University of Southern Queensland
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Accuracy Assessment of VRS in a Dynamic Environment

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ABSTRACT

The Virtual Reference Station (VRS) concept is one method that is being employed around the world to overcome some of the limitations with conventional Real Time Kinematic (RTK) positioning. There has been an increasing amount of research into the accuracy of VRS RTK GPS measurements, and the Department of Natural Resources and Water has identified the need to investigate the use of VRS in a dynamic environment.

This project has compared the accuracy, precision and latency of conventional RTK and VRS RTK GPS measurements taken in a dynamic environment. This gives an insight into the suitability of the VRS RTK GPS system to real time dynamic applications.

The testing regime used for this project involved attaching RTK GPS equipment to a trolley and positioning reference marks (a series of stakes with barcodes attached) adjacent to a pathway. As the trolley passes these reference marks, a barcode reader on the trolley will scan the barcodes and will initiate a GPS measurement for both conventional RTK and VRS RTK methods. These measurements are compared to the true locations of the reference marks to determine the accuracy, precision and latency.

The results show that the VRS RTK method may be suitable for real time dynamic applications such as machine guidance. However this testing has resembled only slow speed dynamic applications in the range of 1-5 km/h. Further testing would be required for faster speeds.

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CERTIFICATION

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Signature

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ABBREVIATIONS

C/A	Coarse Acquisition code
CORS	Continually Operating Reference Stations
DGPS	Differential Global Positioning Systems
GPRS	General Packet Radio Service
GPS	Global Positioning System
GSM	Global System for Mobile communications
P	Precise code
RTK	Real Time Kinematic
UHF	Ultra High Frequency
USB	Universal Serial Bus
USQ	University of Southern Queensland
VHF	Very High Frequency
VRS	Virtual Reference Station
NAVSTAR	Navigation Satellite Timing And Ranging

CHAPTER 1

INTRODUCTION

1.1 Outline of the Study

Conventional Real Time Kinematic (RTK) positioning using a Global Positioning System (GPS) has been capable of achieving centimetre accuracy since the mid 1990's and as a result has become a widely used technique in surveying (Wanninger 2005). More recently the use of Virtual Reference Station (VRS) technology is beginning to replace the base station necessary for conventional RTK, however there are still uncertainties with the VRS systems.

The main advantage with GPS RTK positioning is that the processing occurs in real-time, this allows GPS RTK positioning to be effectively applied to applications where time is critical, such as machine guidance (Rizos & Han 2002). The GPS RTK positioning method does however have limitations, these include:

- The need to set up a base GPS receiver and radio communications link for each period of work (Higgins 2001b).
- The radio communications that are limited in range and can experience interference (Higgins 2001b).
- The distance between the base receiver and rover receiver is limited to approximately 10-20 kilometres to resolve carrier phase ambiguities to achieve centimetre accuracy (Wanninger 2005).

The VRS concept is one method that is being employed around the world to overcome some of the limitations of conventional RTK positioning. The conventional RTK GPS method has been extensively tested and the centimetre level accuracy is common when the rover is within 10 kilometres of the base station (Hu et al 2002). However there is less certainty with VRS RTK GPS measurements. There has been some level of testing of VRS RTK GPS measurements in static environments, but little is known about the accuracy of VRS RTK GPS measurements in a dynamic environment, especially with respect to the effects of latency.

Latency is the time delay between when a position is occupied and when the measurement at that position is recorded (Gibbings & O'Dempsey 2005). This is a critical aspect in the accuracy of GPS measurements in dynamic environments because the position that is taken from the RTK may not correspond to the actual position of any machinery being controlled by RTK. This project attempts to assess the relatively unknown accuracy, precision and latency of VRS RTK GPS measurements as opposed to the more established conventional RTK GPS method under dynamic conditions.

1.2 Research Aim and Objectives

1.2.1 Aim

The aim of this project is to compare the accuracy, precision and latency of conventional RTK and VRS RTK GPS measurements taken in a dynamic environment. This will give insight into the effectiveness of the VRS RTK GPS system, and will also assist in determining if this system is reliable for certain applications such as machine guidance and precision agriculture.

1.2.2 Objectives

The objectives of this project are as follows:

- Critically analyse operations and past research on RTK GPS, use of GPS in dynamic environments and VRS networks.
- Develop and validate a method for testing the accuracy and precision of conventional RTK and VRS RTK in a dynamic environment.

- Design a field measurement plan and collect data simultaneously using conventional RTK and VRS RTK methods in a dynamic environment.
- Analyse field data to assess the accuracy and precision of the different methods of surveys.
- Evaluate and compare the effect of latency on conventional RTK and VRS RTK.

1.3 Justification

There has been extensive research into GPS RTK positioning in the past decade and users can now achieve centimetre accuracy (Wanninger 2005). As a result of the achievable accuracy RTK positioning has been applied to precise applications such as surveying, construction and precision farming (Hu et al 2002). However there are still restrictions involved with the conventional RTK method when undertaking large-scale operations, such as the ability to solve carrier phase ambiguities between the base receiver and rover receiver over a distance greater than 10-20 kilometres, and the reliability of the radio connection.

In recent times VRS RTK has been studied as a method of improving the efficiency and reliability of RTK positioning, and overcoming the distance restrictions. There has been an increasing amount of research into the accuracy of VRS RTK GPS measurements, but this is mostly limited to measurements made in static environments. One of the major issues with GPS measurements in a dynamic environment is the accuracy, particularly the effect of latency of which there has been little research. Therefore there is a need for an accuracy assessment of VRS RTK GPS measurements in a dynamic environment, because there are many potential dynamic large-scale VRS RTK GPS applications. One application in which VRS RTK GPS would have a significant impact on is machine guidance and control. This is because the machinery could be linked to GPS and the progress of the operation can be updated in real time.

1.4 Research Methodology

The purpose of this project is to gain an understanding of the accuracy and precision of the VRS RTK GPS compared to conventional RTK GPS, and also evaluate the effect of latency on both methods. To provide a direct comparison, it is planned that the conventional RTK GPS and VRS RTK GPS measurements be gathered simultaneously using a common antenna. The use of a common antenna will eliminate much of the external influences such as atmospherics, because these effects will be the same for both sets of data.

To test the accuracy and latency of the GPS measurements in a dynamic environment, a stationary reference frame and a dynamic platform are required. The stationary reference frame is established adjacent to the test track, and this involves a series of stakes with barcodes on them positioned at known locations.

A barcode scanner is mounted directly under the antenna and as the trolley passes these barcodes, the barcode scanner will read the barcode and GPS measurements will be made. These measurements will be taken with the dynamic platform travelling in both directions at the same speeds. The GPS coordinates measured from the dynamic platform are compared to the known coordinates of the barcodes. This will facilitate the determination of the accuracy for the conventional RTK GPS and VRS RTK GPS measurements. Latency will also be determined for each of the measurements.

1.5 Scope and limitations of Research

There are various types of network based RTK systems that are being implemented around the world to correct GPS observations. The VRS system is just one of these methods. It is not the focus of this research to compare the different methods of correcting GPS observations, and therefore only the VRS system is compared to the conventional RTK method. The assessment of any other network based RTK system would require additional research.

There are also many alternative configurations with which a VRS network can be established. The network used for this project is operated by the Department of Natural Resources and Water and is located in South East Queensland. The speeds that will be tested will only resemble dynamic applications that operate at speeds in the range of 1-5 km/h, such as slow speed machine guidance. Further testing would be required for faster speeds.

The equipment used for this research will involve only Trimble products, the results of this test may not be relevant to other manufacturers or even other Trimble products. The communication technique for transmitting the VRS RTK corrections is another aspect that offers various alternatives. The Global System for Mobile communications (GSM) cellular phone network is going to be sole communication technique utilised in this research, and the use of any other technique would require its own testing.

1.6 Conclusions: Chapter 1

This research aims to assess and compare the accuracy and precision of conventional RTK and VRS RTK GPS measurements taken in a dynamic environment and also evaluate the effect of latency in these measurements. The results of this research would be useful to any persons currently using or thinking about using the VRS networks in dynamic environments and may also lead to the introduction of the many potential dynamic large-scale VRS RTK GPS applications.

Chapter two will present a literature review that will explain in detail the concepts relevant to this project and provide details on the research previously conducted in this field of study. This review of literature will include a background study of the theory of GPS, RTK, VRS, latency and accuracy in relation to GPS measurements, and the applications of GPS in dynamic environments.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter will review any existing literature to date that will assist in developing a method for testing the accuracy and precision of conventional RTK and VRS RTK in a dynamic environment.

This chapter aims to provide an outline of the important background information that is relevant to this project and a review of any existing work that has been completed in testing the accuracy, precision and latency of GPS measurements. This will highlight the need for testing the accuracy, precision and latency of VRS RTK GPS measurements taken in a dynamic environment.

The literature review will begin by giving a clear outline of how GPS operates and more specifically the functioning and requirements of conventional RTK and VRS RTK. Definitions will be provided to clearly indicate what accuracy, precision and latency are, and their importance to GPS measurements taken in a dynamic environment. There will also be a review of any existing work that has been conducted on testing the accuracy, precision and latency of GPS in dynamic environments.

2.2 Global Positioning System (GPS)

The Global Positioning System uses a group of satellites to provide accurate positional coordinates anywhere on the Earth's surface in any weather conditions, day or night (*Geodetic Surveying A Study Book 2* 2004). The system is 'owned, operated, and controlled by the United States Department of Defence' although it is available for civilian use (Trimble Navigation Limited 2003, p. 2).

2.2.1 GPS Segments

There are three segments of GPS: the space segment, the control segment and the user segment. The space segment consists of a minimum of 24 operational NAVSTAR (NAVigation Satellite Timing And Ranging) satellites (*Geodetic Surveying A Study Book 2* 2004). NAVSTAR satellites have an expected life of approximately seven years and satellite numbers are constantly changing as satellites are commissioned and decommissioned (*Geodetic Surveying A Study Book 2* 2004). The satellites orbit at an altitude of about 20 200 km and have an orbital period of approximately 12 hours (*Geodetic Surveying A Study Book 2* 2004). The constellation of satellites is arranged into 'six orbital planes inclined at 55 degrees to the equator and placed evenly in longitude', (see Figure 2.1) (*Geodetic Surveying A Study Book 2* 2004, p. 11.2).

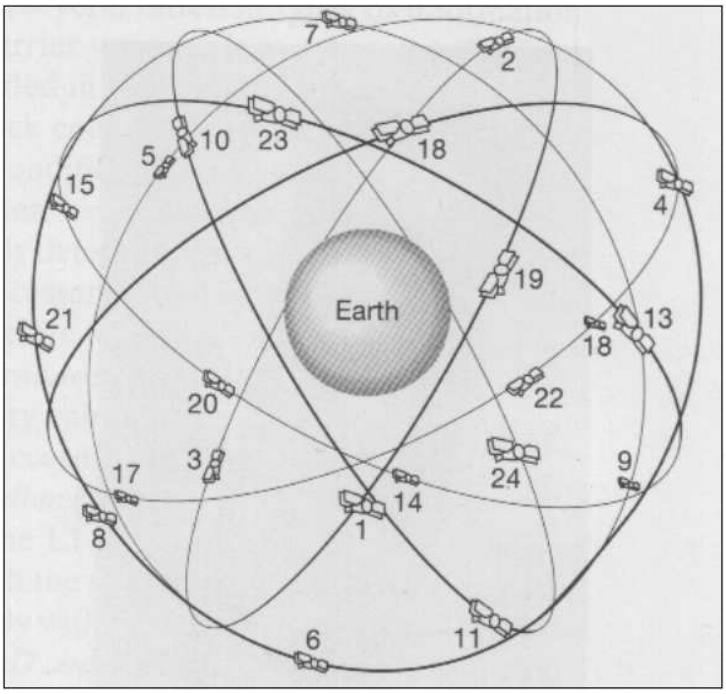

Figure 2.1 GPS constellation (*Source*: Wolf & Ghilani 2002)

The control segment maintains the system and is operated by the United States Department of Defence. The control segment consists of a master control station and four monitor/upload stations (Trimble Navigation Limited 2003). The master control station is located at the Schriever Air Force Base in Colorado Springs, USA and the remaining monitor/upload stations are located at Hawaii, Ascension Island, Diego Garcia and Kwajalein (see Figure 2.2).

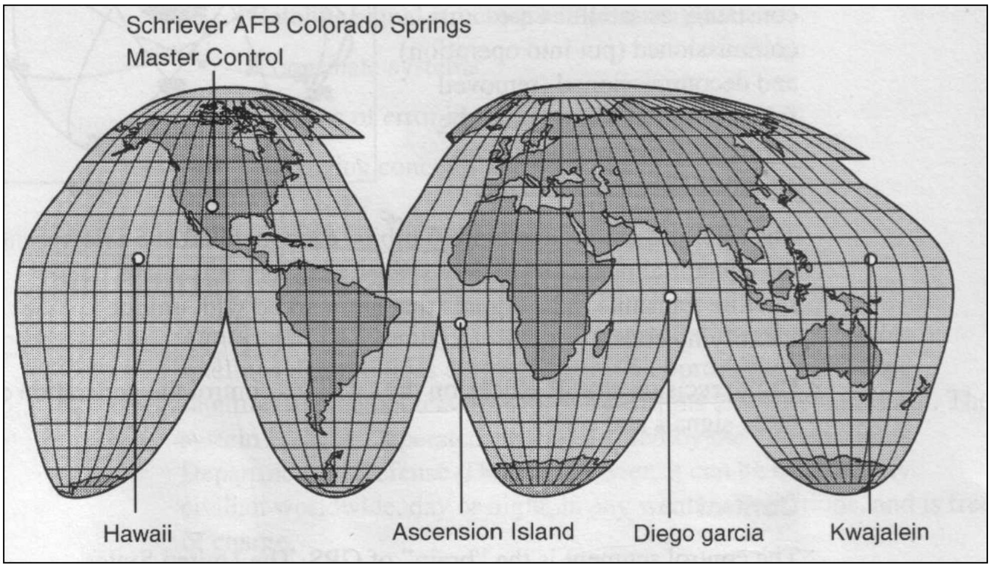

Figure 2.2 GPS monitor/upload stations (*Source*: Trimble Navigation Limited 2003)

The monitoring stations track the satellites continuously with every satellite passing over a monitoring station twice a day (Trimble Navigation Limited 2003). The data that the monitoring stations obtain from the continuous tracking is sent to the master control station (Trimble Navigation Limited 2003). This information is processed to 'yield clock corrections and predicted orbits of each satellite' and is uploaded to the appropriate satellites via the monitor/upload stations (*Geodetic Surveying A Study Book 2* 2004, p. 11.5).

The user segment consists of anyone who has a GPS receiver and this includes both military and civilian users. GPS can be used for tasks on land, on sea and in the air with applications including: surveying, agriculture, aviation, emergency services, recreation and vehicle tracking (Trimble Navigation Limited 2003).

2.2.2 Satellite Signals

Each satellite transmits unique codes including: the C/A (coarse acquisition) code and the P (precise) code, the L2C signal and also the navigation message (Trimble Navigation Limited 2003). These codes are modulated onto carrier waves, two L-band radio signals (L1 and L2). The C/A code is modulated onto the L1 signal and is repeated every second (*Geodetic Surveying A Study Book 2* 2004). The P code is modulated onto both the L1 and the L2 signals and takes approximately seven days to repeat itself (*Geodetic Surveying A Study Book 2* 2004). Single-frequency GPS receivers observe only the L1 signal while dual-frequency GPS receivers observe both L1 and L2 signals (Trimble Navigation Limited 2003).

The principle of GPS is that the position of the satellites is always precisely known. The position on the Earth is determined by knowledge of the range (distance) from each visible satellite to the GPS antenna and using trilateration (Trimble Navigation Limited 2003). The ranges are measured using either the code or the phase of the carrier wave. The testing in this project will involve only the phase observable.

2.2.3 Range based on carrier phase measurements

Survey grade GPS receivers 'measure the difference in carrier phase cycles and fraction of cycles over time' (*Geodetic Surveying A Study Book 2* 2004, p. 13.2). The range is determined by adding the whole number of wavelengths and the partial wavelength; this is then multiplied by the known wavelengths (L1 is about 19 cm and L2 is about 24 cm). Figure 2.3 shows the range based on carrier phase measurements, where A is the whole number of wavelengths and p is the partial wavelength.

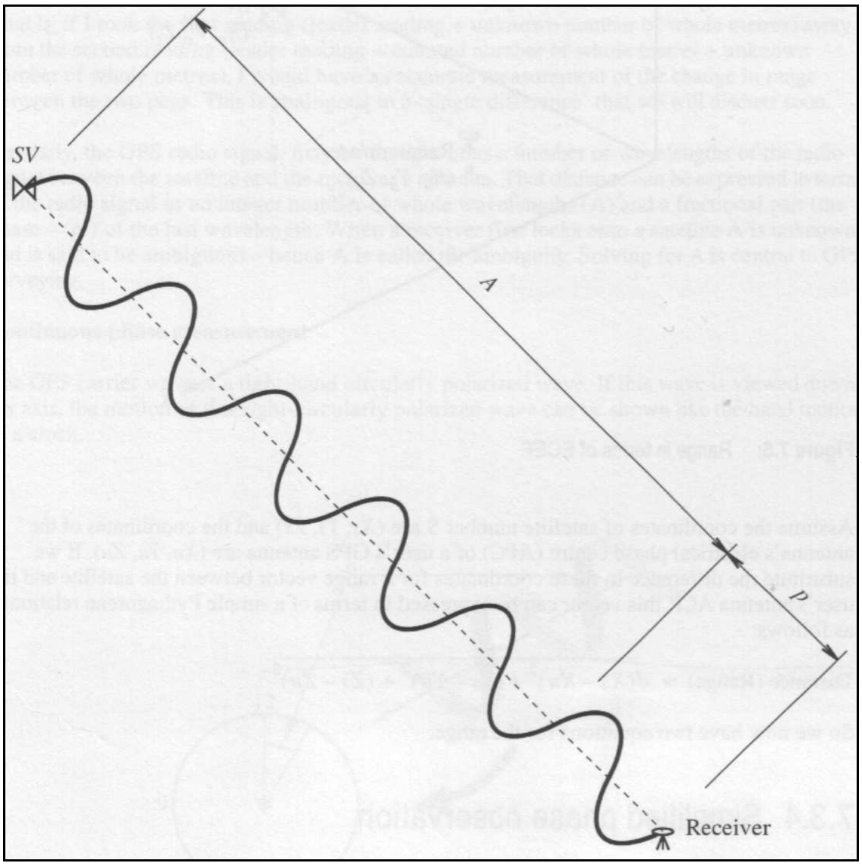

Figure 2.3 Range from carrier phase measurements (*Source*: *Geodetic Surveying A Study Book 2* 2004)

2.3 Real Time Kinematic (RTK) GPS

The Real Time Kinematic (RTK) GPS method uses the carrier phase measurements and 'the simultaneous use of two or more receivers' (Wolf & Ghilani 2002, p. 349). The measurements are made in real-time where the data is processed in the field as the data is logged (Trimble Navigation Limited 2003).

This method involves setting up a base (or reference) station at a location with known coordinates, and this station transmits data to one or more roving receivers (Higgins 2001b). There are many possible ways of transmitting data, however the most common method used in RTK is radio transmission in Ultra High Frequency (UHF) or Very High Frequency (VHF) bands (Wegener 2005).

The transmitted reference station data is combined with the rover data to estimate carrier phase ambiguities (Talbot et al 2002). Many of the systematic atmospheric and satellite related errors are cancelled out when the data is processed (Talbot et al 2002). This relies on the assumption that the errors at the base station are the same as the errors at the rover. However, this method of cancellation limits the distance between the rover and the base station to 10-20 kilometres because the error characteristics are dissimilar in different regions and the assumption becomes unreliable.

2.4 Virtual Reference Stations (VRS)

The GPS network based Virtual Reference Stations (VRS) system was announced by Spectra Precision Terrasat in 2000 (Vollath et al 2000). The VRS concept is a method of transmitting network correction information to RTK roving receivers using the system, to remove any distance dependant biases that limit the range of conventional RTK use. Network RTK using VRS operates at distances of many tens of kilometres and aims at achieving accuracy that is comparable to single base RTK systems at distances up to 10 kilometres (Rizos & Han 2002).

Key to the concept of VRS is a computer-linked network of three or more permanently running GPS reference stations that continually gather data. This data is sent to a central processing computer to model the errors affecting the signals within the network (Higgins 2001a; Talbot et al 2002). The error sources that are modelled include: multipath errors, ionospheric errors, tropospheric errors, ephemeris errors, and carrier phase ambiguities (Landau et al 2002; Vollath et al 2002).

Vollath et al (2002) has researched the effectiveness of VRS measurements of six different VRS networks using Trimble GPSNet software. Comparisons were made between measurements with and without VRS corrections for each network, and the measurements using VRS experienced an average improvement factor of between two and ten (Vollath et al 2002). However this research only involved static measurements, and further research is required in dynamic environments.

The functioning of the VRS system involves roving receivers located within the network that send their approximate location to a central processing computer and request corrections (Higgins 2001a) (refer to Figure 2.4). The central processing computer uses the approximate position of the rover and the error model to create a 'virtual' reference station near the location of the roving receiver (Landau et al 2002). This 'virtual' reference station does not physically exist, however it acts as a base station similar to the conventional RTK method and the corrections are generated as though they were coming from the 'virtual' reference station (Higgins 2001a). The configuration of a network RTK system and the data flows involved are shown in Figure 2.4.

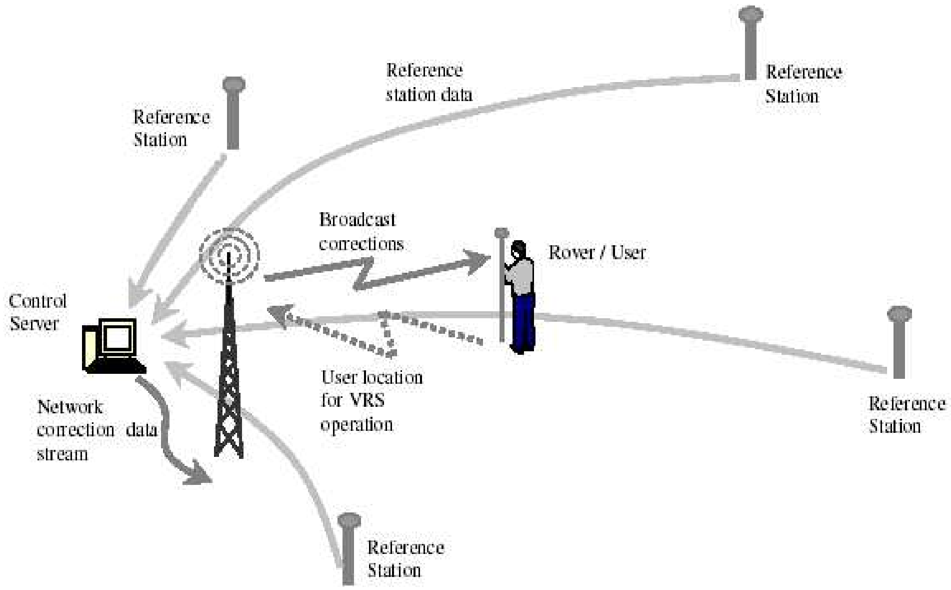

Figure 2.4 Network RTK system and data flow (*Source*: Talbot et al 2002)

A wireless two-way communication link is required between the central processing computer and the rover. This link may be the Internet or GSM (Global System for Mobile communications), both of which can utilise GPRS (General Packet Radio Service) (Hu et al 2002). These methods of communication are quite reliable and can be transmitted over a large area without interference, thus overcoming the problems associated radio transmission in UHF or VHF bands that is commonly used for conventional RTK.

There are many network RTK systems using VRS around the world with ‘more than 80 Trimble infrastructure installations networks’ in countries such as ‘China, Germany, Austria, Switzerland, U.S. including Alaska, Canada, Norway, Sweden, Finland, Denmark, Belgium, France, Spain, Italy, United Kingdom, Netherlands, Poland, Slovenia, Australia, Malaysia, Taiwan, Korea, and Japan’ (Trimble 2006).

The VRS network that is going to be utilised in this project is located in South-East Queensland (see Figure 2.5). This network was established by the Department of Natural Resources and Water, and Trimble Australia. The technical specifications for the VRS system are in included in Appendix B. There are five reference stations incorporated into the network and are separated by distances of between 29 and 76 kilometres. The locations of the reference stations are:

- Ipswich;
- Caboolture;
- Beenleigh;
- Gold Coast; and
- Brisbane Land Centre (central processing computer).

Figure 2.5 VRS Network in South-East Queensland (*Source*: RACQ 2006)

2.5 Accuracy and Precision

Accuracy is the absolute closeness of observations to their exact values and precision is the refinement or consistency of a group of observations (Wolf & Ghilani 2002). Figure 2.6 illustrates the difference between accuracy and precision, where **(a)** demonstrates high precision with poor accuracy, **(b)** demonstrates poor precision with poor accuracy, and **(c)** demonstrates high precision with high accuracy.

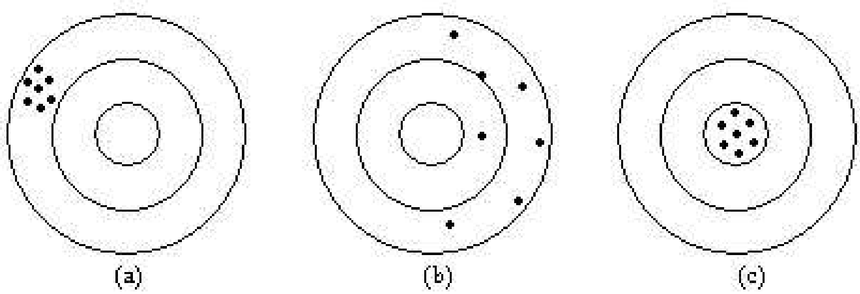

Figure 2.6 Examples of Precision and Accuracy (*Source*: Wolf & Ghilani 2002)

Because it is possible for observations to be highly precise but still be inaccurate, as shown in Figure 2.6 (a), most applications, including surveying, are more concerned with accuracy over precision. This project will investigate both accuracy and precision of the GPS measurements.

2.5.1 Accuracy in GPS Measurements

Accuracy in the context of GPS measurements is the difference between the actual position of the point being measured and the apparent position of the point as measured by the GPS equipment (Campbell et al 1998). In dynamic environments accuracy is a function of both the variability of the method being used and also the latency that is present in the equipment (Campbell et al 1998). The testing of accuracy on the conventional RTK method has been well documented and the variability is reasonably well known, and to some extent, so is the effect of latency. The testing of VRS systems is increasing as the system becomes more popular, however the majority of the accuracy tests are conducted in static environments where latency is not as crucial and as a result, little is known about the effect of latency on VRS RTK measurements.

It has been suggested that if the permanently operating base stations of a Trimble VRS network have real time recording and transmitting of one-second data, it is expected that the horizontal positional accuracy will be 1-2 centimetres (Office of the Surveyor-General 2003). It is necessary for:

> *'The coordinates of the physical VRS reference stations to be consistent at the 1 centimetre level if the VRS software is to model the GPS errors well enough to provide centimetre accuracy corrections to the rovers'. (Higgins 2001a, p. 13)*

Initial testing of the VRS network located in South-East Queensland gathered 115 observations in two weeks at locations in and around the network (Higgins 2001a). Nine of these observations were discarded as they had residuals greater than 3σ from the mean (Higgins 2001a). The results on the remaining 106 observations include a mean horizontal distance of 32 mm, with a precision of ±14 mm at 1σ (Higgins 2001a). This testing also verified that each initialisation has a horizontal accuracy of 1-3 centimetres (Higgins 2001a).

The ability of Continually Operating Reference Stations (CORS) to provide centimetre accuracy is highly dependant on the maximum baseline length between the rovers and the nearest reference station. Roberts et al (2004) explain that most CORS networks are of sufficient density to restrict the maximum baseline length between the rovers and the nearest reference station to under 40 kilometres, which is often sufficient to provide centimetre accuracy.

The observations obtained in the initial testing of the South-East Queensland VRS network are at locations that ranging from 8-30 kilometres from the nearest reference station, with an average of 18 kilometres (Higgins 2001a). The distances of these observations from the nearest reference station are well under 40 kilometres and provide reasonable accuracy (Higgins 2001a).

The testing of VRS RTK accuracy is increasing confidence in the capability of achieving centimetre accuracy in static conditions. However this accuracy may have minimal relevance in dynamic environments. One critical aspect of accuracy in dynamic environments is the effect of latency.

Ong and Gibbings (2005) have conducted additional testing of the VRS network located in South-East Queensland. Fifteen test sites within and around the VRS network were used to test the accuracy and precision of the VRS RTK and the conventional RTK methods (Ong & Gibbings 2005). The VRS RTK and conventional RTK data were obtained simultaneously at each test site using the same antenna and an antenna splitter. There were between 35 and 50 measurements made at each test site for each method (Ong & Gibbings 2005). The measured results were compared to ground truth positions (measured using classic post-processed GPS) to obtain the accuracy and precision.

The VRS RTK measurements of this test found that most of the points (13 points) were within 20 mm of the ground truth and the largest difference being 26 mm (Ong & Gibbings 2005). Only two points in the conventional RTK method fell outside 20 mm with the largest difference being 36 mm (Ong & Gibbings 2005). The average values of each method were similar with the VRS RTK average difference being 14 mm and the conventional RTK average difference being 13 mm (Ong & Gibbings 2005). The precision of the VRS RTK method was estimated to be ±10 mm at 1σ, and the precision of the conventional RTK was estimated to be ±15 mm at 1σ (Ong & Gibbings 2005).

2.6 Latency

Latency is the 'time delay experienced when data is sent from one point to another' (Industrial Networking and Open Control 2002). However with reference to GPS measurements latency is the 'delay between the time of fix and when it is available to the user' and it is a contributing factor to the final accuracy of derived positions (Raymond 2005; Wolf & Ghilani 2002). This is a significant issue in

RTK GPS measurements especially in dynamic environments, where it may cause positional error. The positional error experienced as a result of latency is a function of the update rate and the velocity of the moving platform (Campbell et al 1998).

2.6.1 Latency in GPS Measurements

In GPS measurements a 'time lag (latency) may be experienced between when a GPS position is measured and when it is recorded' (Gibbings & O'Dempsey 2005, p. 6). This is a crucial factor in dynamic environments because the location of the position as determined by the GPS may not correspond to the correct position. To illustrate the significance of the latency effect consider the following: a one second delay in the updating of an exact position of a moving platform travelling 100 km/h would result in an error of 27.8 m (Campbell et al 1998).

There are several processes in the functioning of an RTK GPS system where latency can occur. These processes are defined by (Wolf & Ghilani 2002) as the time taken to calculate the corrections at the base station, the delays in transmitting the corrections to the rover, and time taken to apply these corrections at the rover.

It is assumed that latency also exists in VRS RTK GPS measurements because these systems involve the processes that cause latency in the conventional RTK GPS. However the extent of the latency may differ due to the differences in the systems. For example the communication link in conventional RTK is often VHF/UHF radio and VRS RTK often uses GSM or the Internet. Figure 2.7 shows the effect of latency on positional error and the sources of latency in RTK GPS measurements.

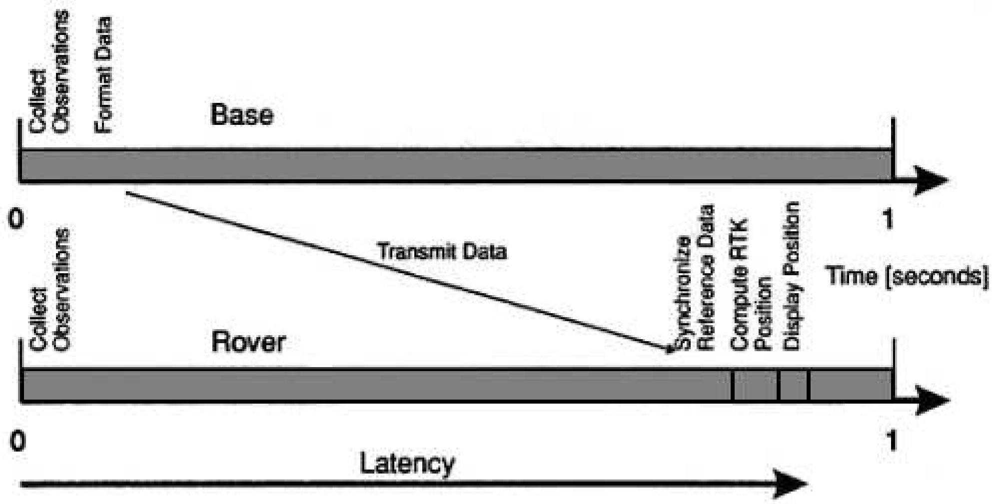

Figure 2.7 Effect and Sources of Latency (*Source*: Trimble Navigation 1999)

One method that is in use in RTK GPS to achieve high update rates and lower latency involves the rover accurately predicting the reference receiver carrier phase measurements in advance (Scarfe 2002). This is achievable as rovers are able to predict the path of satellites and also because the atmospheric errors are considered constant over a short period of time (Scarfe 2002). However, this method works best when the travel path is consistent, such as a straight line, and is not so successful when the travel path is constantly changing direction.

Early RTK systems had receiver latency of approximately three seconds, however some current systems have latency of just 20 milliseconds, such as the Trimble MS750 (The Hydrographic Society 2002). Most Differential Global Positioning Systems (DGPS) and RTK GPS often have receiver latency values ranging from 300-500 milliseconds (The Hydrographic Society 2002). For most applications total latency of five seconds is acceptable, however for applications in dynamic environments it is recommended that the total latency be one second or less (Office of the Surveyor-General 2003). To achieve centimetre-accurate positioning in static conditions the transmission latency is required to be one second or shorter (Wegener 2005). However this is not directly applicable to VRS measurements as there is very little known about the effect of latency in VRS systems. One aspect of this research is to compare the effect of latency that is present in VRS RTK GPS measurements with the latency present in conventional RTK GPS measurements.

2.7 GPS in a Dynamic Environment

> *Future testing will need to more fully investigate the use of VRS in dynamic platforms such as rail and road surveys and in earth moving applications. (Higgins 2001a, p. 9)*

The term dynamic environment refers to activities that involve motion as a critical aspect. There is uncertainty as to the accuracy of GPS measurements in dynamic environments, especially using VRS. In fact Coyne et al (2003, p. 15) identifies that 'few standards exist for testing GPS performance under dynamic conditions' and that tests conducted on the static performance of GPS systems are not necessarily indicative of dynamic performance. A major contributing factor in the accuracy of GPS measurements in dynamic conditions is latency, as previously mentioned. Different tests have been conducted to measure the latency of different GPS systems, such as those performed by Smith and Thomson (2003); Gibbings and O'Dempsey (2005); and Inglis (2006).

Smith and Thomson (2003) have conducted a test on latency to measure the difference between the physical position of an aircraft and the GPS coordinates available when that position was occupied. This test involved establishing a reference point on the ground with measured GPS coordinates. A mirror was placed at the reference point, such that it vertically reflected a beam of light. This beam of light was detected as the aircraft flew over the reference point and caused the time and GPS position at this instant to be recorded. The latency was determined by comparing the GPS coordinates of the reference point with the recorded GPS position of the aircraft. Multiple runs were conducted in this test and determined that the latency in each case was less than 9 m with a consistency of less than 0.7 m difference between runs (Smith and Thomson 2003). These results are quite good considering the aircraft is travelling at speeds of 58 m/sec

(Smith and Thomson 2003). Using 9 m as the latency distance and 58 m/sec as the speed, the latency as a time is calculated to be 0.15 seconds.

Latency is also present in hydrographic measurements when using a depth sensor and RTK GPS. Tests have been conducted by Gibbings and O'Dempsey (2005) to evaluate the use of GPS asset mapping software for hydrographic measurements in still water using a Trimble ProXR GPS receiver. The test involved calculating the latency so that a correction can be applied to the data.

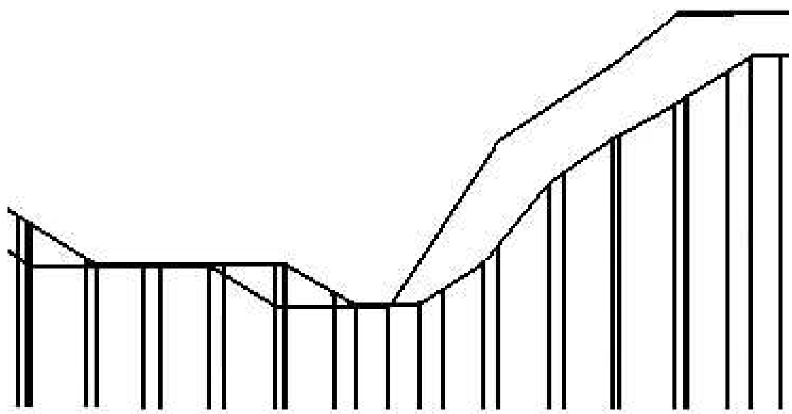

Figure 2.8 Latency in Both Directions (*Source*: Gibbings & O'Dempsey 2005)

A short transect over a rapidly changing surface was measured at a constant speed in both directions. The measurements from each direction were plotted and the latency (as a distance) can be observed, as shown in Figure 2.8. The double latency distance (difference between forward and reverse measurements) was approximately 1.4 m, and is converted to time using the boat speed (1.2 m/sec) and divided by two to give latency as time of 0.29 seconds (Gibbings & O'Dempsey 2005).

The test of latency conducted by Inglis (2006) tested the effect of latency as a distance using conventional RTK GPS. The test used a barcode scanner attached to the back of a utility directly under the GPS antenna. As the barcode scanner passed the barcodes that were positioned on stakes, a GPS measurement would be made. The GPS receiver used for this test was a Trimble 5800/R8 and involved testing at speeds within the range 0.5 to 2.6 km/h and the results show that latency as a distance increases as the speed increases. The latency distance ranged from 0.03 m at 0.5 km/h to 0.26 m at 2.4 km/h (Inglis 2006). Using these latency distance values, the latency as time was calculated to be in the range of 0.21 to 0.38 seconds.

The need to assess the accuracy achieved in current GPS systems, including VRS, in dynamic environments is very important. This is because there are many fields that could benefit from this technology and there are many potential applications.

2.7.1 Potential Applications

The strength of RTK is its ‘ability to track moving equipment and to implement management decisions in real-time based on geographic position’ (Coyne et al 2003, p. 15). The strength of VRS is the ability to provide accurate measurements to a large area. Because of these strengths the applications that will benefit most from accurate VRS RTK GPS are machine control applications such as earth moving, mining, and precision agriculture (Scarfe 2002). This is because the operating costs of these activities are quite high and any improvement in the efficiency of the operations, such as that provided by VRS, can provide significant cost savings (Scarfe 2002).

The methods employed for earth moving and precision agriculture when utilising VRS RTK GPS are very similar. They both involve continuous and accurate tracking of the equipment so the current position of the equipment can be compared to a digital plan. The equipment used in the earth moving application includes bulldozers, graders, etc and precision agriculture often includes equipment such as aircraft that dispense chemicals and fertilisers. The digital plans used for earth moving are the desired topology of the surface, while the digital plans used for precision agriculture can include the different proportions of chemicals and fertilisers required in different regions of the fields.

However there are other applications that would benefit from this system. These include: surveying and mapping, harbour fleet management, rescue and emergency services, structural monitoring, and any other autonomous robotic navigation applications (Roberts et al 2004; Rizos & Han 2002).

2.8 Conclusions: Chapter 2

This chapter has provided background information on conventional GPS, RTK, VRS RTK, accuracy, precision and latency; and has shown that there is a need to further test VRS RTK in a dynamic environment. This information has assisted in defining the requirements of what needs to be tested and the current limitations of the conventional RTK and VRS RTK methods.

The review of the past tests has illustrated the different methodologies that have been employed to test accuracy, precision and latency in dynamic environments. The information form these tests has aided in the design of a testing regime for this project and has provided an indication of what values can be expected for the accuracy, precision and latency.

The next chapter will provide a detailed account of the methodology that was employed to test the accuracy, precision and latency of conventional RTK and VRS RTK GPS. The testing also provides a comparison between these two methods of GPS.

CHAPTER 3

METHODOLOGY

3.1 Introduction

The background information provided in the previous chapter has recognised the importance and need for testing the accuracy and latency of VRS RTK GPS in a dynamic environment. The background information, particularly the tests that have been conducted by others, also provided ideas that helped devise a method for the testing in this project.

This chapter will outline the data collection and analysis plan that will be employed to test the accuracy, precision and the effect of latency on VRS RTK GPS measurements in a dynamic environment.

The conventional RTK GPS method and the VRS RTK GPS method will be compared with respect to accuracy, precision and latency. The testing will involve the collection of conventional RTK GPS measurements and VRS RTK GPS measurements simultaneously. This will provide comparisons against the VRS RTK method to assess its potential effectiveness. The test method will replicate slower dynamic applications such as slow speed machine guidance with speeds in the range of 1-5 km/h, and testing at higher speeds may need to modify this method.

3.2 Reference Frame

A reference frame is a crucial aspect when testing in a dynamic environment. The reference frame is a set of stationary marks at known locations. The reference frame for this project includes four stakes positioned approximately two metres apart and adjacent to a straight section of road or railway track, depending on the location of the testing. These stakes will be measured using the conventional RTK method in static mode to obtain the coordinates of the stakes.

The use of stationary reference marks is extremely important when researching the accuracy and latency in a dynamic environment because they provide a mechanism for comparison between the stationary reference marks and those measurements obtained when moving.

To enable GPS measurements to be made as the dynamic platform passes the reference stakes, an optical barcode reader is utilised. The barcode reader will be attached to the dynamic platform and barcodes will be positioned on each of the stakes. As the dynamic platform moves past the stakes the barcode reader scans the barcodes and a GPS measurement will be made.

3.3 Dynamic Platform

A dynamic platform is a fundamental component when conducting any form of work in a continuously moving environment. For this testing the dynamic platform must be capable of following a straight line and maintaining a steady speed.

A car was going to be used for the initial testing, and a railway trolley was a possibility to obtain more accurate data. These two dynamic platforms were both found to be unusable and this will be explained in section 3.6.2. A frame attachment was required to effectively fix the equipment to the car and this is shown in Figure 3.1.

The dynamic platform will contain all the equipment necessary to make and record both the VRS RTK GPS measurements and the conventional RTK GPS measurements, and this also includes the barcode reader. The equipment required for testing is outlined in the section 3.4 of this dissertation.

Figure 3.1 Car with Frame Attachment.

3.4 Equipment Configuration

To justify a direct comparison of the two methods (VRS RTK GPS and conventional RTK GPS) it is important that the equipment configuration for each method be as similar as possible. To allow this comparison the data for each method will ideally be obtained simultaneously through the use of a single external antenna. The use of a common antenna will eliminate the influence of much of the external influences, such as atmospherics, on the comparison because these effects will be the same for both sets of data. The antenna that is to be used is a Trimble Zephyr antenna, shown in Figure 3.2 (B).

There will be two GPS receivers used, one allocated to conventional RTK and one allocated to VRS RTK (see Figure 3.3). Trimble 5800 receivers were planned to be used but they have inbuilt antennas that cannot be bypassed to use an external antenna. Therefore Trimble 5700 receivers are to be used as they don’t contain an antenna and do require the input of an external antenna. A Trimble 5800 receiver is shown in Figure 3.2 (A) and a Trimble 5700 receiver is shown in Figure 3.2

(C). A splitter will be used to connect the two GPS receivers to the single external antenna (Zephyr).

Figure 3.2 Equipment (A) 5800 Receiver (B) Zephyr Antenna, (C) 5700 Receiver, (D) TSC2 Data Recorder, and (E) Microvision Flic Barcode Scanner.

The measurements will be recorded in a single data recorder, so that all the recorded data is in one place and so there is less equipment required. A Trimble TSC2 data logger will be used (see Figure 3.2 (D)) with TerraSync software installed. This data recorder was chosen because it has more available ports than the previous model (Trimble TSCe) and these additional connections are necessary to connect all the equipment that is required. Research performed by Inglis (2006) revealed the problems with the Trimble TSCe not containing an adequate number of available ports for this kind of research.

A mobile phone will be connected to the TSC2 via bluetooth connection and this will provide the communication with the VRS network. A barcode scanner is going to be connected to the Universal Serial Bus (USB) port on the TSC2 and TerraSync will manage the scanner as an external sensor. The barcode scanner that will be used is a Microvision Flic Barcode Scanner and is shown in Figure 3.2 (E)). The technical specifications for the Microvision Flic Barcode Scanner are in included in Appendix C. This equipment will be located on the dynamic platform, and Figure 3.3 shows schematically how the equipment will be connected.

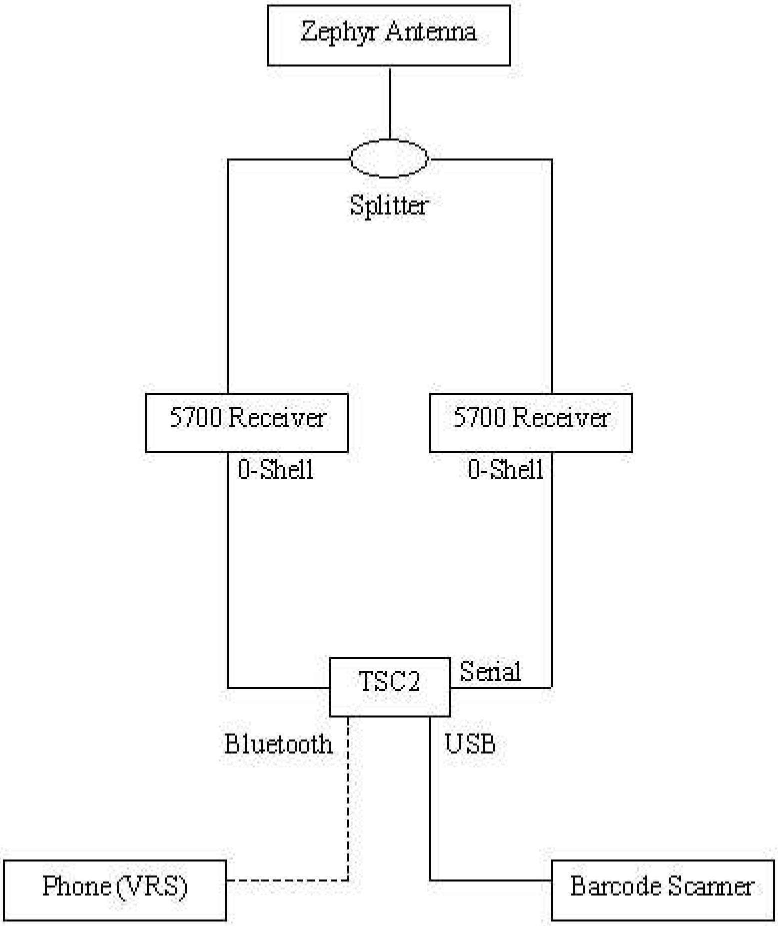

Figure 3.3 Equipment Configuration.

In addition to this equipment, a base station is required to be established for the conventional RTK GPS method. For the base station a Trimble Micro-Centred L1/L2 antenna with a groundplane will be set-up over a known mark using a tripod and a tribrach. A Trimble 4700 receiver will be connected to the antenna and also to a radio that will be set-up on another tripod nearby. An external Trimble battery will power both the Trimble 4700 receiver and the radio. A Trimble TSCe data recorder will be used to manage the base station.

3.5 Data Acquisition

The process of data collection is important because the correct data needs to be collected to provide the intended results. Before any data can be obtained it is important that the reference stakes and barcodes are established correctly such that the barcode reader can scan the barcodes. This involves placing the stakes at the optimum offset from the travel line, and a stringline is used to have the stakes positioned in a straight line. The barcodes are positioned on the stakes at the ideal height to allow consistent and reliable scans. The locations of the barcodes then need to be accurately measured using the conventional RTK method in static mode. The coordinates obtained from these measurements will act as ‘true locations’.

The measurement sequence involves the dynamic platform travelling in a straight line and at a constant speed in one direction past the reference stakes. As the dynamic platform is in motion, the data logger connected to the GPS equipment is logging data at one-second intervals. This means that a GPS measurement is obtained every second for both VRS RTK and conventional RTK methods. As the dynamic platform moves past the stakes the barcode reader scans the barcodes. When a barcode is scanned, TerraSync synchronises and combines the barcode reader information with the GPS information to provide time and position data at that specific moment. These measurements will be taken for both GPS methods simultaneously.

Several runs are required at various speeds past the stakes. When sufficient data has been recorded in one direction, the same quantity of data is required travelling past the stakes in the other direction at the same speeds. At the completion of the final run it is important to remeasure the locations of the barcodes using the static GPS survey technique. This ensures that the stakes and/or barcodes have not moved during the course of testing.

The effect of latency may cause the measured GPS positions of the barcodes on the stakes to be recorded at a different position to the true location. The method used to test the latency is similar to the tests conducted by Smith and Thomson (2003), but there are differences, such as:

- The speeds of the dynamic platform will be much slower;
- A car will be used instead of a plane; and
- A barcode scanner is used instead of a light detector.

The dynamic platform will be run in both directions and the latency of both directions will be recorded. When the vehicle is moving left to right the measured position is anticipated to be right of the true position and when the vehicle is moving right to left it is anticipated that the barcodes will be measured with a position to the left of the true position, as shown in Figure 3.4.

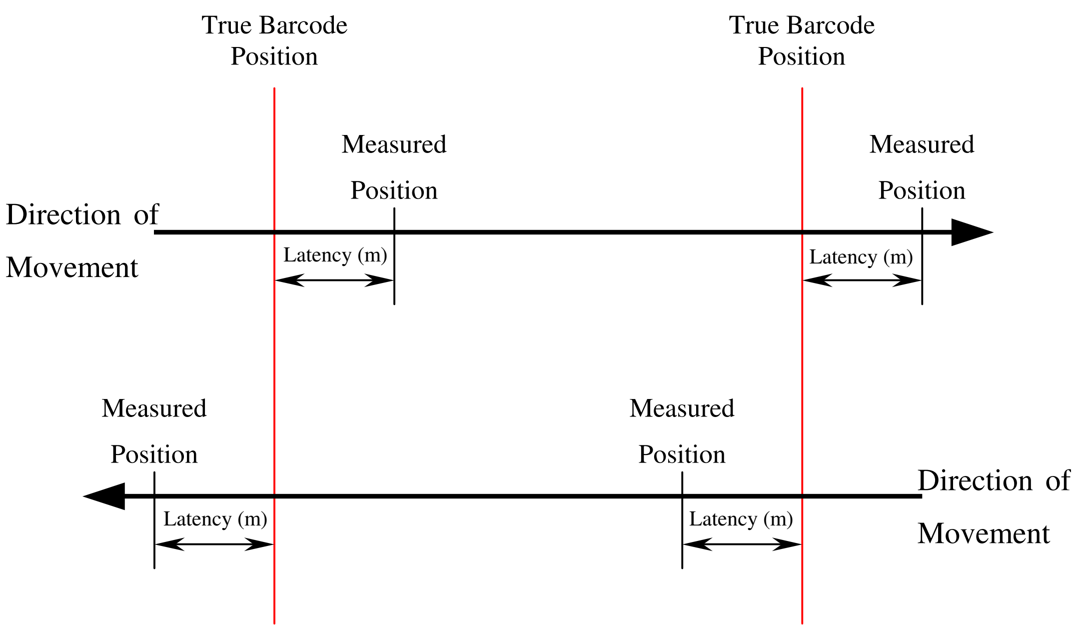

Figure 3.4 Extent of Latency.

The latency of both directions together will provide double latency as a distance, which can be divided by two to obtain the single latency as a distance. The single latency as a distance can be converted to time by applying the speed of the dynamic platform. Having the dynamic platform travel at different speeds, it is possible to see the impact that speed has on latency. The effect of latency between the conventional RTK and VRS RTK can also be compared.

3.6 Pilot Test of Method

Before conducting the actual testing it is important that a pilot test is performed to verify that the method will work as planned. The pilot test of the conventional RTK GPS equipment (without VRS) was performed at the University of Southern Queensland (USQ) campus in Toowoomba. The pilot test of the method included tests on the cricket pitch at the university and also along Baker Street in Toowoomba. The pilot tests encountered various problems that needed to be overcome before the actual testing could commence.

3.6.1 Equipment Testing and Problems

The equipment problems were encountered first with the Trimble TSC2 data recorder unable to handle two separate streams of data simultaneously. Therefore the TSC2 cannot be used because it is required that both methods obtain the data at the same time. To overcome this issue it was decided to use a laptop computer with the Trimble TerraSync software installed and a USB multi-serial port adapter to allow for the many required serial inputs. The USB multi-serial port adapter is shown in Figure 3.5.

Figure 3.5 USB multi-serial port adapter.

This new equipment configuration is shown in Figure 3.6 and needs to be tested to verify that it will work. This configuration includes a laptop to record the GPS data, however a survey controller, such as a Trimble TSCe, is still required to communicate with the VRS system because the laptop does not recognise the mobile phone as an external modem and therefore the laptop cannot connect directly to the VRS system.

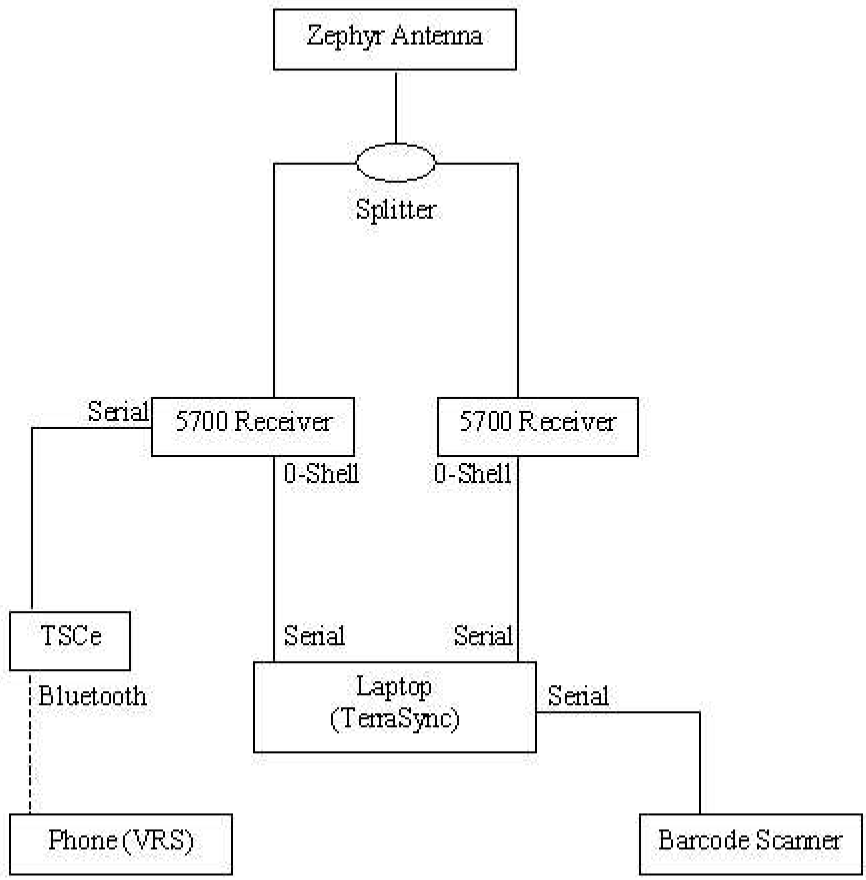

Figure 3.6 Equipment Configuration 2.

There were also problems with the second equipment configuration that is shown in Figure 3.6. The concern with this configuration was to record positions on the laptop. The 5700 receivers effectively established a connection with the laptop through TerraSync however there were often no positions shown from the GPS. Occasionally positions were achieved but this only lasted for a very short time. Because VRS isn't being used at this stage, the laptop was replaced with a data recorder and that worked well. It was assumed that the 5700 receivers did not perform well when controlled from the laptop.

To attempt to overcome the issue between the 5700 receivers and the laptop, the two 5700 receivers were replaced with two 5800 receivers. As previously mentioned, 5800 receivers have an inbuilt antenna that cannot be bypassed. This means that two 5800 receivers will also be used as the antennas, and that there will not be a common antenna for the two methods. This is not ideal, but because the accuracy and latency is being tested primarily in the direction of travel, there is no major problem if the two 5800 receiver/antennas are perpendicular to the direction of travel. The technical specifications for the Trimble 5800 receiver is included in Appendix D. This new configuration is shown in Figure 3.7.

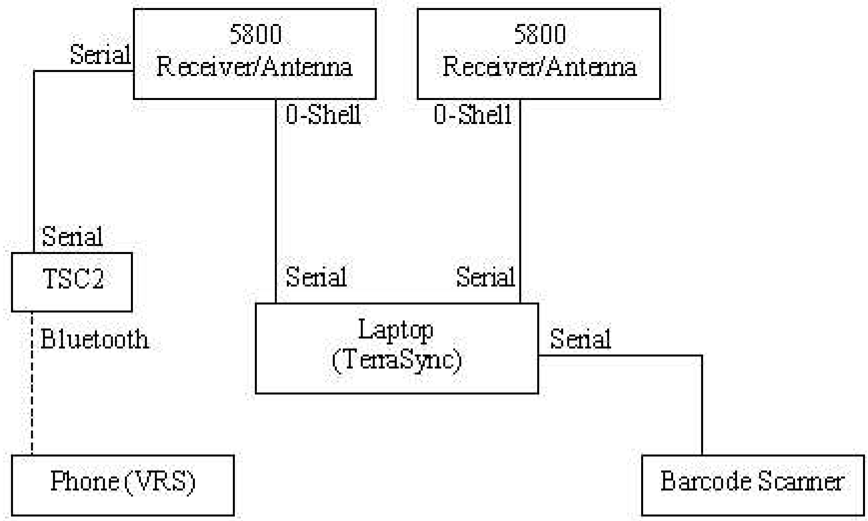

Figure 3.7 Equipment Configuration 3.

It is important to note that all of these equipment tests involved only the conventional RTK method because these tests were conducted in Toowoomba, which is outside the VRS network. The intention was to record the VRS RTK data as an external input into TerraSync. However, there was a problem in the actual testing with the VRS RTK equipment because access to the VRS RTK equipment was limited to one weekend. This limitation did not allow much time to alter the equipment configuration to get the data to be input as an external sensor. It also became apparent that it might not be possible for the barcode scanner to initiate GPS measurements for the data that is being recorded as an external input.

3.6.2 Method Testing and Problems

The testing of the method at Toowoomba using only the conventional RTK GPS method revealed problems with the dynamic platform. The initial tests using a car as the dynamic platform were performed along a cricket pitch at the USQ Toowoomba campus. The major issue with the car was trying to get the barcode reader to scan the barcodes consistently.

The main reasons why the barcodes wouldn't always scan are because:

- It was difficult to maintain a straight line and have the barcode reader the ideal distance from the barcodes.
- The frame attached to the car allowed a slight vertical movement (bounce) due mainly to the pneumatic tyres and vehicle suspension, which caused the barcode reader to fail in scanning the barcodes.
- Sun on the barcodes reduced the ability of the barcode reader to scan.

To overcome this issue a different dynamic platform was implemented into the method and cardboard sunshades are positioned above each of the barcodes. A walking trolley will now be the new dynamic platform because:

- The wheels can be adjusted so that the dynamic platform will travel consistently in a straight line.
- There is limited vertical movement (bounce) because there is no suspension on the trolley and the wheels are solid plastic (no give from tyres).
- It easily travels at slower speeds, at which the barcode reader is more reliable.

It is necessary for the walking trolley to have an attachment frame similar to the one required for the car. The attachment frame is required to position the GPS antennas at a height above the person pushing the walking trolley to allow a clear view of the satellites. The attachment frame is also needed to attach the barcode reader at the required position.

There is also a need to monitor the speed at which the walking trolley is moving because the speed needs to be relatively constant and must be the same for reverse runs in opposite directions. To observe the speed at which the walking trolley is moving a Trimble GeoXT hand-held GPS will be used. The Trimble GeoXT is shown in Figure 3.8.

Figure 3.8 Trimble GeoXT.

The railway trolley is ideally suited to the testing of accuracy, precision and latency in a dynamic environment because it can consistently repeat the travel path. The testing of the method has also shown that it is not viable to use a railway trolley for more accurate testing for this project. This is because the barcode scanner has a timeout function and the scanner turns off after four seconds. This means that the button on the scanner needs to be pressed before each barcode is passed. This would create a safety problem if the railway trolley was used and therefore a different method is required for any future testing with the railway trolley.

3.6.3 Final Validation Test

The method described in section 3.5 was followed exactly as planned to verify that the method would function correctly, now that all the equipment and dynamic platform problems had been resolved. This final test was conducted along a pathway alongside Baker Street, Toowoomba, and therefore only used the conventional RTK GPS method with ANANGA used as the base station.

Several runs were conducted in both directions to ensure that the process and equipment worked satisfactorily. More runs would be necessary for the actual data collection to gain a sufficient quantity of data. This test worked successfully with the barcode reader scanning the barcodes at every pass. It was also found that the barcode reader was only reliable for speeds up to approximately 3 km/hr.

3.7 Final Data Collection

The site chosen for the actual test is located at the USQ campus in Springfield, which is central to the VRS coverage area. The site was chosen because:

- It has a pathway that is relatively level and straight.
- It is clear of obstructions to the satellites, such as tall trees and buildings.
- It is in a quiet area with limited pedestrian use.

The data collection occurred on 16 September 2006 following the method described in section 3.5. A concrete nail was positioned on the pathway and measured using VRS RTK under static conditions. The base station for the conventional RTK method was then established over this mark. The base station is shown in Figure 3.9.

The reference frame was established with the four stakes and barcodes positioned approximately two metres apart adjacent to the pathway. A stringline was used to position these stakes in a straight line. These reference marks were then measured using conventional RTK GPS using the established base station over the concrete nail. The reference frame is shown in Figure 3.10.

Figure 3.9 Conventional RTK Base Station.

Figure 3.10 Reference Frame.

The equipment for both the conventional and VRS RTK GPS was mounted on the walking trolley. The two 5800 receiver/antennas were positioned perpendicular to the direction of travel. The straight line of the reference marks is the line of travel and this was used to effectively position the 5800 receiver/antennas. The dynamic platform is shown in Figure 3.11 with all of the equipment attached.

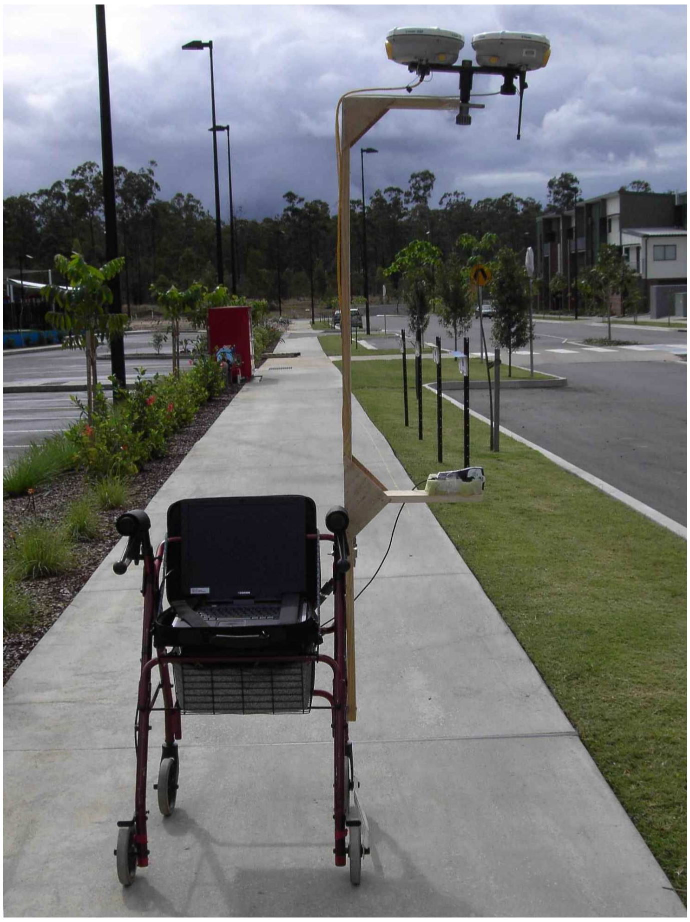

Figure 3.11 Dynamic Platform.

As explained in section 3.6.1, the initial tests didn't involve the VRS equipment and the actual testing couldn't obtain data for both methods simultaneously. The actual testing involved collecting the VRS RTK GPS measurements first and collecting the conventional RTK GPS measurements immediately after. The influencing factors for this testing are not identical for the two data sets but they are very similar. All of the site-specific influences, such as multipath, are still the same for both methods. It is only the satellite signal that is slightly different.

3.8 Conclusions: Chapter 3

This chapter has given a detailed account of the methodology that was undertaken to obtain the data to test the accuracy, precision and latency of conventional RTK and VRS RTK GPS.

The initial method did encounter several problems, particularly with the equipment configurations and the dynamic platform, and therefore had to be amended. These included the inability of the Trimble TSC2 to have two inputs of data, the incompatibility of the Trimble 5700 receivers with the laptop, and the unreliability of the barcode scanner when using the car as the dynamic platform. The final method used for this project may be useful as the basis of designing a better method for further testing of GPS measurements in a dynamic environment, this may include the use of a railway trolley for more accurate data.

The next chapter will show how the raw GPS measurements were processed to obtain the results of the accuracy, precision and effect of latency for each method. A comparison will also be made between these conventional RTK and VRS RTK GPS methods.

CHAPTER 4

DATA ANALYSIS AND RESULTS

4.1 Introduction

The raw data was collected using the field measurement plan as described in the previous chapter. This raw data needs to be analysed to produce the useful information that will show the latency, accuracy and precision for both the VRS RTK and conventional RTK methods.

This chapter aims to show how the data was analysed and to present the results that were achieved. These results will indicate whether the VRS RTK method is suited to dynamic applications.

The processes that were performed to interpret the raw data and make it into useful information will be presented. The processing of the data involves exporting the data into a database file where all of the analysis occurs. The results of the latency, accuracy and precision for both the VRS RTK and conventional RTK methods will also be presented with the support of several graphs. This chapter will also include a comparison between the two methods.

4.2 Outputting Data for Analysis

The GPS data that was recorded during the testing was saved on the laptop as a data file in the TerraSync software (refer to section 3.6). The GPS data that was recorded includes both the GPS measurements that were made at one-second intervals and also the measurements that were initiated by the barcode scanner. This data was transferred from the Terrasync program into a .SSF file format, which can be opened in the Pathfinder Office program.

The Data Transfer utility is located within the Pathfinder Office software. This function is used primarily to transfer data from an external device, such as a data recorder, onto a personal computer (PC). However, in this situation the data is already recorded on the computer and only the file format needs to be changed. The source device is ‘TerraSync on PC’ because this is where the required data is located.

The new file is opened in Pathfinder Office and the Export option in the Utilities menu is used to export the required data attributes as .DBF files that can be viewed using Microsoft Excel. The data attributes that were chosen include: the measured coordinates, the GPS time and the sensor information.

Table 4.1 Combined outputs of GPS measurements every second and sensor data.

ID	Easting	Northing	Elevation	Text	Channel	GPS Date	GPS Time	GPS Second
6	490750.877	6937799.108	51.309			16/09/2006	02:53:36pm	536030.000
7	490750.622	6937799.588	51.307			16/09/2006	02:53:37pm	536031.000
8	490750.354	6937800.055	51.311	□1	2	16/09/2006	02:53:37pm	536031.925
9	490750.332	6937800.093	51.311			16/09/2006	02:53:38pm	536032.000
10	490750.011	6937800.629	51.298			16/09/2006	02:53:39pm	536033.000
11	490749.676	6937801.185	51.287			16/09/2006	02:53:40pm	536034.000
12	490749.402	6937801.698	51.287	□2	2	16/09/2006	02:53:40pm	536034.942
13	490749.385	6937801.730	51.287			16/09/2006	02:53:41pm	536035.000
14	490749.032	6937802.342	51.280			16/09/2006	02:53:42pm	536036.000
15	490748.691	6937802.910	51.261			16/09/2006	02:53:43pm	536037.000
16	490748.415	6937803.431	51.257	□3	2	16/09/2006	02:53:43pm	536037.912
17	490748.389	6937803.481	51.257			16/09/2006	02:53:44pm	536038.000
18	490748.046	6937804.114	51.222			16/09/2006	02:53:45pm	536039.000
19	490747.677	6937804.708	51.200			16/09/2006	02:53:46pm	536040.000
20	490747.428	6937805.139	51.180	□4	2	16/09/2006	02:53:46pm	536040.754
21	490747.347	6937805.279	51.173			16/09/2006	02:53:47pm	536041.000
22	490747.159	6937805.507	51.174			16/09/2006	02:53:48pm	536042.000

There were two .DBF files that were created: one file included the measurements that were made at one-second intervals, and the other file consisted of the measurements that were initiated by the barcode scanner. These two data files are then combined and saved in Microsoft Excel for later processing. The data in this file was sorted using the point ID number. Table 4.1 shows a segment of the sorted data. It is important to note that each of the barcodes used in this test were encoded differently. The barcodes were encoded with the numbers 1 to 4 so that each barcode can be easily defined. These numbered codes are shown in the Text column of Table 4.1.

4.3 Latency

4.3.1 Latency Analysis

The first step is to determine the exact speed that the dynamic platform was travelling when each of the barcodes were scanned. This is achieved using the measurement coordinates that were recorded every second. Those measurements recorded immediately before and after the barcode is scanned are used. The formula used to determine the speed is:

$$\text{Speed} = \frac{\text{Distance}}{\text{Time}}$$

The distance between the coordinates is calculated and is used as the distance, while the time is the one-second interval. The formula used to calculate the distance between the coordinates is:

$$\text{Distance} = \sqrt{(E_1 - E_2)^2 + (N_1 - N_2)^2}$$

Where E_1 is the easting of point 1 and E_2 is the easting of point 2, N_1 is the northing of point 1 and N_2 is the northing of point 2. This calculation is performed for each barcode scan for each direction. The measurements that are made at the same speed and in the opposite directions are paired together. Only these paired measurements were used for the analysis of the latency, accuracy and precision.

The latency is then determined for each pair of measurements. This begins by calculating the distance between the coordinates for each pair of measurements, which represents the double latency as a distance. This distance is divided by two to obtain the single latency value as a distance of each pair of measurements. This is converted to time with the speed formula, using the speed the dynamic platform was travelling and the single latency as distance. The latency as a distance is described in section 2.6 and is shown in Figure 3.4. These latency values will provide a comparison between the VRS RTK and conventional RTK measurements.

4.3.2 Latency Results

The results of the latency as a distance are shown in Figure 4.1 and indicate that the distance increases as the speed increases. This occurrence is what was expected because the faster the dynamic platform travels, a larger distance is travelled before the measurement is made. There is a slight variation between the VRS RTK and the conventional RTK methods however the general effect is the same. That is, the latency distance increases with speed for both methods.

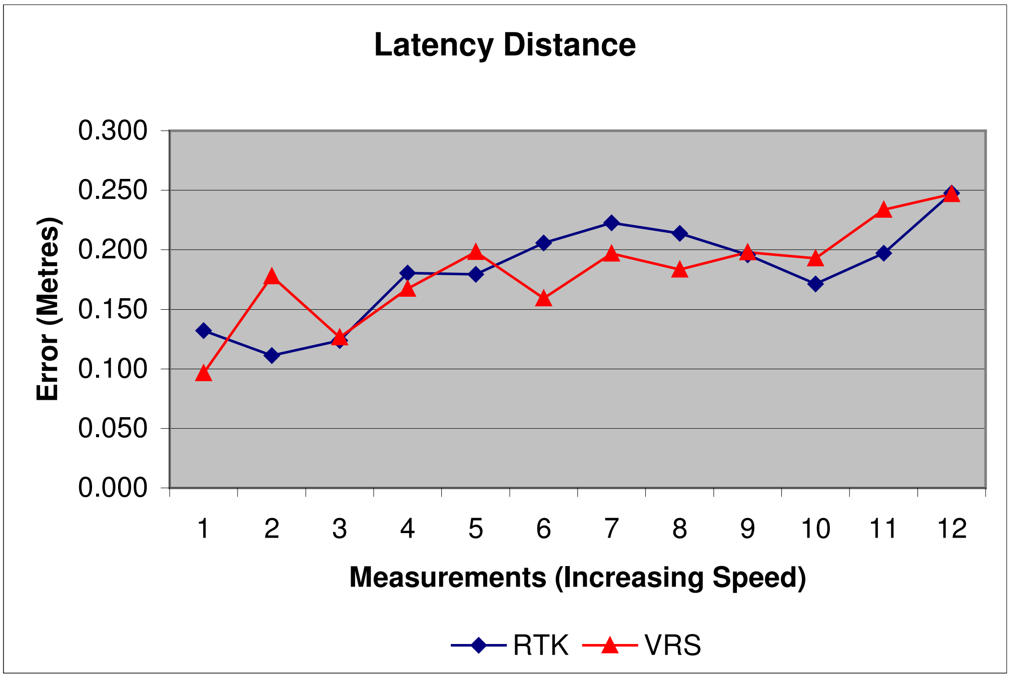

Figure 4.1 Latency as Distance.

The latency time was expected to be constant because latency is caused by the time taken for signals to travel through equipment, including wiring. Therefore each system would have its own latency. The latency as time for the two methods is reasonably constant and this is shown in Figure 4.2. The average latency time for the VRS RTK is 0.26 seconds and the average latency time for the conventional RTK is 0.25 seconds.

These results are very similar to previous testing performed by Gibbings and O'Dempsey (2005), and Inglis (2006) that were reviewed in section 2.7. Gibbings and O'Dempsey (2005) determined the effect of latency on conventional RTK to be 0.29 seconds, and Inglis (2006) also found the latency of conventional RTK to be in the range of 0.21 to 0.38 seconds at speeds from 0.5 km/h to 2.4 km/h.

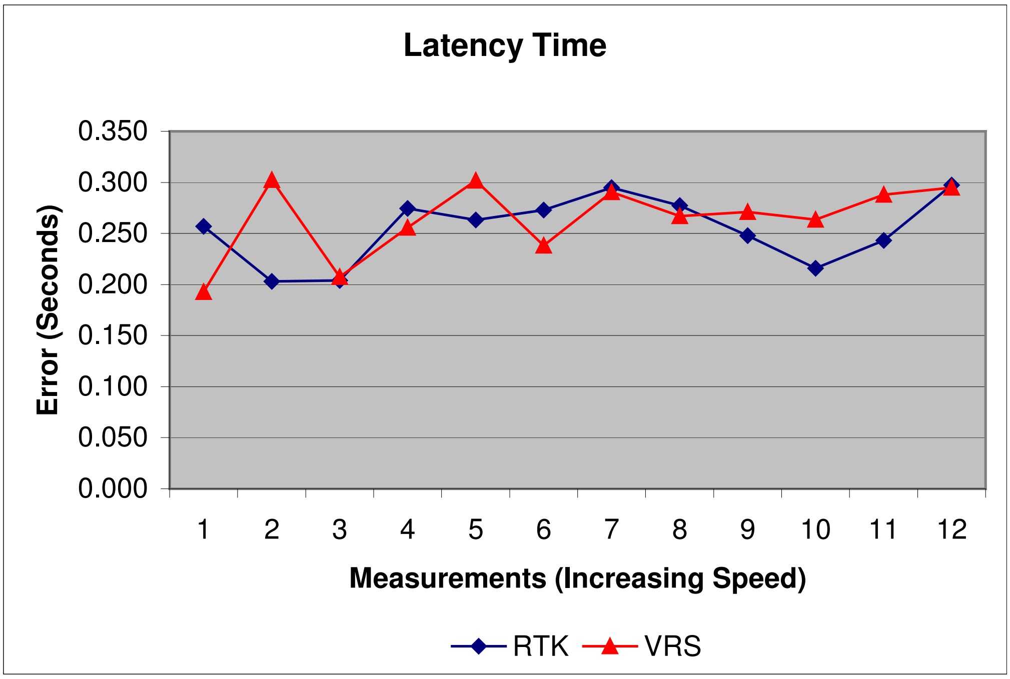

Figure 4.2 Latency as Time.

The similarity of the latency time resulting for the two methods was surprising. The corrections transmitted to the roving receiver using the VRS RTK system have to travel a greater distance and suffer from the additional processing time required for the virtual reference station corrections to be created. It was assumed that the latency of the VRS RTK system would have been much greater than the conventional RTK method, but this was not the case.

The possible reason why the VRS RTK isn't much slower was not investigated, as it wasn't within the scope of this project. The majority of the latency in the VRS RTK system would occur when the errors are determined using the error model and the approximate position of the rover. Only minimal latency would be generated in the transmission of the corrections to the rover. The differences in the operating speeds of the computer systems and software of each GPS method may be a considerable reason why the latency is so similar.

4.4 Accuracy

4.4.1 Accuracy Analysis

The accuracy of each method is determined using the raw coordinates that were measured and also with coordinates that are calculated to remove the effect of latency. This is achieved by comparing these measurements to the 'true locations' (refer to section 3.5) of the reference marks, as measured using the conventional RTK method in static mode before testing. The variation between the measured coordinates and the 'true' coordinates will provide the error that is present in each of the measurements.

To determine the accuracy of the measurements with the effect of latency removed, new coordinates are calculated to eliminate the latency from the raw coordinate measurements. These new coordinates are again compared to the measurements to the 'true locations' of the reference marks to determine the accuracy. This will show the extent of all the remaining error sources present in the measurements.

4.4.2 Accuracy Results

The accuracy results show that there is a major difference between the accuracy of the two methods. The average difference between the raw GPS measurements and the 'true positions' for the conventional RTK method is 29.809 m for direction one and 29.446 m for direction two. The average difference for the VRS RTK method is 0.204 m for direction one and -0.158 m for direction two. Figures 4.3 and 4.4 show the raw GPS measurements that were obtained in each direction. The negative values illustrate the effect of latency in the opposite directions. The adjusted measurements after latency would be positioned midway between the measurements of each direction.

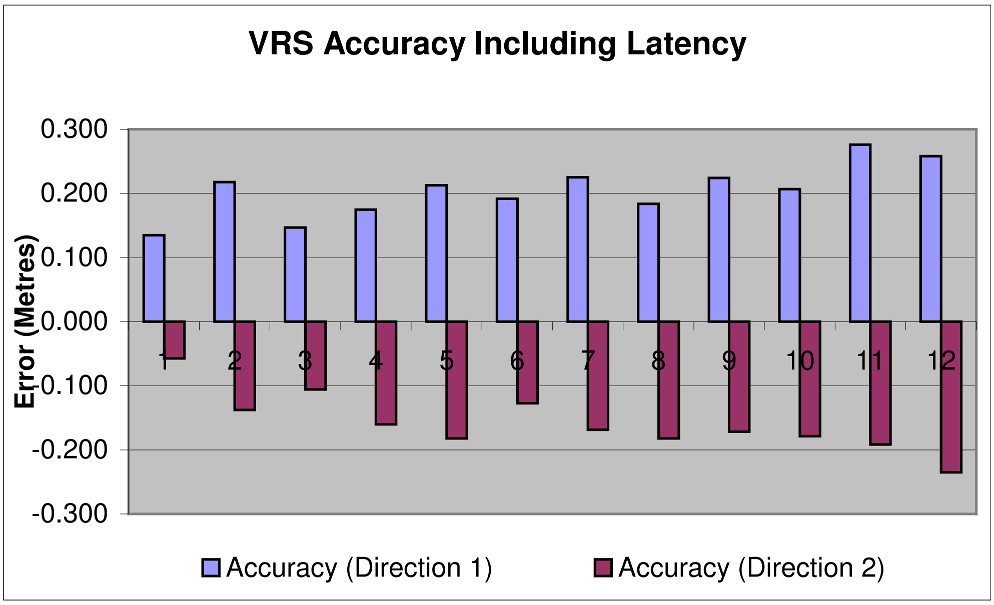

Figure 4.3 VRS RTK Accuracy Including Latency.

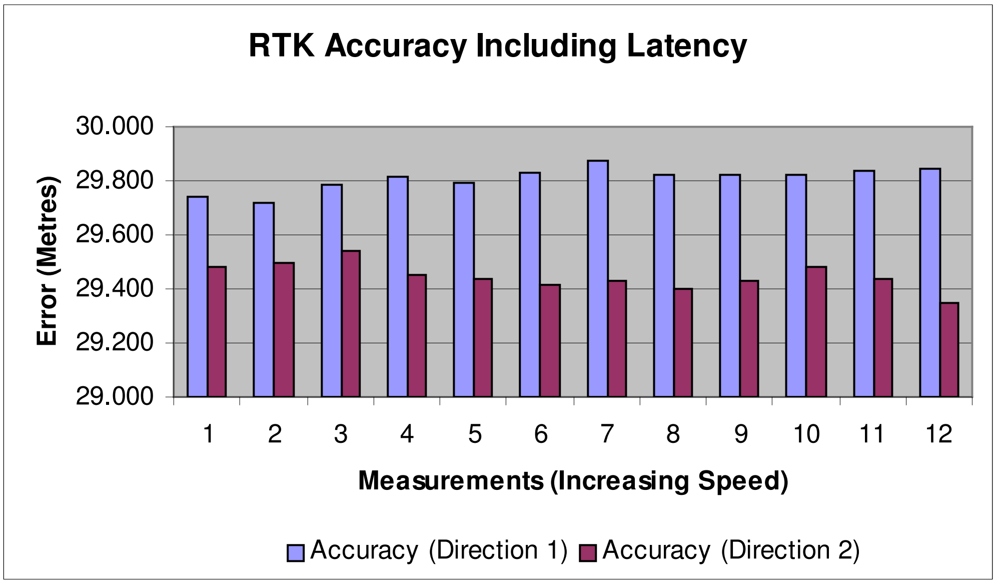

Figure 4.4 Conventional RTK Accuracy Including Latency.

The average difference between the coordinates with the effect of latency removed and the 'true positions' for the conventional RTK method is 29.628 m and for the VRS RTK method is 0.023 m. Figures 4.5 and 4.6 show the accuracy of the coordinates with the effect of latency removed. The 'true locations' of the reference marks are represented where the error is zero.

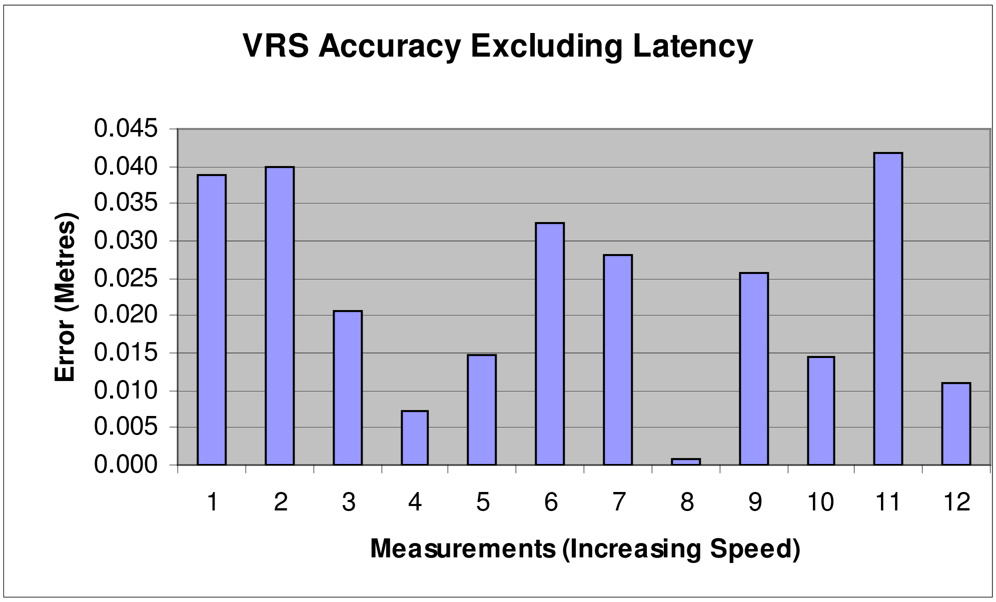

Figure 4.5 VRS RTK Accuracy Excluding Latency.

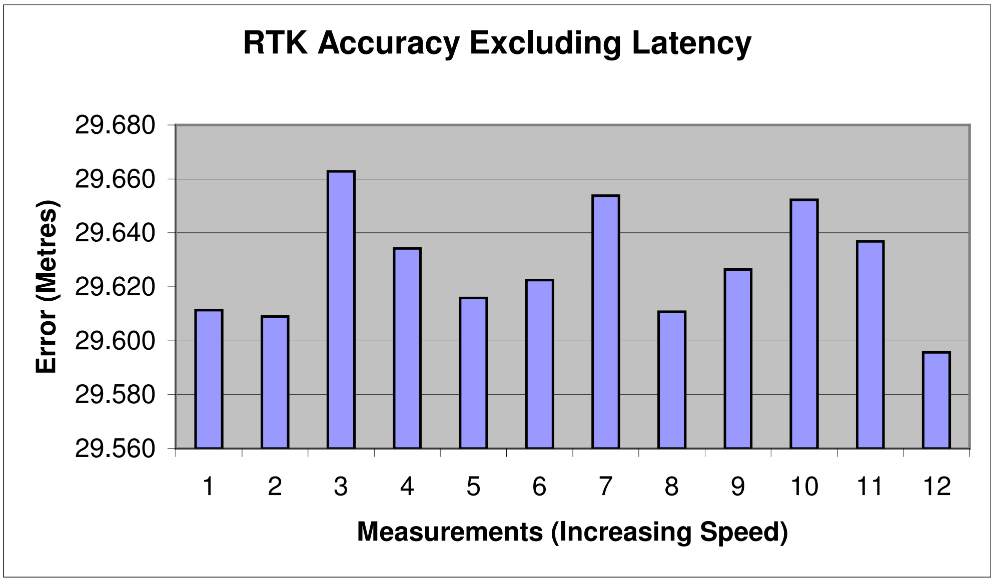

Figure 4.6 Conventional RTK Accuracy Excluding Latency.

The extent of these differences indicates that the data may be unreliable and that there may have been a problem with the testing. It was thought that the coordinates used for the conventional RTK base station were keyed incorrectly into the survey controller. This possibility was ruled out because of the measurement sequence. The static GPS measurements conducted to obtain the true locations of the reference marks was achieved using the conventional RTK method in static mode. These measurements are similar to the dynamic VRS RTK measurements but are vastly different to the dynamic conventional RTK measurements. It is still unsure what caused the problem.

The testing of the accuracy should be conducted again to try and determine what happened to cause the large offset in these measurements. However the limited availability of the VRS RTK equipment and the costs of using the VRS have prevented doing the test again for this project.

The accuracies presented in this section should not be considered as a true comparison of the two methods and are included only to show the extent of the offset difference. It is still possible to determine the latency and precision from these measurements because these results are relative (it is just the accuracy that has problems).

4.5 Precision

4.5.1 Precision Analysis

The precision is assessed using only the calculated coordinates that have had the effect of latency removed. The mean value for each barcode is determined by calculating the average of all the calculated coordinates. The variance from the mean of each of the measurements provides a measure of the range within which the measurements fell. Less precise measurements are represented by a large variance. The standard deviation for these measurements is also determined to illustrate the precision of the two methods.

4.5.2 Precision Results

The precision of the two methods is quite good with all the VRS RTK measurements being within ±28 mm of the mean and all the conventional RTK measurements being within ±27 mm of the mean, however this includes the outliers. The precision for the both methods is ±14 mm at 1σ and there are three outliers for both sets of measurements.

These precision results are very similar to previous testing performed by Higgins (2001a), and Ong and Gibbings (2005) that were reviewed in section 2.5. Higgins (2001a) found the precision of the VRS RTK to be ±14 mm at 1σ, which is the same as the results achieved for this test. Ong and Gibbings (2005) however found the precision of the VRS RTK to be different at ±10 mm at 1σ. The precision of the conventional RTK was determined by Ong and Gibbings (2005) to be ±15 mm at 1σ, which is very similar to the result achieved for this testing.

The mean position of the barcodes in Figures 4.7 and 4.8 is where the variance is zero, the purple shaded bars represent the measurements and the singular lines represent the standard deviations. These results show that both the VRS RTK method and the conventional RTK method achieve similar levels of precision.

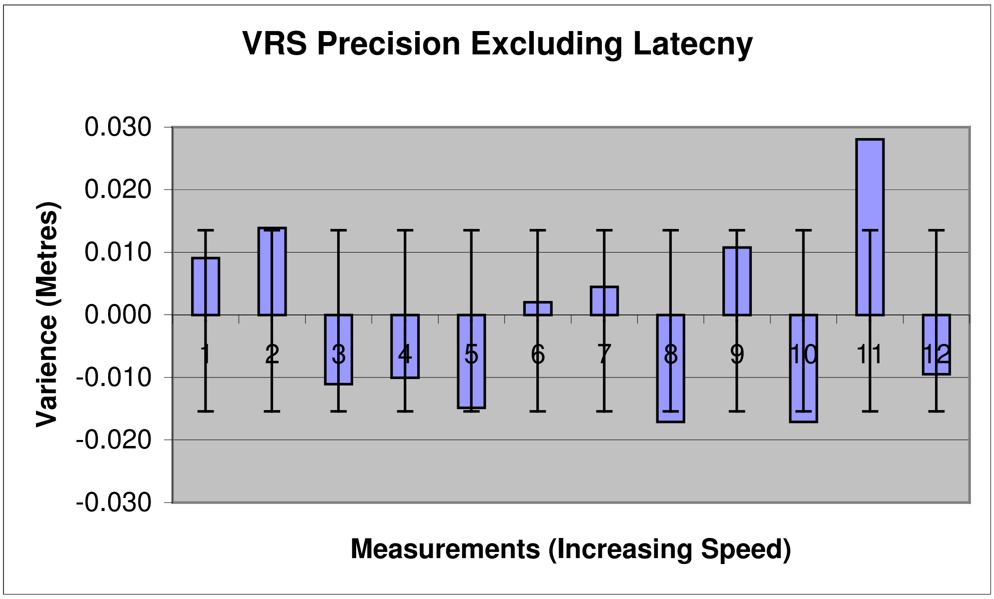

Figure 4.7 VRS RTK Precision Excluding Latency.

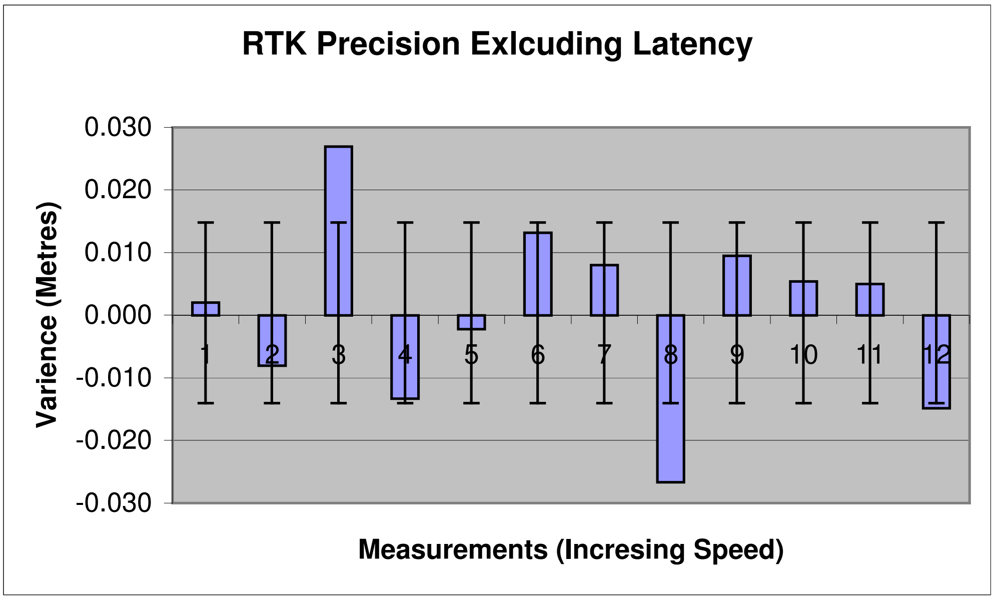

Figure 4.8 Conventional RTK Precision Excluding Latency.

4.6 Conclusions: Chapter 4

This chapter has shown how the raw data was processed and the results that were achieved. The results of the latency, accuracy and precision for both the VRS RTK and conventional RTK methods have also been presented along with a comparison between the two methods. The individual results for each measurement pair is included in Appendix E.

There was a problem in assessing the accuracy of the measurements and it was found that the data was unreliable for this purpose. The results for the precision and the latency were found to be reasonable because they are both relative values. It was unknown what caused the unreliability of the accuracy in the measurements, and further testing should be conducted.

The next chapter will include a summary of the project and the results that were achieved. Recommendations will also be provided to assist in the continuation of further work into related fields.

CHAPTER 5

CONCLUSIONS

5.1 Introduction

Chapters 3 and 4 presented the method and the data analysis processes that were involved in determining the latency, accuracy and precision of the conventional RTK and VRS RTK methods. From this information conclusions and recommendations will be made in this chapter.

The conclusions provide a summary of the current limitations of the conventional RTK GPS method and will outline the importance of testing the accuracy, precision and latency in the VRS RTK method.

There are recommendations provided to assist in any continued research that is to be undertaken in assessing the accuracy of GPS measurements in a dynamic environment.

5.2 Conclusions

The conventional RTK positioning has been capable of achieving centimetre accuracy since the mid 1990's (Wanninger 2005). As a result of this achievable accuracy, RTK positioning has been applied to precise applications such as surveying, construction and precision farming (Hu et al 2002). However, the conventional RTK positioning method has several limitations, these include:

- The need to set up a base GPS receiver and radio communications link for each period of work (Higgins 2001b).

- Radio communications are limited in range and can experience interference (Higgins 2001b).
- The distance between the base receiver and rover receiver is limited to approximately 10-20 kilometres to resolve carrier phase ambiguities to achieve centimetre accuracy (Wanninger 2005).

The VRS concept is one method that is being employed around the world to overcome some of the limitations with conventional RTK positioning. VRS is a method of transmitting network correction information to RTK roving receivers using the system, to remove any distance dependant biases that limit the range of conventional RTK. Network RTK using VRS operates at distances of many tens of kilometres and aims at achieving accuracy that is comparable to single base RTK systems at distances up to 10 kilometres (Rizos & Han 2002).

There has been an increasing amount of research into the accuracy of VRS RTK GPS measurements, but this is mostly limited to measurements made in static environments, and almost no testing in dynamic environments. The major issues with GPS measurements taken in a dynamic environment are the accuracy, precision, and the effect of latency of which there has been little research.

The testing of this project has attempted to compare the accuracy, precision and latency of conventional RTK and VRS RTK GPS measurements taken in a dynamic environment. This gives an insight into the suitability of the VRS RTK GPS system to real time dynamic applications such as machine guidance.

The accuracies determined in this test indicate that the data was unreliable for the purpose of an accuracy assessment. However it was still possible to effectively determine the latency and precision from this data because these measurements are relative. The average latency time for the VRS RTK is 0.26 seconds and the average latency time for the conventional RTK is 0.25 seconds. The precision for both methods was determined with the effect of latency removed from the measurements. The precision for the both methods is ±14 mm at 1σ, with all the VRS RTK measurements being within ±28 mm of the mean and all the conventional RTK measurements being within ±27 mm of the mean. These results show that the VRS RTK method may be suitable for real time dynamic applications such as machine guidance.

5.3 Further Research and Recommendations

As a result of this testing there are various recommendations for any further research that is to be conducted in similar fields. These include: retesting the accuracy of the VRS RTK GPS, testing the conventional RTK and VRS RTK GPS measurements simultaneously, testing the VRS RTK GPS at higher speeds, and testing the VRS RTK using different manufacturers.

There is a need to conduct further testing to assess the accuracy of the VRS RTK GPS measurements taken in a dynamic environment. This is because the data obtained during this project contained a significant offset from the 'true locations' of the barcodes. This indicated that the data was unreliable for assessing the accuracy.

It should also be attempted to obtain the conventional RTK and VRS RTK GPS measurements simultaneously. This would reduce the effect of any external influences because the external influences for the two data sets would be the same. The problem encountered in this project when attempting to record the two data sets simultaneously was recording the data as the external sensor in TerraSync. It is possible that the external sensor GPS data will record if the data is recorded as a NMEA output.

Future testing of the accuracy, precision and latency of VRS RTK GPS measurements taken in a dynamic environment is required at higher speeds. This will give a better indication of the suitability of VRS RTK to higher speed applications such as precision agriculture. It is recognised that the method used in this project is unsuitable for higher speed testing because of the limitations of the barcode scanner that scans inconsistently at speeds greater than 3 km/h. The incorporation of a different method for initiating the GPS measurements may allow testing at higher speeds and may also allow the use of a railway trolley to become a viable option as the dynamic platform.

The testing conducted in this project and all of the researched testing of the VRS network in South East Queensland has involved only Trimble GPS equipment. The main reason for this is because this VRS network uses Trimble infrastructure. It is recommended that further research be performed to analyse the accuracy, precision and latency of GPS equipment from different manufacturers using the VRS network. This will allow potential users to know if they can use their existing non-Trimble GPS equipment with the VRS network.

5.4 Summary

This chapter provided a summary of the current limitations of the conventional RTK GPS method and outlined the need to test the accuracy, precision and latency of the VRS RTK method. These precision and latency results achieved from this testing shows that the VRS RTK method might be suitable for real time dynamic applications such as machine guidance. However the data was found to be unreliable for the purpose of an accuracy assessment and should be retested.

Recommendations have been provided to assist in any continued research that is to be undertaken in assessing the accuracy of GPS measurements in a dynamic environment. These recommendations include: retesting the accuracy of the VRS RTK GPS, testing the conventional RTK and VRS RTK GPS measurements simultaneously, testing the VRS RTK GPS at higher speeds, and testing the VRS RTK using different manufacturers.

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APPENDICES

Appendix A - Project Specifications

University of Southern Queensland
Faculty of Engineering and Surveying

ENG 4111/4112 Research Project
Project Specification

FOR: Jeremy REYNOLDS

TOPIC: Accuracy Assessment of VRS in a Dynamic Environment

SUPERVISOR: Peter Gibbings

SPONSORSHIP: Faculty of Engineering and Surveying, USQ

PROJECT AIM: Assess and compare the accuracy and precision of conventional RTK and VRS-RTK GPS measurements taken in a dynamic environment.

PROGRAMME: Issue A, 16 March 2006

1. Critically analyse operations and past research on RTK GPS, use of GPS in dynamic environments and VRS networks.
2. Develop and validate a method for testing the accuracy and precision of conventional RTK and VRS RTK in a dynamic environment.
3. Design a field measurement plan and collect data simultaneously using conventional RTK and VRS RTK methods in a dynamic environment.
4. Analyse field data to assess the accuracy and precision of the different methods of surveys.
5. Evaluate the effect of latency on conventional RTK and VRS RTK.

As time permits:

6. Evaluate the effect of physical site characteristics, satellite numbers and DOPs to the accuracy and precision of the collected data.

AGREED:

______________________(Student) ______________________(Supervisor)

____/____/____ ____/____/____

Appendix B - Trimble Virtual Reference Station Specifications

(*Source:* Trimble Navigation)

FEATURES

General

• High-accuracy real-time kinematic GPS positioning
• Fixed virtual reference station network available at any time without setting up a base station
• Common control network for large areas
• Real-time atmospheric error correction
• Built-in integrity monitoring by VRS server
• Seamless package of GPS hardware, modeling and networking software, and communications interface

5700 CORS Receiver

• Tough, lightweight magnesium alloy casing
• Compact flash data storage expandable up to 128 MB
• Low power consumption
• Up to 10 hours backup receiver operation on 2 internal miniature camcorder batteries
• Dual rate logging up to rates of 10 Hz

Zephyr TM Geodetic Antenna

• 4-point antenna feed for sub-mm phase centre repeatability
• Trimble StealthTM ground plane for reduced multipath
• Superior phase center repeatability

GPSNet Software

• Communications control of remote receivers (no PC required at site)
• RINEX file creation and archiving
• Statistical analysis and integrity monitoring of reference stations
• Single base RTCM generation

DGPSNet Software

• Network modeled RTCM messages optimized for networks with reference station spacing of 70–300 km, and L1 C/A roving receivers

RTKNet Software

• Full network modeling of ionospheric, tropospheric and ephemeris errors
• VRProcessor provides network modeled RTK messages to roving receivers

SYSTEM COMPONENTS

5700 CORS Receiver

GPS measurements: Advanced Maxwell 4 custom survey GPS chip
High precision multiple correlator L1 and L2 pseudorange measurements
Unfiltered, unsmoothed pseudorange measurements data for low noise, low multipath error, low time domain correlation and high dynamic response
Very low noise L1 and L2 carrier phase measurements with <1mm precision in a 1 Hz bandwidth
L1 and L2 Signal-to-Noise ratios reported in dB-Hz
Proven Trimble low elevation tracking technology
24 Channels L1 C/A code, L1/L2 full cycle carrier
WAAS/EGNOS tracking
Casing: Tough, lightweight fully sealed magnesium alloy
Waterproof: IPX7 for submersion to depth of 1 m
Shock: Will survive a 1 m drop onto concrete; shock and vibration tested to 40 G random
Weight: With internal batteries, battery charger 2.9 lbs (1.3 kg)
Power: DC input 10.5 to 28 V with over voltage protection
Power consumption: 2.5 Watts
Power output: 10.5 V–20 V (Port 1), 10.0 V–27.5 V (Port 3)
Certification: Class B Part 15 FCC certification and CE Mark approved
Operating temperature: –40oC to +65oC (–40oF to +149oF)
Storage temperature: –40oC to +80oC (–40oF to +176oF)
Humidity: 100%, condensing, passes testing per MIL-STD 810F, FIG. 514.5C-17
Communications and data storage:
CompactFlash—advanced lightweight and compact removable data storage. Options of 64 MB and 128 MB from Trimble
Dual position and data logging at rates of 1, 2, 5, and 10 Hz
Continuous logging support
Update firmware remotely over a modem line
Support for modem initialization
Logging and streaming of meteorological data

Zephyr Geodetic Antenna

Tracking characteristics: 4-point antenna feed for sub-mm phase center repeatability
Integral Low Noise Amplifier
50 dB antenna gain
Superior low elevation tracking performance
Trimble Stealth ground plane for reduced multipath
Phase center repeatability <0.5 mm horizontal
Dimensions: 34.3 cm (13.5") diameter x 7.6 cm (3") max depth
Weight: 1.0 kg (2.2 lbs)
Operating temperature: –40oC to +70oC (–40oF to +158oF)
Humidity: 100% humidity proof, fully sealed
Shock: MIL-810-F Figure 514 5c-17 vibration levels on each axis
Shock tested to MIL-810-F Table 516.5-I to survive a 2 m (6.56 ft) drop
Shock tested for a drop of 2 m (6.56 ft) onto concrete

GPSNet Software

Sensor compatibility: Interfaces to Trimble's 5700, 4700, MS750, and 4000 receivers
Interfaces to most third party receivers
Data integrity monitoring: Gross error detection
Provides detection and correction of cycle slips
RAIM monitoring
Watchdog timer for reliable operation
User definable alarms via e-mail / SMS
Logging capability: Capacity to log multiple RINEX files at different rates to local or LAN drives
FTP capability: FTP mirror functionality for ease of publishing data
IGS compatibility: Ability to use IGS Ultra Rapid Orbits
Single base positioning: Single point RTCM or CMR RTK messages from the nearest base station
Reporting capability: XML reports for easy web publishing

DGPSNet Software

Error modeling: Modelling of atmospheric and orbital biases, reduction of mutipath by network solution, optimized for differential positioning networks
Accuracy: Allows differential positioning with sub 0.5 m accuracy using single frequency receivers
Message types: RTCM 1,2,3, and 9

RTKNet Software

Error modeling:	VRProcessor models systematic RTK errors (ionospheric, tropospheric, and ephemeris)
Accuracy:	Network corrected RTCM generator for fast initalization and centimeter level accuracy anywhere in the network
Postprocessing data:	RINEX files for postprocessing

MINIMUM SOFTWARE REQUIREMENTS

Reference station requirements:

Geodetic quality dual frequency receiver
Terminal adapter or modem for ISDN or PTSN or terminal server for TCP/IP communications

Central server requirements:

PC with 1.7 GHz or faster processor with 512 MB RAM, a 40 GB hard drive, and a parallel port
SVGA color monitor 800 x 600
Multiple serial interface or Ethernet router
Keyboard with mouse or trackball
CD-ROM drive
Microsoft Windows 2000, or
Windows NT 4.0
Access server or modem bank

Mobile user requirements:

GPS Receiver that accepts RTCM v2.1, 2.2, or CMR
Cellular or CDPD modem

Appendix C - Microvision Flic Barcode Scanner Specifications

(*Source:* Microvision)

Bar Codes Supported	UPC/EAN/JAN, Code 128, Code 39
Minimum X Dimension	10 mil
Depth of Field	2 inches to 7 inches
Memory Capacity	Approximately 500 12-character codes
Interface	RS-232 compatible; Baud Rate: 4800 or 9600; Data Bits: 8; Parity: None; Stop Bits: 2; Flow Control: None
Cable	DB9 to Stereo plug
LED Indicator	Indicates “Good Scan”, “Memory Full”, and blinks while downloading
Audible Indicator	Indicates “Good Scan”, “Memory Full”, and “Download complete” Can be disabled
Operating Temperature	0° to 35°C
Storage Temperature	-40° to 70°
Power	Three (3) AAA Alkaline Batteries
Safety	EN60950-1:2002; IEC60825-1:1993 +A1(1997) +A2 (2001)
EMC	EN55022: 1998; EN55024: 1998; EN61000-4-2: 1995; EN61000-4-3: 1997 FCC 47 CFR, Part 15 Class B

Appendix D - Trimble 5800 GPS Receiver Specifications

(*Source:* Trimble Navigation)

Performance specifications

Measurements

• Advanced Trimble Maxwell Custom Survey GPS Chip
• High precision multiple correlator for L1 and L2 pseudorange measurements
• Unfiltered, unsmoothed pseudorange measurements data for low noise, low multipath error, low time domain correlation and high dynamic response
• Very low noise L1 and L2 carrier phase measurements with <1 mm precision in a 1 Hz bandwidth
• L1 and L2 Signal-to-Noise ratios reported in dB-Hz
• Proven Trimble low elevation tracking technology
• 24 Channels L1 C/A Code, L1/L2 Full Cycle Carrier, WAAS/EGNOS support

Code differential GPS positioning[1]

Horizontal . . . .±0.25 m +1 ppm RMS
Vertical . . . .±0.50 m +1 ppm RMS
WAAS differential positioning accuracy[2] . .Typically <5 m 3DRMS

Static and FastStatic GPS surveying[1]

Horizontal . . . . ±5 mm +0.5 ppm RMS
Vertical . . . . ±5 mm +1 ppm RMS

Kinematic surveying[1]

Horizontal . . . . ±10 mm +1 ppm RMS
Vertical . . . . ±20 mm +1 ppm RMS
Initialization time . .Single/Multi-base minimum 10 sec +0.5 times baseline length in km, up to 30 km
Initialization reliability[3] . . . . .Typically >99.9%

HARDWARE

Physical

Dimensions (WxH) . 19 cm (7.5 in) × 10 cm (3.9 in), including connectors
Weight . . .. 1.31 kg (2.89 lb) with internal battery, internal radio, standard UHF antenna. 3.67 kg (8.09 lb) entire RTK rover including batteries, range pole, ACU controller and bracket

Temperature[4]
Operating . . . .–40 °C to +65 °C (–40 °F to +14°F)
Storage . . . . 40 °C to +75 °C (–40 °F to +167 °F)
Humidity . . . . 100%, condensing
Water/dustproof . . . . . .IP67 Dustproof, protected from temporary immersion to depth of 1 m (3.28 ft)
Shock and vibration . . .. Tested and meets the following environmental standards:
Shock . Non-operating: Designed to survive a 2 m (6.6 ft) pole drop onto concrete. Operating: to 40 G, 10 msec, sawtooth
Vibration MIL-STD-810F, FIG.514.5C-1

Electrical

• Power 11 to 28 V DC external power input with over-voltage protection on Port 1 (7-pin Lemo)
• Rechargeable, removable 7.4 V, 2.0 Ah Lithium-Ion battery in internal battery compartment. Power consumption is <2.5 W, in RTK mode with internal radio.
• Operating times on internal battery: 450 MHz or 900 MHz receive only 5.5 hours, varies with temperature
• Certification Class B Part 15, 22, 24 FCC certification, Canadian FCC, CE Mark approval, and C-tick approval

Communications and Data Storage

• 3-wire serial (7-pin Lemo) on Port 1. Full RS-232 serial on Port 2 (Dsub 9 pin)
• Fully Integrated, fully sealed internal 450 MHz receiver
• Fully Integrated, fully sealed internal 900 MHz receiver
• Fully integrated, fully sealed 2.4 GHz communications port (Bluetooth)[5]
• External GSM, Cellphone and CDPD modem support for RTK and VRS operations
• Data storage on 2 MB internal memory: 55 hours of raw observables based on recording data from 6 satellites at 15 second intervals
• Data storage on controller with 128 MB memory: Over 3400 hours of raw observables based on recording data from 6 satellites at 15 second intervals
• 1 Hz, 2 Hz, 5 Hz, and 10 Hz positioning
• CMRII, CMR+, RTCM 2.1, RTCM 2.3, RTCM 3.0 Input and Output
• 14 NMEA outputs, GSOF and RT17 outputs
• Supports BINEX and smoothed carrier

1 Accuracy and reliability may be subject to anomalies such as multipath, obstructions, satellite geometry, and atmospheric conditions. Always follow recommended survey *practices.*
2 Depends on WAAS/eGNOS system performance.
3 May be affected by atmospheric conditions, signal multipath, and satellite geometry. Initialization reliability is continuously monitored to ensure highest quality.
4 Receiver will operate normally to –40 °C, Bluetooth module and internal batteries are rated to –20 °C.
5 Bluetooth type approvals are country specific. Contact your local Trimble Authorized distribution Partner for more information.

Appendix E - Data Tables

Table AE.1 VRS RTK Data

Barcode	Speed (km/hr)	Measured Easting	True Easting	Measured Northing	True Northing
1	2.1	490750.354	490750.716	6937800.055	6937800.014
	2.1	490750.542	490750.716	6937799.753	6937800.014
1	2.4	490750.355	490750.716	6937800.064	6937800.014
	2.4	490750.557	490750.716	6937799.726	6937800.014
1	2.6	490750.374	490750.716	6937800.054	6937800.014
	2.6	490750.578	490750.716	6937799.727	6937800.014
2	2.4	490749.388	490749.723	6937801.718	6937801.711
	2.4	490749.562	490749.723	6937801.432	6937801.711
2	2.5	490749.372	490749.723	6937801.719	6937801.711
	2.5	490749.579	490749.723	6937801.416	6937801.711
2	2.9	490749.346	490749.723	6937801.810	6937801.711
	2.9	490749.597	490749.723	6937801.416	6937801.711
3	2.4	490748.415	490748.752	6937803.431	6937803.381
	2.4	490748.642	490748.752	6937803.106	6937803.381
3	2.6	490748.410	490748.752	6937803.441	6937803.381
	2.6	490748.599	490748.752	6937803.093	6937803.381
3	3.0	490748.394	490748.752	6937803.471	6937803.381
	3.0	490748.629	490748.752	6937803.037	6937803.381
4	1.8	490747.458	490747.750	6937805.091	6937805.105
	1.8	490747.567	490747.750	6937804.932	6937805.105
4	2.2	490747.448	490747.750	6937805.099	6937805.105
	2.2	490747.581	490747.750	6937804.884	6937805.105
4	2.4	490747.428	490747.750	6937805.139	6937805.105
	2.4	490747.599	490747.750	6937804.870	6937805.105

Table AE.2 Conventional RTK Data

Barcode	Speed (km/hr)	Measured Easting	True Easting	Measured Northing	True Northing
1	2.3	490709.832	490750.716	6937810.701	6937800.014
	2.3	490710.007	490750.716	6937810.385	6937800.014
1	2.7	490709.801	490750.716	6937810.754	6937800.014
	2.7	490710.032	490750.716	6937810.373	6937800.014
1	2.8	490709.837	490750.716	6937810.713	6937800.014
	2.8	490709.993	490750.716	6937810.408	6937800.014
2	1.9	490708.893	490749.723	6937812.345	6937801.711
	1.9	490708.997	490749.723	6937812.102	6937801.711
2	2.7	490708.845	490749.723	6937812.417	6937801.711
	2.7	490709.044	490749.723	6937812.057	6937801.711
2	3.0	490708.842	490749.723	6937812.432	6937801.711
	3.0	490709.062	490749.723	6937811.988	6937801.711
3	2.2	490707.912	490748.752	6937814.060	6937803.381
	2.2	490708.020	490748.752	6937813.837	6937803.381
3	2.8	490707.885	490748.752	6937814.089	6937803.381
	2.8	490708.079	490748.752	6937813.708	6937803.381
3	2.9	490707.883	490748.752	6937814.098	6937803.381
	2.9	490708.077	490748.752	6937813.755	6937803.381
4	2.0	490706.949	490747.750	6937815.731	6937805.105
	2.0	490707.058	490747.750	6937815.537	6937805.105
4	2.4	490706.916	490747.750	6937815.798	6937805.105
	2.4	490707.082	490747.750	6937815.480	6937805.105
4	2.8	490706.897	490747.750	6937815.818	6937805.105
	2.8	490707.096	490747.750	6937815.481	6937805.105

Table AE.3 Conventional RTK Results

Barcode	Speed (km/hr)	Latency Distance (m)	Latency Time (sec)	Accuracy (with Latency) Direction 1	Accuracy (with Latency) Direction 2	Accuracy (without Latency)	Precision (without Latency)
1	2.3			29.81501			
	2.3	0.18061	0.27441		29.45388	29.63419	-0.01334
1	2.7			29.87641			
	2.7	0.22278	0.29477		29.43093	29.65385	0.00800
1	2.8			29.82286			
	2.8	0.17129	0.21595		29.48080	29.65226	0.00539
2	1.9			29.74204			
	1.9	0.13216	0.25688		29.47971	29.61130	0.00200
2	2.7			29.82841			
	2.7	0.20567	0.27307		29.41717	29.62254	0.01315
2	3.0			29.84287			
	3.0	0.24776	0.29731		29.34849	29.59569	-0.01487
3	2.2			29.78596			
	2.2	0.12389	0.20400		29.53889	29.66286	0.02693
3	2.8			29.82460			
	2.8	0.21378	0.27732		29.39858	29.61073	-0.02668
3	2.9			29.83338			
	2.9	0.19703	0.24309		29.43935	29.63680	0.00500
4	2.0			29.72053			
	2.0	0.11126	0.20310		29.49802	29.60902	-0.00806
4	2.4			29.79503			
	2.4	0.17936	0.26317		29.43670	29.61586	-0.00224
4	2.8			29.82187			
	2.8	0.19569	0.24799		29.43052	29.62638	0.00949
Average		**0.18177**	**0.25426**	**29.80908**	**29.44609**	**29.62762**	

Table AE.4 VRS RTK Results

Barcode	Speed (km/hr)	Latency Distance (m)	Latency Time (sec)	Accuracy (with Latency) Direction 1	Direction 2	Accuracy (without Latency)	Precision (without Latency)
1	2.1			0.21765			
	2.1	0.17787	0.30226		-0.13793	0.03986	0.01389
1	2.4			0.22493			
	2.4	0.19688	0.29034		-0.16881	0.02806	0.00447
1	2.6			0.20672			
	2.6	0.19271	0.26354		-0.17851	0.01454	-0.01709
2	2.4			0.17468			
	2.4	0.16739	0.25581		-0.16002	0.00733	-0.01005
2	2.5			0.18360			
	2.5	0.18348	0.26709		-0.18241	0.00078	-0.01712
2	2.9			0.27591			
	2.9	0.23358	0.28781		-0.19147	0.04167	0.02807
3	2.4			0.21285			
	2.4	0.19822	0.30173		-0.18224	0.01462	-0.01487
3	2.6			0.22400			
	2.6	0.19801	0.27091		-0.17183	0.02584	0.01077
3	3.0			0.25798			
	3.0	0.24677	0.29474		-0.23532	0.01108	-0.00949
4	1.8			0.13490			
	1.8	0.09639	0.19283		-0.05736	0.03895	0.00906
4	2.2			0.14684			
	2.2	0.12641	0.20729		-0.10588	0.02066	-0.01105
4	2.4			0.19147			
	2.4	0.15938	0.23812		-0.12704	0.03240	0.00200
Average		**0.18142**	**0.26437**	**0.20429**	**-0.15824**	**0.02298**	