobile phone).

High end vehicle manufacturers offer built-in connectivity, such as BMW's ConnectedDrive or Audi's Audi Connect, with most other manufacturers expected to follow suit with their own versions. Procedures to allow brought-in connectivity have been developed in collaborative fashion by some vehicle manufacturers (such as MirrorLink), or by mobile phone manufacturers (such as Apple's CarPlay).

The main barrier to built-in systems is their inherent ability to become out-of-date quickly. Whereas the design life of a smartphone may be only two years (before new technology makes it redundant), the design life of a passenger vehicle is expected to be much longer. Updating the on-board communication technology during a vehicle's life is not feasible for vehicle manufacturers.

Fifth generation cellular networks.

The IoT is likely to mean that billions of devices will place unprecedented demand on the cellular communications network. For this reason, the development of the fifth generation of mobile communications (5G) is aiming to deliver one thousand times the capacity, ten times the energy efficiency and data rate, and twenty five times the mobile cell throughput of the current state-of-the-art 4G networks (Li et al., 2014).

The standards for 5G are likely to be defined between 2016 and 2018, with 5G-ready products available from 2020. The specific technology is yet to be determined, but candidates range from massive-input massive-output (MIMO) antenna systems to cognitive radio networks and visible-light communications.

6.2.2.5 Satellite communications

Satellite communications is regarded as a sensible solution for those remote areas where a data connection is not available (Yang et al., 2009b, 2010). Traditionally, the areas in question are in countries with poor terrestrial communications networks or in areas with significantly low population. However, the same argument can be made for satellite communications technology for road vehicle communication. As shown in Section 5.7 and Section 5.7.2.2, the signal strength of cellular communications is a significant weakness on roads in rural areas.

6.3 Cooperative positioning of road vehicles

Work carried out in Basnayake et al. (2011) concentrates on using GNSS code and Doppler measurements for the relative positioning of vehicles, as it offers a simpler implementation method and is not susceptible to the cycle slips attributed to carrier-phase measurements. However, this means sacrificing the higher accuracy solution available from carrier-phase measurements. A major obstacle to GNSS positioning for V2X applications, is the likely scenario of mixed receiver and antenna technology between vehicles. As noted by Alves et al. (2010), this has a major influence on the performance of relative positioning. By comparing various V2X relative positioning solutions, Basnayake et al. (2011) found that an increase in positioning accuracy was typically accompanied by a decrease in availability and an increased demand for transmission bandwidth between the vehicles.

6.4 Cooperative positioning and GNSS

The sharing of GNSS information between vehicles requires standardisation. This is aided by the established data formats and communication standards for GNSS information services such as DGNSS and N-RTK corrections. The following sections outline these formats and standards, and relate them to cooperative positioning for road vehicles.

6.4.1 GNSS information data formats

Due to bandwidth considerations, the format of the data exchange also needs to be considered. The Radio Technical Commission for Maritime Services (RTCM) define standards for GNSS data exchange, which could be adopted in C-ITS applications (more details about RTCM can be found in Section 6.4.1.1). But other positioning data may also be exchanged, including the positioning of other road agents by terrestrial sensors (for example, lasers, cameras, and UWB), situational awareness, the size of the vehicle, and environmental conditions, amongst many other things.

The available bandwidth and data transmission losses or delays are potentially major limitations for cooperative GNSS positioning. For this reason, additional experiments have been carried out in this paper to assess the acceptable data transmission limits. DGNSS positioning techniques and algorithms are designed to deal with data latency, although high accuracy geodetic applications typically impose a limit of 10 seconds on the AoC for carrier-phase positioning, beyond which only DGNSS positioning is available.

6.4.1.1 Radio Technical Commission for Maritime Services (RTCM)

Special Committee 104 of the RTCM is tasked with developing and recommending standards for the transmission of DGNSS information. The binary format RTCM-SC 104 is an internationally recognised standard for the transmission of GPS and GLONASS correction data (Hofmann-Wellenhof et al., 2008). The latest version (RTCM Standard 10403.1 (RTCM, 2006)) was released in October 2006. This international standard is widely used by GNSS receiver manufacturers and service providers to communicate DGNSS and RTK information between receivers and control servers. It supports various GNSS positioning techniques, including the latest N-RTK methods.

Table 6.1 – RTCM message types (V3.1).

Message Type	Description
1001	DGPS corrections
1002	Delta Differential GPS Corrections
1003	Reference Station Parameters
1004	Surveying
1005	Constellation Health
1006	Null Frame
1007	Beacon Almanacs
1008	Pseudolite Almanacs
1009	Partial Satellite Set Differential Corrections
1010	P-Code Differential Corrections (all)
1011	C/A-Code L1, L2 Delta Corrections
1012	Pseudolite Station Parameters
1013	Ground Transmitter Parameters
1014	Surveying Auxiliary Message
1015	Ionosphere (Troposphere) Message
1016	Special Message
1017	Ephemeris Almanac
1018	Uncorrected Carrier-Phase Measurements
1019	Uncorrected Pseudorange Measurements
1020	RTK Carrier-Phase Corrections
1021	RTK Pseudorange Corrections
1022	Undefined
1023	Undefined
1024	Undefined
1031	Undefined
1059	Proprietary Message
1060-63	Multipurpose Usage

There are 64 types of messages, and each binary message format is a sequence of 30 bits. A selection of the predefined message types are shown in Table 6.1. The message types 1001 to 1017 are available in older RTCM standards, while messages 1018-1021 were added in Version 2.3 to make the standard applicable to RTK corrections. Versions 3.0 and 3.1 added additional messages to deal with modern GNSS positioning techniques like N-RTK. Proprietary messages 4001 to 4096 are reserved by RTCM, and can be assigned to organisations for their own use (RTCM, 2006).

The RTCM messages required for VRS positioning are the station coordinates 1003 and the GNSS observables using either 1018 and 1019, or 1020 and 1021. The sampling rate of RTCM messages is 1 Hertz.

6.4.1.2 Receiver-Independent Exchange format

The receiver independent exchange (RINEX) format was developed to allow the exchange of GPS data between receivers from different manufacturers (Hofmann-Wellenhof et al., 2008). A RINEX file is an ASCII file type, so no specialist software is required to read the data - only a text editor. There are two main types of RINEX file: The observation file and the navigation file.

The observation file contains the carrier phases, code ranges, Doppler measurements, and signal-to-noise ratios for each epoch. A header at the top of the file records the configuration of the receiver at the time of observation. The navigation file contains the ephemerides of the satellites during the observation period (Kaplan and Hegarty, 2009).

The main software package used to convert proprietary file formats into RINEX format is TEQC, which is maintained by UNAVCO (UNAVCO, 2015). The software is freely available, and a well documented manual is also available.

6.4.1.3 National Marine Electronics Association

The National Marine Electronics Association (NMEA) in the US developed the NMEA-0183 standard in the 1980s to specify the data format for electronic interfaces. Some of these formats have been developed to share position information, hence the adoption of NMEA-0183 for the use of sharing GNSS information. NMEA formats are now available for the transmission of quality indicators, speed over ground, and DGNSS corrections (Hofmann-Wellenhof et al., 2008).

One NMEA record is known as a sentence, with a maximum length of 82 characters. No NMEA format is available for the sharing of raw GNSS information, such as carrier phase and code measurements.

6.4.2 Communication standards

The RTCM have developed a standard that describes the protocol for streaming differential correction data and other GNSS information over the internet to mobile users (RTCM, 2004). Called the Networked Transport of RTCM via Internet Protocol (NTRIP), and designated as RTCM 10410.1, the subsequently revised standard was first developed by the Bundesamt für Kartographie und Geodäsie (BKG) in 2004. NTRIP is an open and non-propriety protocol that enables the streaming of data to multiple users over the internet, using a wide range of internet enabled devices. Most importantly, NTRIP supports the use of wireless communications through cellular networks such as GSM, GPRS, EDGE, and UMTS (Inside GNSS, 2009).

6.4.3 Data latency

In Yang et al. (2009a), the researchers found that the average delay to the GNSS correction message over mobile internet for N-RTK positioning was 0.85 seconds. This is an important factor, as the correction information is only valid for 10 seconds from the epoch it is created. Clearly, 0.85 seconds is well below the 10 second limit, but any additional transmission delay caused by sharing the information between vehicles could be an issue.

It is important to note that if there is a disconnection of the N-RTK corrections service, the N-RTK position solution can continue to be available as long as there are no cycle slips and there are a high number of common satellites in view. The integer ambiguity has been fixed, and the receiver will be continuously counting the number of phases. If the correction service is disconnected without first achieving an N-RTK position solution, a DGNSS solution is available for up to one minute. This is an internal setting from the manufacturer of the receiver, based on the validity of the tropospheric information.

6.5 Cooperative GNSS relative positioning

The relative positioning accuracy of two GNSS receivers operating on two separate vehicles is shown in Figure 6.1. Each vehicle carried a matching Leica GR10 GNSS receiver and Leica AS10 antenna. The known baseline between the two vehicles was calculated by differencing the post-processed absolute positions of each receiver, using a very local CORS. The absolute positions of each vehicle were checked independently with total station and INS systems. By sharing the raw RINEX information of one receiver with another, it is possible to calculate the baseline vector between the two receivers, and as the receivers are relatively close geographically (within 100 metres), the integer ambiguity is easily and successfully fixed.

The figure includes the results from two GNSS positioning solutions. The first uses dual frequency observations (GPS L1 and L2): The dark blue line shows the distance error in the calculated baseline length, and the green line shows the corresponding fix type (in this case either

1: fixed, or 2: float). The second technique uses single frequency observations (GPS L1 only): The red line shows the baseline distance error, and the purple line the fix type. The same original data was used in each method, post-processed using open-source GNSS processing software (RTK LIB, (Takasu, 2010)), hence there is only one line for the number of available satellites (light blue).

There is little difference between the two techniques. When the number of satellites increases or decreases, the ambiguity resolution process can be disrupted causing a float solution to be adopted (fix type 2), which also introduces an error into the relative baseline length (the worst case here is an error of 0.38 metres). Otherwise, when the ambiguity is fixed, the relative baseline length is accurate to a few centimetres. The dual frequency technique has the advantage when the number of visible satellites drops, as shown towards the end of this short test when the number of visible satellites drops to seven.

This example shows the ease with which relative RTK positioning can achieve a high accuracy baseline length between two receivers. However, this is a best case scenario: The vehicles are relatively close (less than 100 metres), moving slowly, and observing the same number of satellites. Section 4.4 provides more detail about the relationship between baseline length and baseline length error.

An important aspect of this cooperative positioning solution is that the resulting information provides the vehicle with a relative position to another vehicle. This is useful for a small number of ITS or V2X applications, but the ability to calculate the absolute position of the vehicle in a global reference frame would enable more advanced applications.

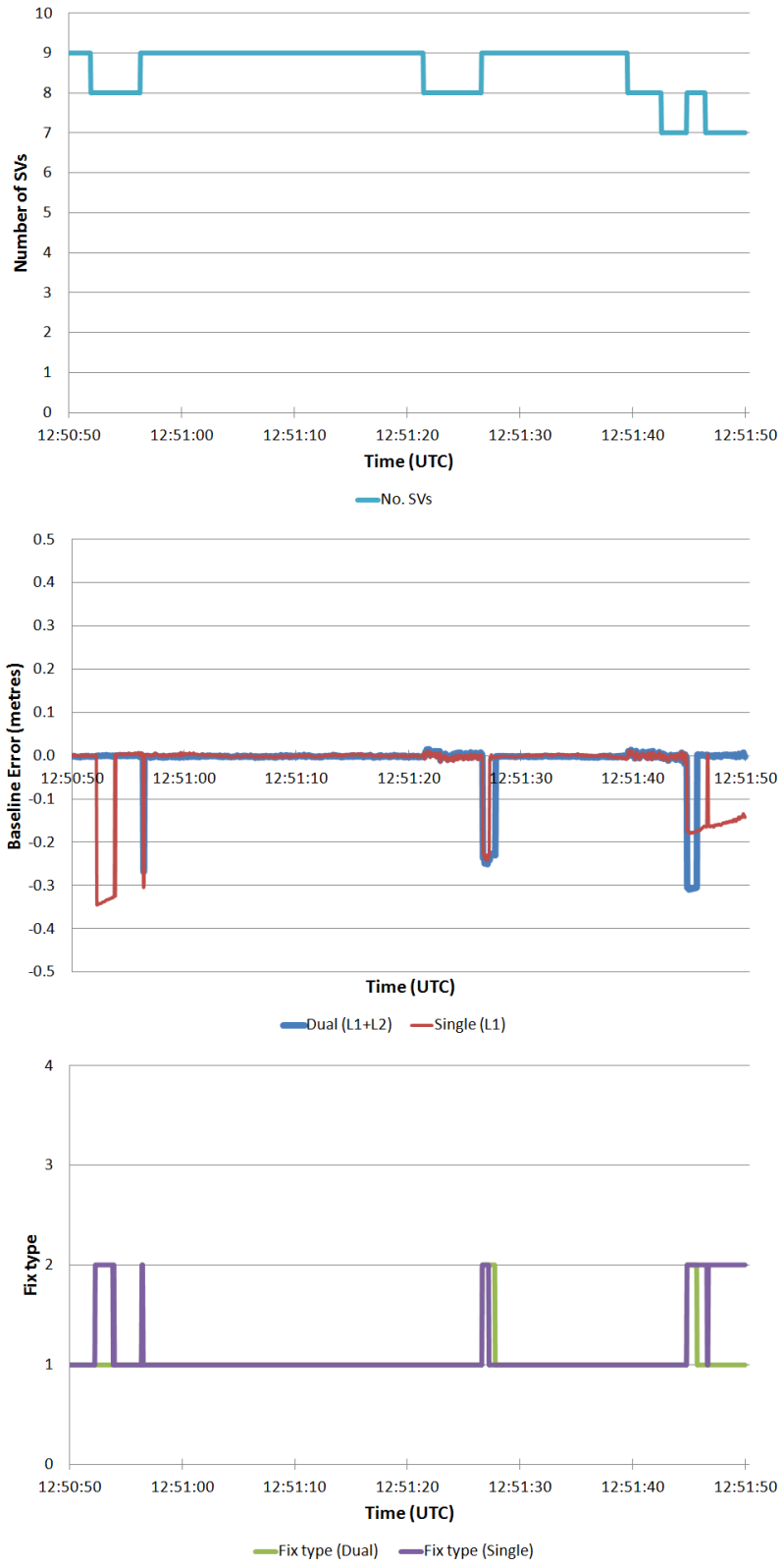


Figure 6.1 – Relative positioning accuracy during real-world driving trial.
Top: The number of visible satellite vehicles.
Middle: Baseline errors during relative positioning trials.
Bottom: Type of RTK fix.

6.6 Cooperative GNSS absolute positioning

As described in Section 6.5 and outlined by other researchers as described in Section 6.3, the relative positioning of vehicles is possible through sharing GNSS information. However, the ability to calculate the absolute position of a vehicle is still the main goal. This would enable more advanced ITS and V2X applications.

This section explores this idea through two methods:

- The sharing of N-RTK corrections information between vehicles; and
- The generation of VRS-like corrections by one vehicle and the transfer to another - and given the name of Pseudo-VRS.

These techniques have been developed to show how one of the major limitations of N-RTK for road vehicle positioning can be reduced: The availability of the N-RTK correction information.

6.6.1 Sharing N-RTK corrections between vehicles

If vehicles could communicate with one another on the road, this would help to overcome the communication system limitation in N-RTK positioning of road vehicles. For instance, if vehicle A has an external connection to a N-RTK service provider (for example, a mobile internet connection) and a local connection to a second vehicle (B), such as through Wi-Fi or Bluetooth, then it could share its N-RTK correction messages directly. Effectively vehicle A would re-broadcast the correction information it has received from the corrections provider to the receiver on vehicle B. However, this would rely on the functional capability of the receiver of vehicle B, as N-RTK real time processing can be computationally intensive.

Not all N-RTK correction messages can be shared in this way, and the range over which the correction messages are still valid needs to be determined. As vehicles communicating with V2X devices are likely to be relatively close (a few hundred metres at most), the feasibility of sharing N-RTK information is good. For instance, Figure 6.2 shows that MAC N-RTK correction messages cover large cell areas (inter-reference station distances are 50-100 kilometres), and even roving receivers such as X and Y that are in separate cells could share relevant information.

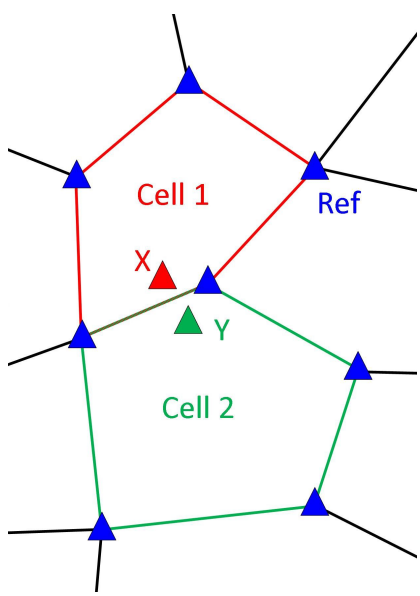


Figure 6.2 – An example of N-RTK cells formed from clusters of CORS defined in the MAC concept of N-RTK positioning.

However, the N-RTK VRS technique may offer more advantages. It is the most common form of N-RTK used around the world, and requires significantly less bandwidth (approximately 10 Kbps

at 10 Hertz). The rover receiver is also less burdened by processing requirements. A VRS system operating on buses in Minnesota restricts the baseline to 2 miles, by updating the VRS location every 2 minutes (Shankwitz, 2010).

Correction messages typically have a lifespan – in the case of the Leica SmartNet corrections this has been determined to be 10 seconds. After this time the receiver determines the messages to be too old and does not compute a fixed integer position. However, it can use the information to calculate a DGNSS position - which is still extremely useful for many ITS and V2X applications. Therefore the relayed message must arrive at the receiver on vehicle B well within 10 seconds. Previous trials at the NGI found that the typical message latency of the original correction message reaching vehicle A via a GSM/GPRS connection is 0.85 seconds (Yang et al., 2009a). The additional V2X communication to transfer the message to vehicle B should not add a significant delay.

6.6.1.1 Capturing N-RTK messages

To demonstrate the potential benefit of sharing N-RTK messages between vehicles, N-RTK messages were captured on board a vehicle and shared with a second vehicle. Vehicle A is the NGI road test vehicle (shown in Figure 1.14), and vehicle B is the NGI electric locomotive (shown in Figure 6.3). Most off-the-shelf N-RTK enabled GNSS receivers are designed to communicate directly with the N-RTK server using a connected communication device (for instance, a GSM modem, UHF/VHF radio, or mobile phone), which typically provides a stable connection to minimise data loss.

Figure 6.3 – The NGI electric locomotive.

In order to intercept the N-RTK correction message, the GNSS receiver was set up to accept the correction message from a smartphone via Bluetooth. In this case, the connection to the N-RTK service provider is established between the smartphone and the N-RTK server. An application running on the smartphone, as shown in Figure 6.4, requests information from the N-RTK server, logs the data, and passes the message directly to the Bluetooth connected GNSS receiver on vehicle A. By intercepting the correction message, it can also be passed on to a second receiver, in this case on vehicle B.

6.6.1.2 Sharing N-RTK messages with second receiver

Figure 6.5 shows the positioning solutions generated by a shared N-RTK correction message. The original message was captured by the smartphone application operating on board vehicle A (the NGI road test vehicle), and applied to GNSS observations made by a receiver on vehicle B (the NGI locomotive). The baseline between the two vehicles was less than 100 metres, and the location

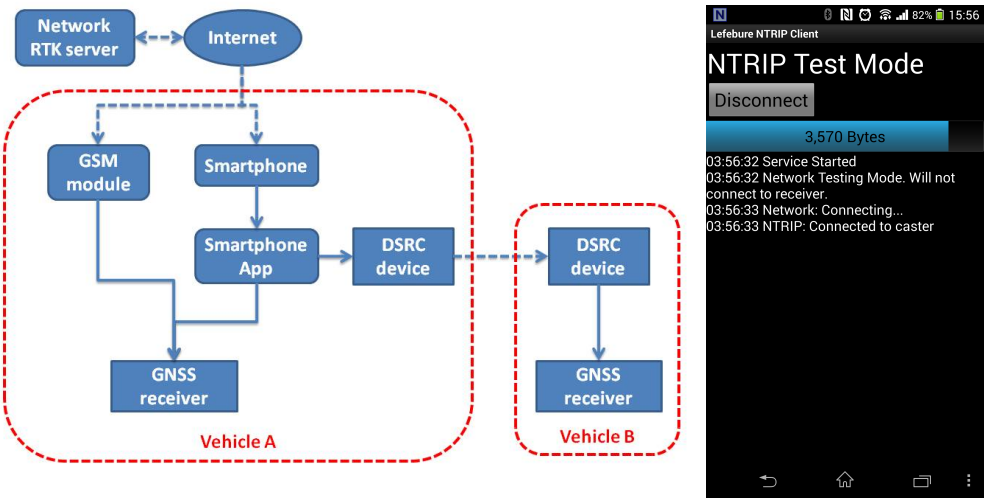


Figure 6.4 – Flowchart showing the capturing and sharing of N-RTK correction messages (left), and the NTRIP client program running on an Android smartphone (right).

of the VRS requested from the N-RTK server was the NGI building (in geodetic coordinates to three decimal places). As Figure 6.5 clearly shows, the shared VRS corrections are equally valid for any receiver operating in the vicinity of the VRS. The thick red line is the fixed position of the train track, and the thin blue line represents the positions generated by the GNSS receiver using the shared N-RTK corrections.

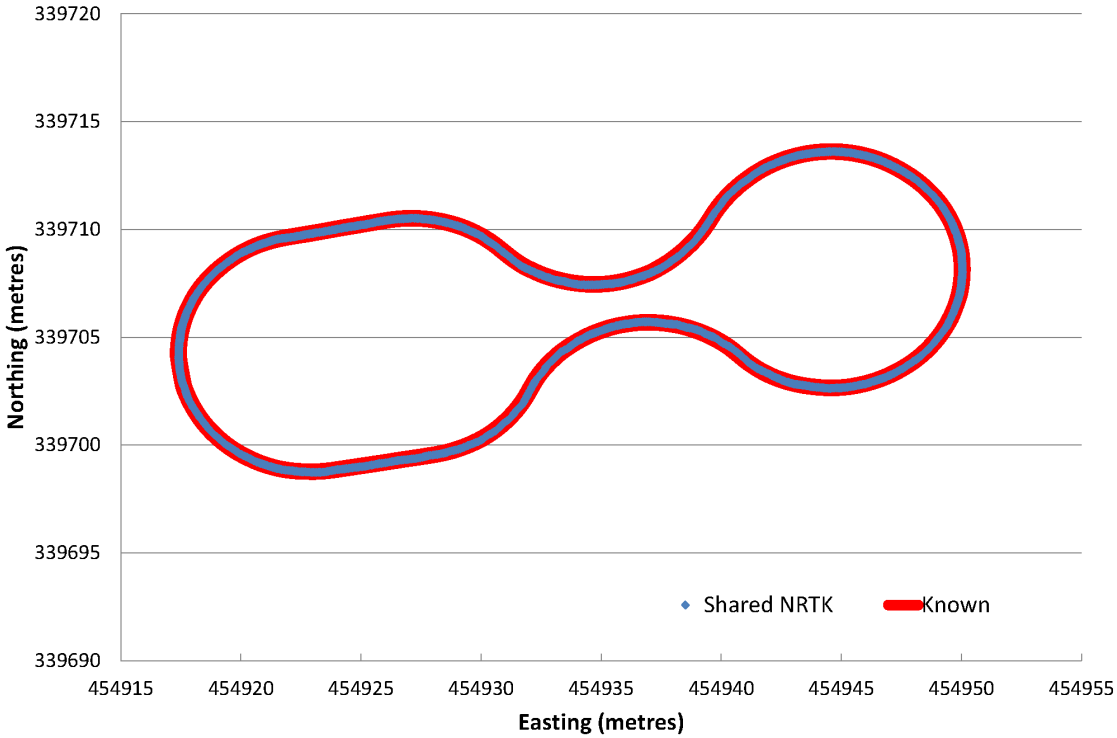


Figure 6.5 – Sharing the N-RTK message from vehicle A to vehicle B.

The VRS message type was chosen as it requires much less bandwidth (Janssen, 2009), takes

less processing capacity, and is prevalent amongst legacy receivers. N-RTK users typically require download speeds of 1.8 Kbps (VRS) and 5.6 Kbps (MAC) (Rubinov et al., 2011). This is well within the typical speeds available from cellular wireless communications, which offer 80 Kbps down-link speed from 2.5G systems to beyond 40 Mbps for recent 4G systems.

The GNSS receiver on vehicle B is operating in an ideal location, with a clear view of the sky and a high number of visible satellites, which improves the probability of successful RTK ambiguity resolution.

6.6.2 Pseudo-VRS

A new cooperative GNSS positioning system for road vehicles is proposed here, based on existing and established GNSS positioning techniques. The most widely used N-RTK positioning technique is the VRS concept (described in more detail in Section 4.3.6.3). N-RTK VRS positioning generates GNSS observation data for a non-existent reference station (a *virtual* reference station) very close to the rover receiver. The rover treats the VRS as a fixed base station with known position, from which it can perform RTK or DGNSS positioning. As the VRS is very close to the rover (typically within metres, and updated if the rover is dynamic), the ambiguity resolution process tends to be relatively fast (often instantaneous given a good sky view, a high number of common satellites, and dual frequency observations).

The transfer of the VRS observation data is prescribed by established standards and communication protocols. A central server generates the VRS observations by analysing a number of surrounding permanent (and real) GNSS reference stations. The server is able to re-create GNSS observations at a VRS close to the rover, including adjustments for most of the errors and biases (for example, satellite clock and atmospheric effects). A concise message is constructed, which simply includes the raw GNSS observations and geodetic coordinates of the VRS. The message is structured using the RTCM standards (described in Section 6.4.1.1), and then transferred to the rover receiver (typically via mobile internet).

The concise nature of the VRS correction message allows the exploitation of the technique for cooperative GNSS positioning for road vehicles. If one vehicle has an accurate known position, then it can assist neighbouring vehicles by sharing its known position and GNSS observations. By dressing this information in a similar style to VRS correction messages, existing GNSS receiver technology and principles can be used to carry out cooperative positioning. As the message appears to the second vehicle like a VRS message, it has been named Pseudo-VRS.

6.6.2.1 Generating VRS-like correction information

The potential benefit to GNSS positioning of using V2X communication between various road vehicles and infrastructure can be expanded by the implementation of Pseudo-VRS positioning. This system resembles the children's fairy tale Hansel and Gretel, where in order to help remember the route through a forest that guides them back to their home, Hansel drops markers along the path (in separate cases small white pebbles, and then breadcrumbs). By using the markers the children can navigate their way through the forest, but without them they are left lost and disoriented (Grimm and Grimm, 1812).

The Pseudo-VRS system uses a similar principle, where vehicle A marks its path by leaving behind small packets of information that can be used by other nearby vehicles. The small packets of information are VRS-like, and are broadcast using V2X communication devices and technology. Like the breadcrumbs in the fairy tale that are eaten by birds shortly after being dropped by Hansel, the VRS-like packets of information have a short lifespan.

6.6.2.2 Pseudo-VRS positioning

Using the established VRS techniques and standards described in Section 4.3.6.3, it is proposed here to use the GNSS observations and subsequent position information to simulate the existence of a VRS. Imagine vehicle A carries a GNSS receiver together with the means to calculate its position accurately (for instance, it is also receiving DGNSS corrections or has other positioning devices on

board). As long as the receiver can successfully resolve the integer ambiguity, it can also produce each component required to describe a VRS. Clearly in this case, the receiver on vehicle A is a real reference station, but the existing VRS standards can be exploited to transfer this information to other local GNSS receivers. For instance, a receiver operating on vehicle B can use the information as a local real time differential correction service.

As the VRS technique is well established (the most popular form of N-RTK positioning), legacy receivers are able to take advantage of this Pseudo-VRS information. RTCM standards are also well defined for the transfer of GNSS information in this form.

The Pseudo-VRS information is valid for several seconds, so the delays introduced in transferring the information from one vehicle to another can easily be accommodated. Like any communication device based on radio waves, V2X communication devices are likely to be subject to message delay and message loss, which requires redundancy in the system. However, it is important that the whole Pseudo-VRS message is delivered during one epoch, as there is little similarity between one epoch and the next. The original reference receiver is likely to be on a moving vehicle.

Effectively, the Pseudo-VRS imitates the VRS in Equation 4.4 by providing the VRS coordinates ($\delta_r^s(X_V, t)$) and carrier-phase observable ($\Phi_r^s(X_V, t)$). The information is also delivered to the second receiver in the same format RTCM message. A slight difference here is that only one-way communication is needed, as the original coordinates of the virtual reference station do not need to be supplied by the second receiver.

In the following tests, the Pseudo-VRS processing is carried out using the RTK LIB open-source software (described in Section 6.7.1.2). RTK LIB has limited options to vary the position of the base station during RTK positioning, so the program is seeded with customised configuration files and run independently for each epoch. This creates an additional feature: The processing of each epoch has no effect or influence on any other.

6.7 Pseudo-VRS tests

To test the Pseudo-VRS concept, a series of tests were designed at the NGI. the following sections describe the test setup, the data processing, and the results.

6.7.1 Pseudo-VRS real-world tests: Method

The tests were designed to compare three variations of Pseudo-VRS cooperative positioning:

- Dual frequency RTK;
- Single frequency RTK; and
- DGNSS.

The GNSS receivers used were geodetic grade Leica Geosystems GS10 receivers with AS10 antennas. The single frequency RTK and DGNSS results were obtained by processing L1-only data.

6.7.1.1 Test setup

To test the performance of a Pseudo-VRS positioning system, and the success of different configurations, real-world tests were carried out at the NGI. Two vehicles were used: Vehicle A was the NGI's road vehicle (shown in Figure 1.14) and vehicle B was the NGI's electric locomotive (the test track is shown in Figure 1.13). As the position of the test track is very accurately known, this can be used to measure the performance of the Pseudo-VRS system.

Vehicle A was equipped with six GNSS receivers (Leica GS10 with individual AS10 antennas), a tactical grade INS system (Applanix POS/RS with Honeywell C-IMU), wheel odometer, and tracked using a Leica Nova TS50 and 360 degree prism. The configuration of the GNSS antennas on the NGI road test vehicle is shown in Figure 6.6. This provided multiple position solutions to ensure significant results.

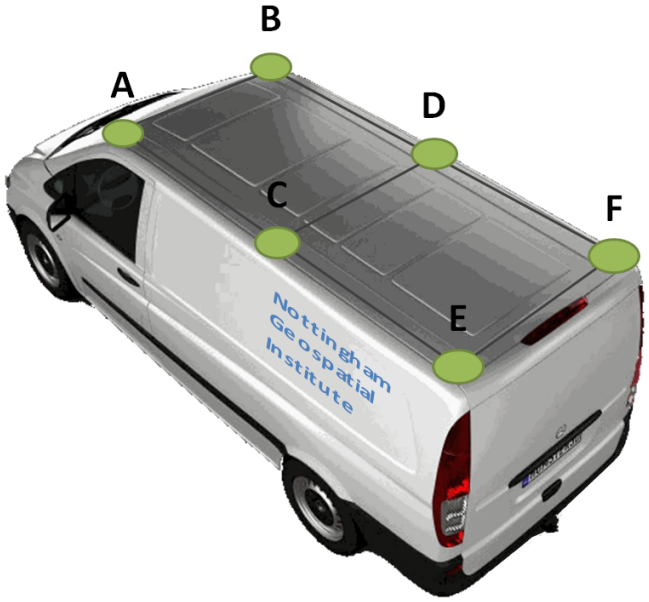


Figure 6.6 – Location of antennas on the NGI test vehicle roof.

Vehicle B was equipped with a GNSS receiver (Leica GS10 and AS10 antenna), and tracked using a proprietary UWB system for related V2X tests.

Also on the roof of the NGB, and lying inside the track perimeter, is the NGB CORS. This hyper-local reference station allows local RTK solutions, and acts as a barometer of GNSS activity when tests are carried out episodically.

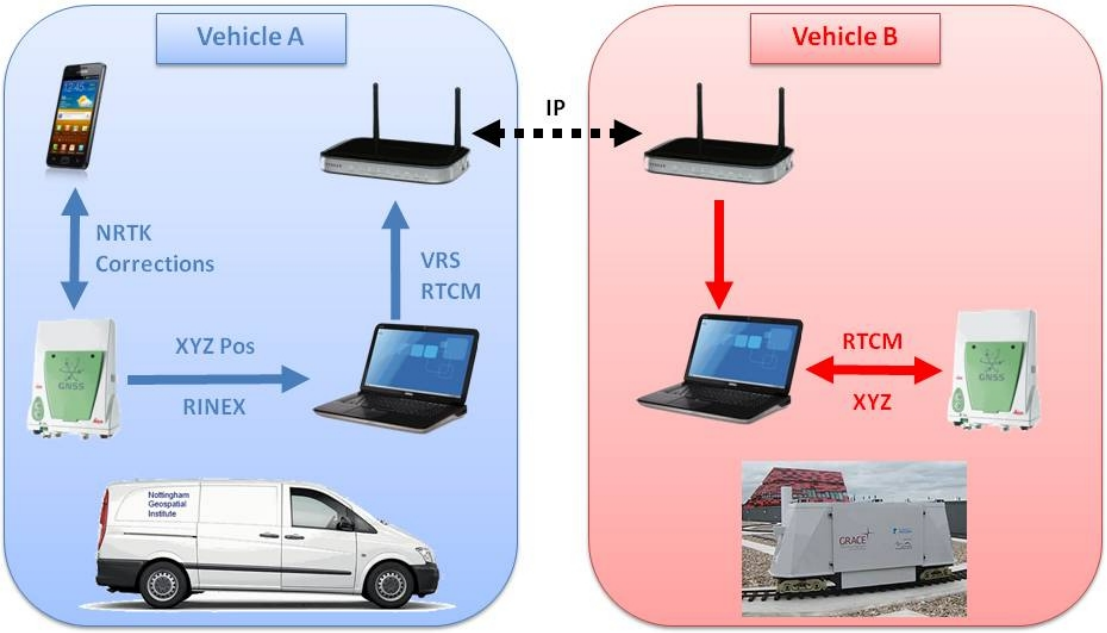


Figure 6.7 – The flow of data during the generation and sharing of Pseudo-VRS data.

The configuration for the Pseudo-VRS system is shown in Figure 6.7. The N-RTK receiver on vehicle A receives N-RTK corrections from the service provider via a mobile internet connection.

The position of the vehicle is calculated, and this information is passed to a laptop with the raw RINEX information. The laptop generates Pseudo-VRS RTCM messages and communicates with a second laptop on vehicle B via a wireless IP access point. The laptop combines these Pseudo-VRS messages with GNSS information from the GNSS receiver on vehicle B. This produces a high accuracy RTK position solution for vehicle B.

Figure 6.8 shows an aerial image of the test scenario. The Google background shows the NGB to the west, and surrounding roads to the south and west (still under construction during the image acquisition). The thin yellow line is a ground distance of 100 metres. The red dots signify the position of vehicle A (in the east), and the purple dots show the position of vehicle B (on the roof of the NGB building). The accuracy of the Google image is unknown, and is used here purely for illustrative purposes.

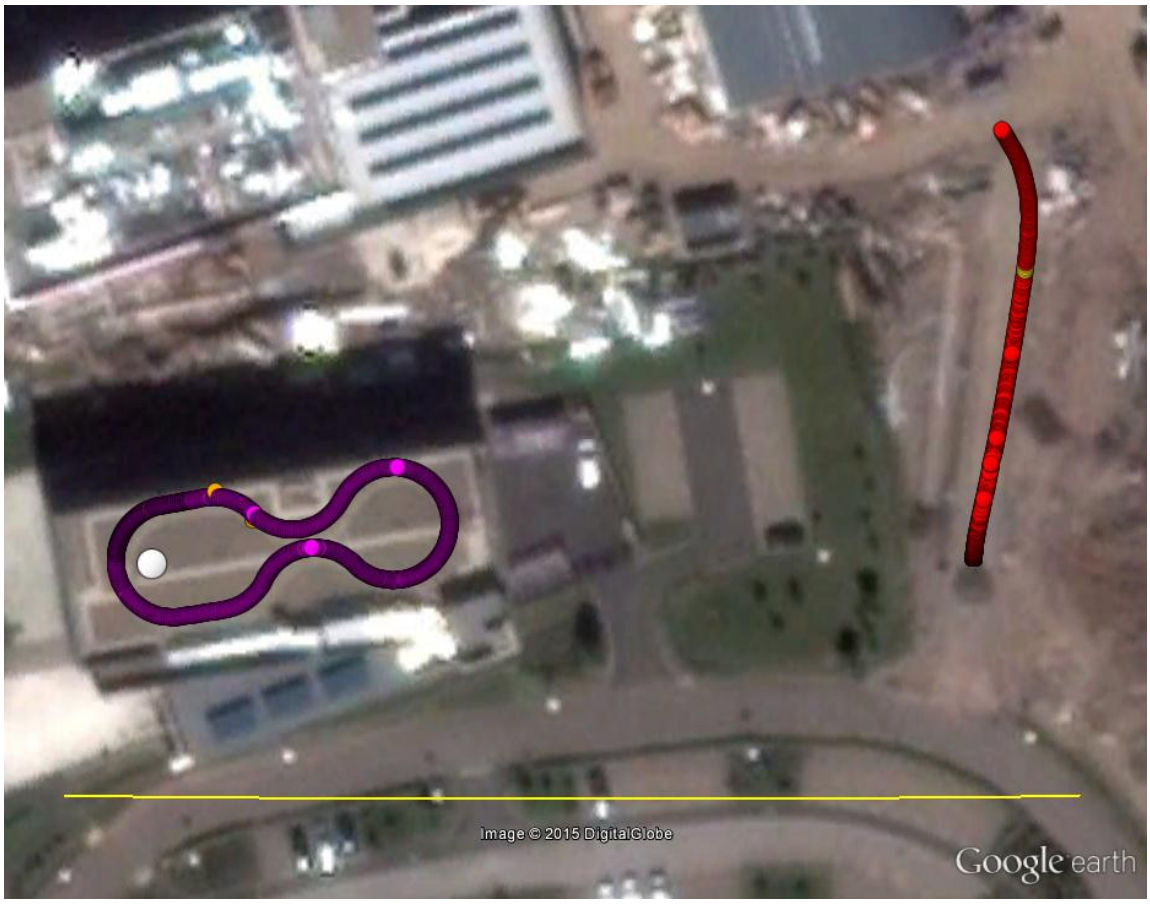


Figure 6.8 – Aerial image of the test.

These tests are designed to show the performance of a Pseudo-VRS system using a V2X communication system. However, the results shown here were created using recorded raw data. The open source GNSS processing software RTK LIB was used. The test results will help to design the correct RTCM message to share between vehicles in future tests.

6.7.1.2 Pseudo-VRS using RTK LIB

The position solution of vehicle B is calculated using the open source software RTK LIB (Takasu, 2010). RTK LIB can perform single and precise point positioning, and allows configuration of the processing parameters. The software can also be called using DOS commands. The RTK LIB process in the Pseudo-VRS system is shown in Figure 6.9, and the DOS commands are explained in Table 6.2.

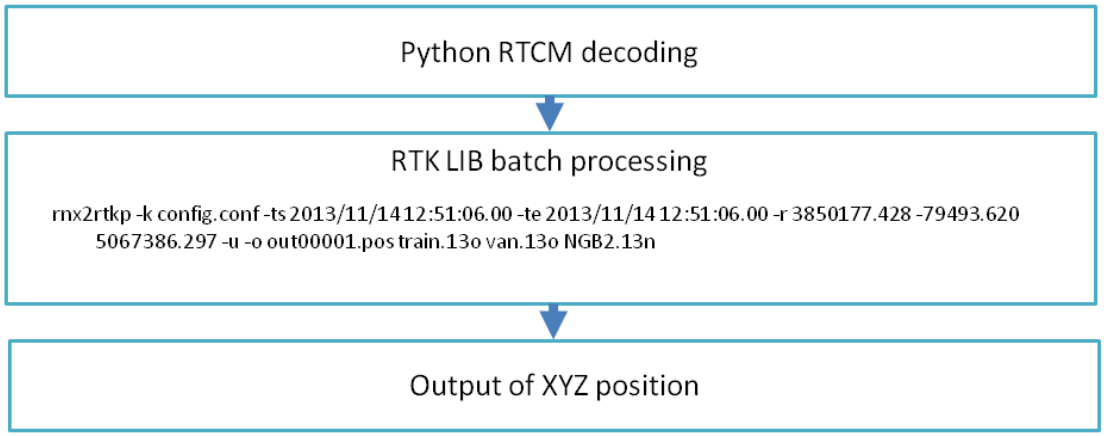


Figure 6.9 – Pseudo-VRS positioning processing steps for vehicle B.

Table 6.2 – The RTK LIB batch processing commands.

Command	Description
rnx2rtkp	Calls the RTK LIB executable.
-k config.conf	The configuration file describing the processing parameters. For example, instantaneous ambiguity resolution (threshold ratio set to 2.0), and atmospheric error modelling.
-ts 2013/11/14 12:51:06.00	The start time of the period to be processed (note that the start and end time are identical, causing a single epoch to be processed).
-te 2013/11/14 12:51:06.00	The end time of the period to be processed.
-r 3850177.428 -79493.620 5067386.297	The Pseudo-VRS base station coordinates in XYZ.
-u	Parameter to output the time in UTC.
-o out00001.pos	The output file name (automatically generated if it doesn't exist).
train.13o	The rover GNSS observation file (RINEX).
van.13o	The Pseudo-VRS GNSS observation file (RINEX).
NGB2.13n	A recent GNSS navigation file (in this case from a local base station).

The Pseudo-VRS processing is carried out by passing the GNSS information to the RTK LIB program, and requesting the data to be processed according to specific parameters. The main parameters are the time and the coordinates of the Pseudo-VRS base station (vehicle A in these tests). The commands are designed to process a single epoch of data (the start and end times of the processing period are the same). This allows the Pseudo-VRS tests to be simulated as real time.

6.7.2 Pseudo-VRS real-world tests: Results

The following sections are the results from the Pseudo-VRS tests. Initially the results of the Pseudo-VRS positioning are assessed using GNSS receivers mounted on one vehicle - the NGI road test vehicle. As the antenna baselines are short and well known, this allows a controlled examination of the Pseudo-VRS performance.

Following this assessment, the Pseudo-VRS system is tested by sharing the data between two GNSS receivers on separate vehicles - the NGI road test vehicle and the NGI electric locomotive.

6.7.2.1 Intra-vehicle correction

The NGI road test vehicle was equipped with six Leica GS10 GNSS receivers, with corresponding Leica AS10 antennas. Each antenna was attached to a different antenna mount on the roof of the vehicle, labeled as A to F in Figure 6.6. The antenna on mount F was attached to a GNSS signal splitter, which was connected to one of the Leica GS10 receivers as well as providing a GNSS signal to the two ground truth systems. The first ground truth system was an Applanix POS/RS INS, and the second was a NovAtel SPAN SE. The antenna mount D also included a 360 degree prism that was tracked by a Leica TS30 total station (the GNSS antenna attaches to the top of the prism).

To test the performance of the Pseudo-VRS system, and assess the optimum configuration of the parameters, the absolute position of antenna F was calculated in turn using data from the other five antenna locations. Firstly the absolute position of the reference antenna was calculated using a CORS base station operated by the NGI on a building close to the test site. The results of these tests are shown in Table 6.3.

Table 6.3 – Intra-vehicle antenna correction results.

Dual frequency (L1 + L2)					
	Reference antenna position				
	A	B	C	D	E
Baseline (m)	3.464	3.188	2.085	1.648	1.348
All observations (fix and float)					
RMS (m)	0.142	0.218	0.177	0.018	0.013
1 SD. (m)	0.140	0.215	0.175	0.016	0.012
RTK Fixed (%)	97	97	98	97	100
Fixed observations only					
RMS (m)	0.017	0.016	0.016	0.016	0.013
1 SD. (m)	0.015	0.014	0.015	0.014	0.012
RTK Fixed (%)	100	100	100	100	100
Single frequency (L1)					
	Reference antenna position				
	A	B	C	D	E
Baseline (m)	3.464	3.188	2.085	1.648	1.348
All observations (fix and float)					
RMS (m)	0.481	0.352	0.351	0.490	0.400
1 SD. (m)	0.344	0.266	0.248	0.302	0.193
RTK Fixed (%)	41	43	41	44	23
Fixed observations only					
RMS (m)	0.584	0.142	0.474	0.505	0.333
1 SD. (m)	0.325	0.140	0.383	0.395	0.313
RTK Fixed (%)	100	100	100	100	100

Figure 6.10 shows the results of this test using dual frequency measurements. In Figure 6.10a, the position error of antenna F with reference to each of the other antennas is shown. In Figure 6.10b, the number of visible satellites from each antenna is shown. The accurate positioning results of the dual frequency RTK fixed solutions shows that the success of correct integer ambiguity resolution is significantly high. In this set of results, the worst positioning accuracy of a fixed solution was 0.085 metres (antenna A as the reference) at epoch 13:07:39, during which the best positioning accuracy from any intra-vehicle reference achieved was 0.070 metres (each of the reference antennas lost a satellite at this time). The following epoch witnessed the removal of one satellite from the calculation, which returned the solution to the previous high positioning accuracy.

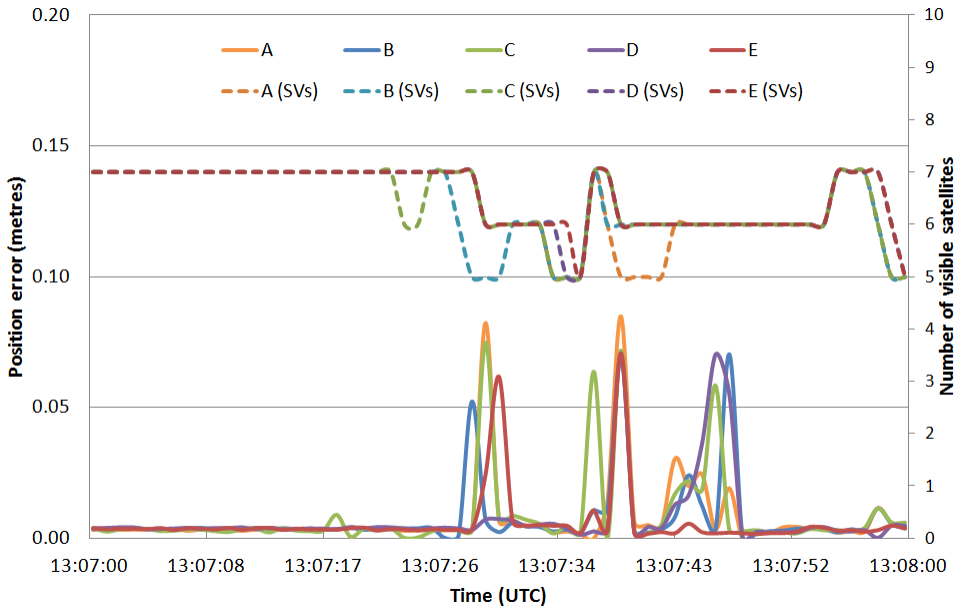


Figure 6.10 – Intra-vehicle Pseudo-VRS positioning results (fixed dual frequency measurements). Showing the position error of each antenna and the number of visible satellite vehicles from each antenna.

It should be noted that an observation at 13:07:48 was removed from the results as a significant tight turning manoeuvre was performed that skewed the ambiguity resolution (a critical combination of very short baseline and the relationship between the antenna positions and the vehicle wheel axles), during which three of the five reference receivers output a float solution.

As can be seen in Table 6.3, the single frequency results appear to degrade as the integer ambiguity is fixed. This suggests that the antenna-antenna baseline is too short to successfully fix the ambiguity.

6.7.2.2 Road vehicle to locomotive correction

To simulate the operation of a Pseudo-VRS system, vehicle A must share its known absolute position and some raw RINEX information for each epoch with vehicle B. Vehicle B can then use this information, together with its own observed RINEX data for the same epoch, to calculate its known absolute position. In practice, there will be a slight delay in the delivery of the information from vehicle A (much like in a traditional RTK system), so that information from concurrent epochs are unlikely to be used.

The RTK LIB software cannot directly handle the variation of a base station's coordinates (and output an absolute solution), so a small separate script was designed to utilise the processing capability of the software in a Pseudo-VRS system. This was discussed in Section 6.7.1.2.

Figure 6.11 shows the results of the inter-vehicle Pseudo-VRS positioning. As described in Section 6.7.1, three types of Pseudo-VRS positioning were compared:

- Dual frequency RTK;
- Single frequency RTK; and
- DGNSS.

During the dual frequency RTK tests, 99.67% of observations achieved fixed ambiguity (1197/1201), whereas during the single frequency RTK tests (using the broadcast ionosphere), 61.45% (738/1201)

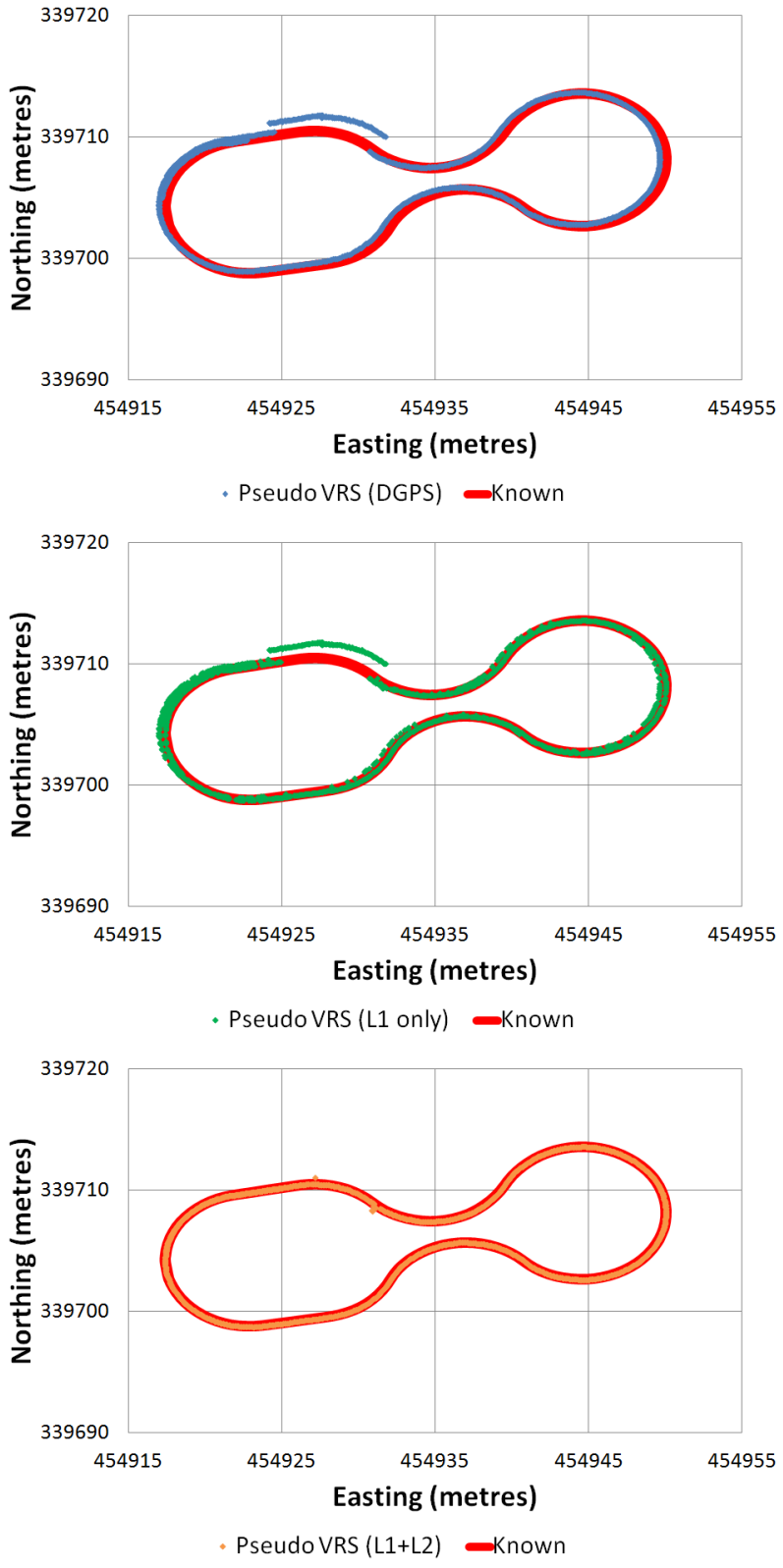


Figure 6.11 – Results from inter-vehicle Pseudo-VRS positioning.

observations achieved fixed ambiguity. The DGNSS solution was available for the entire test (1201/1201).

The ratio test threshold was 2.0. Around the area of 454930E 339708N, the number of common visible satellites dropped from 8 to 7, and then again from 7 to 6 three seconds later. This caused each of the three solutions to degrade slightly. The dual frequency RTK solution very briefly lost its fixed ambiguity solution (for two epochs, or 0.1 seconds), before regaining the fixed solution. The single frequency RTK solution could not achieve a fixed ambiguity solution again until the number of common visible satellites returned to 7 (five seconds after the initial satellite was lost). The DGNSS solution saw a similar degradation in its solution during this period.

The mean coordinate errors for the three solutions are 0.054, 0.707, and 0.323 metres (3D, 1 SD), as shown in Table 6.4. This is compared to an RTK solution calculated using the local CORS base station. The error in the horizontal and vertical directions follows the typical ratio of 1:2. Test results were also completed using a lower Pseudo-VRS update rate. At 1 Hertz the results deliver a better accuracy. Although the latency of the correction is up to 1 second (positioning is calculated epoch by epoch), the results were better than updates at 20 Hertz. The dual frequency RTK solution achieved a fixed ambiguity at every epoch (100%), and when compared to the known track position the ambiguity appeared to be correctly fixed. The single frequency RTK solution achieved a fixed ambiguity for 70.02% (897/1201) of the observations; an improvement over the 20 Hertz results.

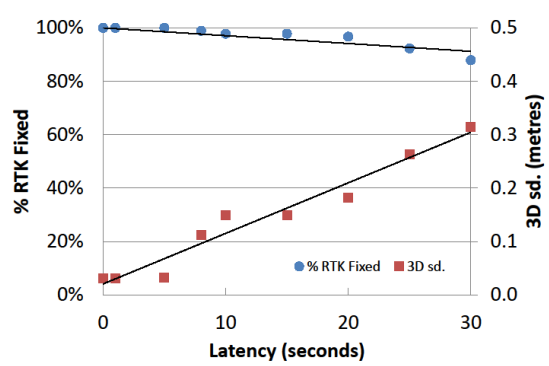
Table 6.4 – The precision (1 SD, 3D, metres) and percentage ambiguity fixed solutions of Pseudo-VRS positioning of vehicle B .

Solution	Precision (m)		Fixed solutions (%)	
	20 Hz	1 Hz	20 Hz	1 Hz
Dual freq. RTK	0.054	0.004	99.7	100.0
Single freq. RTK	0.707	0.669	61.5	70.0
DGNSS	0.323	0.311	100.0	100.0

Table 6.5 and the embedded figure show the performance of the Pseudo-VRS system under different latency scenarios. This is important as a message transmitted by vehicle A may be delayed or newer messages may be disrupted. Once the latency of the correction message reaches 8 seconds, the performance of the positioning solution begins to drop. The number of fixed ambiguity solutions falls, and the resulting positioning accuracy also decreases. However, the solution can still deliver 20 to 30 centimetre accuracy with a message latency up to 30 seconds.

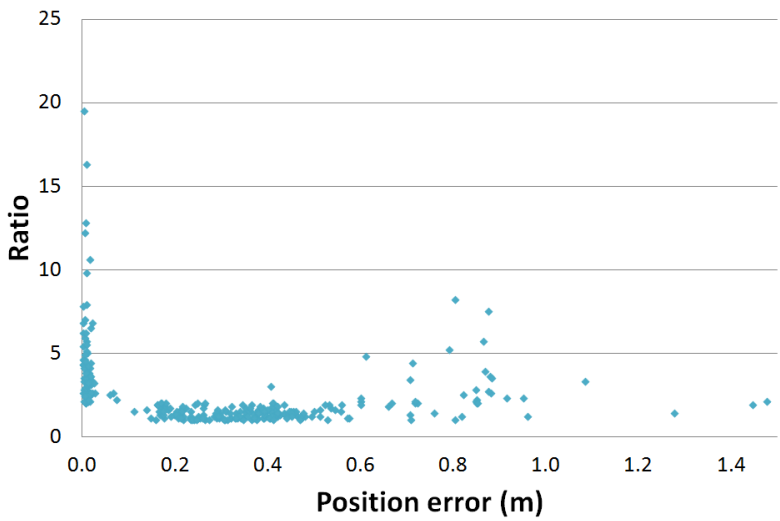
Table 6.5 – The relationship between message latency and positioning quality.

Latency (s)	% fix	3D (1 SD)
0	100	0.031
1	100	0.031
5	100	0.033
8	99	0.112
10	98	0.149
15	98	0.149
20	97	0.182
25	92	0.263
30	88	0.315

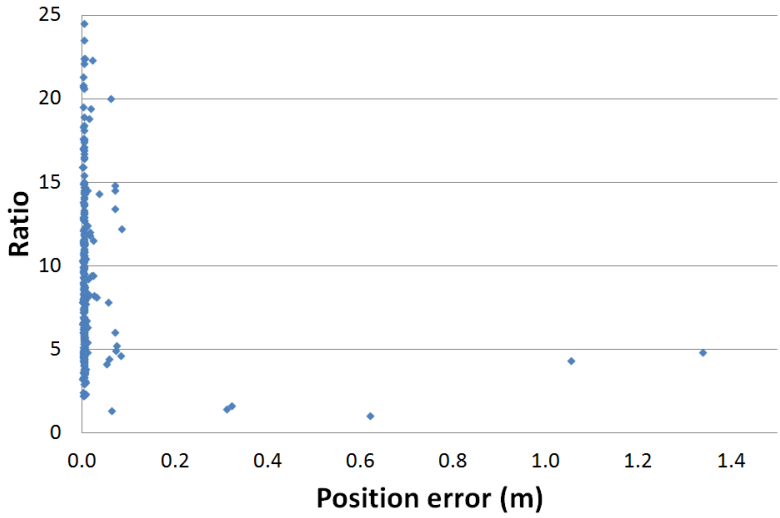


6.7.3 Carrier-phase RTK

The ratio value used in the LAMBDA technique for the N-RTK position calculation is less reliable when calculating positions with single frequency measurements. As can be seen in Figure 6.12, the relationship between the ratio value generated in the integer ambiguity resolution (a product of the LAMBDA method of ambiguity resolution) and the position accuracy is strong when using dual frequency observations. A high ratio is more likely to result in a successful integer resolution, and thus an accurate position. When using single frequency observations the ratio values exhibit an additional, although smaller, peak at a position error of approximately 0.8 metres. The ratio threshold is typically set between 2 and 5 (depending on the application and user preference), but in this case a number of solutions are being miss-classified as ambiguity fixed, and thus misleading the user regarding the solution accuracy.



a). Single-frequency observations.



b). Dual-frequency observations.

Figure 6.12 – Integer ambiguity resolution ratio in relation to positioning error.

As noted by the authors of the LAMBDA method of ambiguity resolution (Teunissen and Verhagen, 2004), the ratio value should not be used as a measure of the successfulness of the fixed solution, but as an assessment of the probability that one set of ambiguities is correct compared to

the next best set. This is a particular problem in a dynamic environment, such as that encountered in automotive applications.

6.7.4 Discussion and evaluation of Pseudo-VRS

The Pseudo-VRS tests described above used geodetic GNSS receivers and antennas, which is unlikely in automotive applications. Geodetic GNSS equipment provides additional benefits such as robust signal tracking, cycle-slip detection, and code smoothing, which can significantly help the positioning performance. The antenna is the most crucial element, as it mitigates the significant impact of the local environment on the GNSS signals.

The latency of the correction message is also important. A data rate of 20 Hertz is unnecessary, and can actually introduce additional problems when dealing with cycle-slips. However, any delay over 8 seconds would be considered too long to successfully resolve the integer ambiguity, so there is a balance required between message delays, data redundancy, and data bandwidth.

The Pseudo-VRS test results have shown that by sharing data between local receivers a single frequency RTK position can be achieved - even when processing epoch by epoch. The percentage of fixed solutions is still low (around 60-70% in the above experiments), but this is significantly better than if a fixed RTK base station was used. This is because the distance between the rover (vehicle) and base station can be up to 50 kilometres in the automotive environment.

Future GNSS constellations are expected to dramatically reduce the cost of dual frequency receivers (Gakstatter, 2009), and the number of satellites in view will also increase if a multi-constellation receiver is used (as discussed in Section 4.5). It should be noted that the use of triple frequencies in GNSS receivers is not anticipated, as the additional cost and complexity required in the receiver design does not translate into a significant improvement in GNSS receiver performance.

Chapter 7

Conclusions and Recommendations

7.1 Conclusions

This thesis aimed to address three subjects. Namely:

1. The evaluation of N-RTK positioning for road vehicle positioning;
2. The connection between the V2X concept and GNSS positioning; and finally
3. The development, testing, and assessment of the Pseudo-VRS cooperative vehicle positioning technique.

Through the systematic evaluation of ITS and vehicle positioning, it was established that high precision GNSS techniques are under-used in automotive applications; yet if they are integrated correctly, there are large benefits for their use. Many of the latest ITS and V2X applications require high precision position information, and through the utilisation of the V2X concept, this can be delivered with N-RTK positioning. Although the N-RTK positioning equipment is relatively expensive and designed for non-automotive applications, this thesis shows that it is possible to adapt the technology, and that a large potential market exists.

However, this relies on the minimisation of the two main limitations of N-RTK for road vehicle positioning. They both stem from the poor availability of the high precision N-RTK fixed solution. Firstly, the N-RTK position relies on good visibility of the GNSS satellites, but in the automotive environment this is not always available. Secondly, the N-RTK positioning technique requires a continuous connection to the corrections service - likewise this is not always available.

Both limitations vary in their magnitude, although by definition they generally peak in different geographic areas. The GNSS signal availability limitation is primarily due to obscuration from infrastructure and buildings - common in urban areas. Whereas the corrections availability limitation is primarily due to poor cellular coverage, which is symptomatic of rural areas.

The corrections availability limitation can be addressed through the use of the V2X concept. Although not widely in use, vehicles are due to become significantly more connected in the future. ITS and V2X applications are due to become more popular due to their safety and journey time benefits - although the main driver may initially be infotainment services.

To demonstrate this potential for improved GNSS positioning, the Pseudo-VRS concept was developed. This borrows the existing techniques and standards from N-RTK positioning (specifically VRS N-RTK), to allow the sharing of GNSS information between vehicles to enable high precision absolute positioning. The Pseudo-VRS technique generates a VRS-like message based on the position of a road vehicle and the raw GNSS information from its GNSS receiver. This message is shared with nearby vehicles, from which they can perform relative GNSS positioning techniques.

The Pseudo-VRS technique takes advantage of the benefits of close proximity in RTK positioning. Due to the short baseline between reference and rover (the two vehicles) a common ambiguity is easier to identify. This is evident from the results of the real-world tests carried out in this thesis.

7.2 Contributions to knowledge

There are five major contributions to knowledge made in this thesis.

- The role of GNSS positioning in future ITS and V2X applications has been outlined. GNSS positioning is not a panacea for vehicle positioning - it has held a strong position in Sat Nav applications for many years, but a single positioning solution for advanced automotive applications is unlikely to be found. Instead, significant positioning performance can be found through the integration of different positioning sensors. There are many options available, such as dead reckoning sensors and terrestrial ranging sensors, but high precision GNSS positioning can make a big contribution to such a solution;

- This thesis provides a thorough analysis of the positioning requirements of a number of specific ITS and ADAS applications. In particular, Table 3.5 outlines the technical requirements of ITS and ADAS applications, and Table 3.6 and Table 3.7 detail the required navigation performance parameters for various current and future ADAS applications;

- This thesis demonstrates the three main GNSS positioning techniques available for vehicle positioning: Stand-alone positioning; DGNSS positioning; and N-RTK positioning. Real-world tests using the NGI facilities outlined the strengths and benefits of each technique. In particular, a detailed study and assessment of RTK positioning (of which N-RTK positioning is a variation) was carried out. One outcome of this study was the potential use of single frequency RTK for road vehicle positioning - a potentially more cost-effective solution;

- Real-world tests were also performed to evaluate the performance of N-RTK positioning for road vehicles. Based on previous research carried out at the NGI, this thesis shows in detail the issues that must be addressed before widespread adoption of such technology is possible;

- The strong link between between GNSS positioning and V2X applications has been outlined and demonstrated. In particular, the complimentary nature of their strengths, and the holistic benefit of combining the two; and finally

- V2X communications have been exploited to develop an innovative new GNSS positioning technique, called Pseudo-VRS.

7.3 Research limitations and future work

The following sections discuss the limitations of the research in this thesis and outlines the recommendations of future work required to further develop the Pseudo-VRS concept.

7.3.1 Research limitations

The configuration of the N-RTK GNSS receivers used throughout this thesis is partially restricted. The N-RTK receivers are designed for geodetic measurement and not for use on road vehicles. For instance, there is a 10 second limit on the age of the correction messages that can be used to create a N-RTK fixed solution - after this time only a DGNSS solution is available. This placed a restriction on several research directions. However, the receivers did allow instant access to a commercial N-RTK positioning service.

This thesis outlined and justified the inclusion of high precision GNSS positioning in the V2X concept, although it is important to recognise that other non-GNSS sensors are delivering strong positioning performance for road vehicles. It is possible that high precision GNSS positioning for road vehicles could be made redundant by the development of these other positioning sensors.

The use of different communication systems were not explored or assessed through trials in this thesis. The sharing of GNSS information between vehicles in Pseudo-VRS positioning relies heavily on the successful transfer of complete Pseudo-VRS messages. It is highly possible that a

V2X communication medium will have fallibilities that will need to be addressed by the Pseudo-VRS concept.

The work carried out in this thesis benefitted from the availability of state-of-the-art N-RTK capable GNSS receivers, but was also limited by the availability of other GNSS receivers for testing. However, it should be noted that the trials included the assessment of lower precision GNSS positioning techniques such as single-frequency RTK and DGNSS. In particular, the results of the trials in this thesis showed that if the high precision N-RTK position is not available, a GNSS receiver is typically able to regress to DGNSS positioning with only a small penalty in positioning accuracy.

The results of the Pseudo-VRS positioning trials were generated from GNSS observation data collected during favourable conditions. There was a clear sky view, limited impact from sources of GNSS signal multipath, and the data was checked for errors before the results were collated.

7.3.2 Future work

The Pseudo-VRS concept was introduced in this thesis. It is a mechanism that enables road vehicles to share positioning information in order to perform cooperative positioning. This thesis concentrated on the sharing of real GNSS observations, in order to perform relative GNSS positioning techniques. Real-world trials of the system were carried out in controlled tests at the Nottingham Geospatial Institute, using a road vehicle and an electric locomotive, and geodetic grade GNSS receivers.

The following six areas of future work have been outlined, based on the research carried out in this thesis.

7.3.2.1 Comprehensive real-world trials

The Pseudo-VRS concept was only tested with data collected from vehicles located in close proximity, with geodetic-grade GNSS receivers, and by carefully controlling the local environment. It would be prudent to carry out further tests across wider environments, such as in urban areas or on high-speed roads. This would determine whether any physical limitations exist to prevent the application of Pseudo-VRS.

7.3.2.2 Explore the practical application of Pseudo-VRS

Pseudo-VRS cooperative positioning requires a communication medium to share data between vehicles. Currently, DSRC technology operating at 5.9 GHz is anticipated to be the preferred communication technology. However, market forces may dictate that a different communication technology becomes prevalent, and this should be explored and monitored closely. Pseudo-VRS positioning should be possible across various communication platforms, although data transfer latency and bandwidth availability are key factors.

Additional trials could also be carried out in real-time using other communication media, such as DSRC, cellular connections, or experimental technology such as long range Bluetooth or UWB. This would be carried out whilst investigating which of the V2X communication technologies is most likely to be adopted, and how V2X applications are being adopted by vehicle manufacturers.

Pseudo-VRS positioning may also be a useful partner for future advanced automotive applications such as vehicle platooning. Other as-yet unknown downstream applications may also benefit from Pseudo-VRS positioning, and these should be identified. The impact of Pseudo-VRS positioning should be quantified in order to estimate its potential impact on ITS and V2X. In particular, the development of V2X concepts from vehicle manufacturers should be explored in order to determine the method of integration of Pseudo-VRS positioning.

7.3.2.3 Pseudo-VRS with different GNSS services

The Pseudo-VRS trials carried out in this thesis used only GPS observation data. A wider investigation should be carried out to assess the performance of Pseudo-VRS positioning using

alternative GNSS services, and the use of multiple constellations. This can be carried out using real-world data for the GLONASS constellation and through simulator experiments for the Galileo and BeiDou constellations.

7.3.2.4 Pseudo-VRS between multiple vehicles

This thesis explored the sharing of Pseudo-VRS data between two vehicles. However, many scenarios are likely to include the interaction of multiple vehicles. This opens up various possibilities such as: Improved integrity through cross checking Pseudo-VRS messages; the processing of a position based on multiple vehicles generating Pseudo-VRS messages; and the collective positioning of multiple vehicles based on partial Pseudo-VRS messages.

7.3.2.5 Pseudo-VRS created from non-GNSS sensors

The Pseudo-VRS concept was created by adopting some of the principles of the VRS concept from N-RTK positioning. Unlike N-RTK VRS positioning, the Pseudo-VRS trials carried out in this thesis used real GNSS observation data for the virtual reference station; hence the term Pseudo.

However, the Pseudo-VRS data could be created from a combination of GNSS and non-GNSS data (or possibly non-GNSS data only). If a vehicle can calculate its position in a GNSS reference frame and has access to up-to-date GNSS almanac and ephemeris data, it is able to create the GNSS observations that would have been received at its position at a particular epoch. This calculated GNSS observation data could be shared with other nearby vehicles. This process results in GNSS data that shares a close similarity with N-RTK VRS data, as it has not been directly observed.

7.3.2.6 Pseudo-VRS as a V2X authentication process

The V2X concept is particularly vulnerable to spoofing and hacking. The authentication of V2X agents is clearly important as fictitious data could potentially be a serious safety issue. Various methods of authentication are being explored by other researchers, but Pseudo-VRS may be able to assist. GNSS observation data is unique to a position and time, and the P(Y) code of GNSS observation data is inherently random with the appearance of white noise to those without the decryption facility. These factors may allow V2X agents to validate the authenticity of other agents.

Appendices

Publications

Journal articles

Liu, H., Meng, X., Chen, Z., Stephenson, S. & Peltola, P., 'A closed-loop EKF and multi-failure diagnosis approach for cooperative GNSS positioning', *GPS Solutions*, Published online, DOI: 10.1007/s10291-015-0489-6, September 2015.

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Conference proceedings

Stephenson, S., Meng, X., Moore, T., Baxendale, A. & Edwards, T., 'Accuracy Requirements and Benchmarking Position Solutions for Intelligent Transportation Location Based Services', in *8th International Symposium on Location-Based Services*, Vienna, 2011.

Stephenson, S., Meng, X., Moore, T., Baxendale, A. & Edwards, T., 'Precision of Network Real-Time Kinematic Positioning for Intelligent Transport Systems', in *European Navigation Conference*, London, 2011.

Stephenson, S., Meng, X., Moore, T., Baxendale, A. & Edwards, T., 'Implementation of V2X with the integration of Network RTK: Challenges and solutions', in *Proceedings of the 25th International Technical Meeting of the Satellite Division of The Institute of Navigation*, Nashville, Tennessee, 2012.

Quan, Y., Meng, X., Yang, L. & Stephenson, S., 'Network RTK GNSS Quality Assessment', in *European Navigation Conference*, Vienna, 2013.

Stephenson, S., Meng, X., Moore, T., Baxendale, A. & Edwards, T., 'A fairy tale approach to cooperative vehicle positioning', in *Proceedings of the 2014 International Technical Meeting of The Institute of Navigation*, San Diego, California, 2014.

Gao, Y., Meng, X., Hancock, C., Stephenson, S. & Zhang, Q., 'UWB/GNSS-based Cooperative Positioning Method for V2X Applications', in *Proceedings of the 27th International Technical Meeting of the Satellite Division of The Institute of Navigation*, Tampa, Florida, 2014.

Zhang, Q., Stephenson, S., Meng, X., Zhang, S., Wang, Y. & Wang, J., 'SVD-based iterative robust cubature Kalman filtering and its application for integrated GPS/SINS navigation', in *Proceedings of the 27th International Technical Meeting of the Satellite Division of The Institute of Navigation*, Tampa, Florida, 2014.

Conference presentations

Stephenson, S., 'Analysis of NRTK positioning for vehicle tracking and attitude determination in dynamic environments', at *Royal Institute of Navigation New Navigator Seminar*, 2011.

Meng, X. & Stephenson, S., 'Location Technologies and Data Sharing in the V2X Contexts', at *SERT @ GVC (Transport iNet)*, March 2012.

Meng, X., Stephenson, S., Ye, H. & Gao, Y., 'Road Vehicle Data Sharing and the Integration of Location Technology', at *UK Seminar on Self-Driving Vehicles 2012*, Nottingham, May 2012.

Stephenson, S.,'The limitations of N-RTK positioning for V2X and ITS applications', at *Royal Institute of Navigation New Navigator Seminar*, Nottingham, May 2012.

Stephenson, S.,'Shifting Transport Paradigms: The ITSS Challenge', at *The Third Annual Digital Economy All Hands Conference: Digital Futures 2012*, Aberdeen, October 2012.

Chen, G., Meng, X. & Stephenson, S., 'Recent V2X Research and Development with its Relevance to Intelligent Transport LBS (ITLBS)', in *10th International Symposium on Location-Based Services*, Shanghai, 2013.

Magazine articles

Stephenson, S., Meng, X., Moore, T., Baxendale, A. & Edwards, T., 'Network RTK for Intelligent Vehicles', *GPS World*, vol. 24, no. 2, 2013.

Stephenson, S., Meng, X., Moore, T., Baxendale, A. & Edwards, T., 'Innovation: Not Just a Fairy Tale', *GPS World*, vol. 25, no. 7, 2014.

Posters

Stephenson, S., Meng, X., Moore, T., Baxendale, A. & Edwards, T., 'Exploiting V2X to improve GNSS vehicle tracking performance', in *European Navigation Conference*, Vienna, 2013.

Memberships

Organisation	Membership type
Chartered Institution of Civil Engineering Surveyors (ICES)	Graduate Member
Chartered Institution of Highways and Transportation (CIHT)	Student Member
Institute of Navigation (ION)	Student Member
Royal Institute of Navigation (RIN)	Student Member
Institute of Engineering and Technology (IET)	Student Member
Institute of Electrical and Electronic Engineers (IEEE) (Member of IEEE Intelligent Transport Systems Society)	Student Member

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