Development of a GPS-reference-station network in Singapore with network-solution capabilities

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Development of a GPS-Reference-Station Network in Singapore with Network-Solution Capabilities

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in fulfilment of the requirement for the degree of
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This thesis is dedicated to my late father, who taught me that one should contribute back to society when he has the ability. He has been my source of inspiration.

Summary

High precision GPS positioning in rapid-static (or fast-static) and real-time kinematic (RTK) modes are now increasingly being used for many surveying and navigation applications. The use of a multiple-reference-station infrastructure with network-solution capability has proven to be able to enhance the reliability and effectiveness of rapid static and RTK survey.

Conventionally, the RTK survey using differential GPS carrier-phase corrections is available only on a single-reference-station mode (single-base solution). GPS reference station infrastructure implemented supports only single-base solution techniques. This single-reference-station correction framework lacks data redundancy and must be located within 10 km of the user. Also, the RTK approach has inherent operational limitations in achieving optimum performance. It requires a minimum of 5 satellites to implement reliable and fast On-The-Fly (OTF) computation, which is the cornerstone for RTK to provide a quick and accurate ambiguity resolution. The post-processed static GPS survey technique, on the other hand, is not cost-effective as it often requires long observation time (an hour or more). These constraints severely limit the use of GPS for critical surveying and navigation applications where the accuracy and reliability of the results cannot be compromised.

Nowadays, the multiple-reference-station infrastructure that supports network-solution has been promoted strongly by research groups and several GPS manufacturers for extending the operational limits of RTK positioning. The network-solution is applicable for both RTK and rapid-static techniques. In RTK, it is widely known as the “network-RTK”. The reference-station network typically surrounds the coverage area so as to generate differential corrections for the roving use GPS receivers. Real-time corrections derived from multiple reference stations provide for data redundancy. They can also significantly improve data reliability and positioning accuracy.

In view of the limitations in the static and RTK methods, a “rapid-static” approach using the multiple-reference-station network is introduced. The post-

processed Virtual Reference Station (VRS) concept was adopted to generate observations for baseline computation. The user is provided with the data of a virtual reference station, as if observed by a nearby actual reference station. In practice, this approach is simple and cost effective as there is no additional requirement on the processing power of the user equipment.

The aim of this research project is to develop, implement and test an operational multiple-GPS-reference-station network, linked to a central server by high-speed data links, in Singapore. Algorithms and software are developed to enable high precision positioning in both real-time and post-processed modes using optimised corrections derived from the network of GPS reference stations. The real-time system was implemented by transmitting carrier-phase corrections on an on-demand basis via Virtual Reference Station (VRS) concept to GPS rover receivers for RTK through a wireless data link from the central server. The system also supports static GPS survey by allowing users to download the GPS data through the FTP (File Transfer Protocol) server.

The idea of creating a grid-based network of virtual reference stations in Singapore to support rapid-static surveys for establishing survey control points is introduced. This would be an additional service on top of the regular services of static and RTK provided by network-based multiple-reference-station system. Test results show that centimetre positioning accuracy is possible using the grid-based virtual reference station network.

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List of Acronyms

AFN	Australian Fiducial Network
AR	Ambiguity Resolution
C/A code	Coarse/Acquisition code
CBD	Central Business District
CDGPS	Carrier-Phase Differential GPS
CDPD	Cellular Digital Packet Data
CMR	Compact Measurement Record
CORS	Continuously Operating Reference Station
COTS	Commercial-off-the-shelf
CPU	Central Processing Unit
DAB	Digital Audio Broadcast
DGPS	Differential GPS
DoD	Department of Defense
DOP	Dilution of Precision
FTP	File Transfer Protocol
GB-VRSN	Grid-Based Virtual Reference Station Network
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communications
GUI	Graphical User Interface
HTML	Hyper Text Mark-up Language
IGS	International GNSS Service
ION	Institute of Navigation
ISN	Integrated Survey Network
LADGPS	Local Area Differential GPS
LAN	Local Area Network
LBS	Location Based Services
LTA	Land Transport Authority
MPA	Maritime and Port Authority

MRS	Multiple Reference Station
NMEA	National Marine Electronics Association
NSTB	National Science and Technology Board
NTU	Nanyang Technological University
OTF	On-the-fly
PDA	Personal Digital Assistant
PPS	Precise Positioning Service
PRN	Pseudo-Random Noise
RDBMS	Relational Database Management System
RINEX	Receiver INdependent EXchange
RS-MRC	Rapid-static – Multiple Reference Correction
RS-VRS	Rapid-static – Virtual Reference Station
RTCM	Radio Technical Commission for Maritime Service
RTK	Real-Time Kinematic
SA	Selective Availability
SIMRSN	Singapore Integrated Multiple Reference Station Network
SiReNT	Singapore Satellite Positioning Reference Network
SMS	Short Message Service
SPP	Single Point Positioning
SPS	Standard Positioning Service
SQL	Structural Query Language
SRS	Single Reference Station
TCP/IP	Transmission Control Protocol/Internet Protocol
TGO	Trimble Geomatic Office
TTF	Time-to-fix
UNSW	University of New South Wales
UPS	Uninterrupted Power System
US	United States
USCG	United States Coast Guard
VHF	Very High Frequency
VRS	Virtual Reference Station
WADGPS	Wide Area Differential GPS
WGS84	World Geodetic System 1984

Chapter 1

Introduction

1.1 Overview

Reliable means of navigation have been sought ever since man started travelling long distances. Various methods have been established since the early days to observe the stars, planets and the moon in order to determine a person's location for navigation. From the late 1970s, constellations of man-made navigation satellites have taken over as beacons to guide the way. The Global Positioning System (GPS), which was commissioned in 1978 by the US Department of Defense (DoD), is the most widely utilised satellite navigation system today.

GPS is regarded by most governments as a utility and a public information service to improve productivity, increase safety, increase security and protect the environment. GPS surveying techniques have completely replaced older technologies such as the Doppler system and the long-range Electronic Distance Meter (EDM) in geodetic surveying (Rizos, 1997). The United States (US) GPS Industry Council has quoted figures for worldwide GPS equipment sales of around US\$6 billion in 1999, rising to US\$16.5 billion for 2003. The diverse uses of GPS technology all over the world have prompted many to research techniques that push the limit of positioning accuracy and applications. Many unknown applications of GPS are still waiting to be discovered.

High precision GPS positioning in rapid-static (or fast-static) and real-time kinematic (RTK) mode are increasingly being used for many surveying and precise navigation applications. Realising the potential and advantages of high precision

GPS positioning, the Agency for Science, Technology and Research (A*STAR) (formerly known as the National Science and Technology Board, NSTB) of Singapore funded an R&D project in 1999, entitled “Development of an integrated multiple base station infrastructure to support concurrent high precision differential GPS positioning applications”. One of the objectives of the project was to promote the use of GPS for surveying in Singapore. This research was carried out as part of that project.

This chapter outlines the background to the GPS system, discusses the evolution of GPS positioning techniques, and sets the ground for further discussion of new techniques in utilising the technology, and its applications. The objectives, motivation, challenges and contributions of this research are also stated.

1.2 Evolution of GPS Positioning Techniques

GPS positioning using one autonomous GPS receiver is known as Single Point Positioning (SPP). This is the most basic usage of GPS for positioning and navigation. This kind of positioning makes use of code measurements to obtain pseudo-ranges (or distances) to satellites by measuring the time difference between the broadcast and the receive times of a pseudo-random code. With the degradation of GPS system through Selective Availability (SA) turned off since 2 May 2000, the achievable positional accuracy is between 6 to 11 metres. This technique of SPP is widely used in recreational navigation like hiking, boat sailing, hunting, etc.

The accuracy of SPP is far too low for surveying purposes. The relative positioning technique was introduced to improve the accuracy. This technique is known as Differential GPS (DGPS). It involves the use of two receivers, one stationary at a reference station (or base), and the other (usually called “remote” or “rover”) roving or simply located at a new station in the vicinity of the reference station. The accuracy of DGPS can be as high as at the sub-metre level. Currently, there are agencies and companies that operate reference stations that are able to generate real-time DGPS corrections, e.g. the United States Coast Guard and the Maritime and Port Authority (MPA) of Singapore. These corrections can be

transmitted to a rover via a radio communication link or geostationary communication satellites.

Differential GPS can employ code measurements or phase measurements. Distance measurements by phase rely upon the accumulation of the phases of the carrier signal. Phase measurements are inherently ambiguous. They need to be “resolved” before high precision positioning can be achieved. The technique of resolving the ambiguity is known as “Ambiguity Resolution” or simply AR. The first application of the processing of carrier phase data was developed in the early 1980s, and led to the introduction of the technique of “GPS Surveying”. This technique has the following characteristics:

- ❑ stationary observation at a point for a period of time (known as an “observation session”);
- ❑ relative positioning mode (two GPS receivers are observing simultaneously);
- ❑ data processing after the observation session (known as post-processing);
- ❑ L-band carrier wave measurements.

Since then, this technique has been used extensively to establish geodetic control. This static surveying technique is considered as having low productivity, but relatively high costs.

In order to reduce the station occupation time, the “stop and go” technique was proposed. Besides that, with improvement in the AR method, another positioning technique called “rapid-static” was developed. All these developments were aimed to improve the productivity and reliability of GPS carrier-phase-based positioning.

Over the past ten years, several major developments have occurred which have led to the progressive improvement of sophisticated positioning technique. This technique enables real-time performance of kinematic positioning. This type of positioning is considered one of the most difficult engineering challenges for GPS system developers. The algorithm used is referred as “on-the-fly” or OTF. Off-the-shelf, these systems are called “real-time kinematic” or RTK systems. This

development has enabled GPS usage for time-critical applications such as machine control, automated container and port operations, to mention just a few.

The RTK system represents the “state-of-the-art” in GPS technology. Although it is able to deliver centimetre-level accuracy in real-time, there are several conditions that must be fulfilled. One of them is dealing with the “loss-of-lock” problem. The integer ambiguities determined at the beginning of a survey would be valid for the whole period that GPS is used. However, the GPS satellite signals at times could be blocked when the GPS antenna passes under a tree, is used in an “urban canyon” environment or under a bridge. The ambiguity values will be “lost” and must be re-determined. This process of “re-initialisation” can take from several tens of seconds up to a few minutes. During this period of time, centimetre accuracy is not possible. Another significant characteristic of carrier-phase-based positioning is that the longer the baseline, the longer the observation time needed to resolve the ambiguities. Hence for short observation times (a few minutes), the baseline length (i.e. distance between reference receiver and rover receiver) is typically restricted to less than 10 – 15 km.

At the University of New South Wales (UNSW), Australia, several revolutionary developments have occurred that appear to have overcome some of the shortcomings (constraints) for carrier-phase-based kinematic GPS positioning:-

- ❑ Under certain conditions, decimetre-level positioning accuracy has been possible even when the baseline lengths are of the order of a few tens of kilometre (Han and Rizos, 1997)
- ❑ Reliable OTF-AR in the shortest period of time possible, even with just one measurement epoch, has been demonstrated (Han, 1997). Re-initialisation of cycle slips can be done instantaneously. This technique is known as Instantaneous OTF (IOTF).

The UNSW’s IOTF algorithm promises centimetre-level accuracy for real-time kinematic positioning on a continuous basis. However, this IOTF technique has short baseline length constraints. The multiple-reference-station technique was introduced to mitigate the effect of satellite orbit bias, ionospheric and tropospheric

delay and observation noise. This technique is able to extend the baseline length up to 100 km.

Figure 1-1: GPS positioning accuracies (Rizos, 1997)

Figure 1-1 illustrates the positioning accuracies associated with the different GPS positioning modes. All of the GPS positioning techniques were developed based on these basic positioning modes. The techniques were introduced to increase productivity by reducing observation time and increasing accuracy by measuring carrier phase and making use of relative positioning.

Permanent GPS reference stations are increasingly being established all over the world for various Differential GPS applications both in GPS navigation and GPS surveying (Rizos, 2002). These active permanent GPS reference stations

support both real-time and post-processing applications. Some of the GPS reference stations are connected in a network approach to achieve the highest standard of accuracy and reliability.

The carrier-phase-based multiple-reference-station algorithm has become very popular due to the achievable benefits. Implementing the algorithm in real-time and incorporating the RTK mode are known as the Network-RTK technique. It is the ultimate technique for positioning and is especially significant for surveying because of the short observation time and high accuracy. Many permanent reference stations network around the world are being upgraded to Network-RTK capability (Rizos *et al.*, 2003). It is predicted that the Network-RTK technique will become a common technique.

1.3 Motivation

In the University of New South Wales, Han & Rizos (1995) has proposed a multiple-reference-station algorithm which is able to improve the RTK survey technique. The algorithm was not implemented anywhere during the initial period of this project in 1999. Although many university investigators have been researching the fundamental challenges in functional and stochastic modelling, at the time this project was initiated there was only one commercially available RTK product based on a multiple-reference-station network in the market - the Trimble VRS system. Today, there are several commercial systems available. Many of these software are still used in pilot studies by various service providers in different countries.

National geodetic infrastructure has moved from a reliance on a network of ground control marks to a network of permanent GPS reference stations. The Singapore Land Authority, which has the responsibility to maintain the geodetic infrastructure in the country, has a strong interest in the implementation of permanent GPS reference stations.

1.3.1 Limitations of Conventional RTK Technique

A clear advantage of GPS techniques over conventional surveying and positioning methods is that it does not require inter-visibility between two control stations. But the carrier-phase-based GPS technique requires long hours of observation in order to achieve high accuracy. Phase measurements on the GPS signal are inherently ambiguous. The analysis of GPS phase data is therefore relatively complex. It was only with the development of sophisticated ambiguity resolution (AR) algorithms that it was possible to reduce the length of time required (from hours of observations to several tens of seconds). Only with resolved ambiguities can centimetre-level baseline accuracies be achieved. Commercial-off-the-shelf (COTS) GPS systems of today can achieve centimetre accuracy results with less than a minute of data for AR, even in kinematic mode (real-time kinematic). GPS technology is still not fully utilised by surveyors and other engineering professionals. Two unsolved “constraints” are:

- (a) High cost for top-of-the-line, dual-frequency GPS receivers;
- (b) Restriction on the baseline length, typically less than 10-15 km. It is even less if one is located in low latitude regions.

It is the objective of this research to address these constraints by introducing multiple-reference-station-network approach. Furthermore, many positioning systems in geodesy, surveying and precise navigation are relying on permanent GPS reference station data. Some systems are intended to support real-time applications such as the generation of corrections for Differential GPS or the monitoring of atmospheric parameters. Others are intended primarily for the recording of tracking data (which is then analysed "off-line"). Increasingly, permanent GPS stations are organised into networks that are intended to support several applications, some real-time and some requiring very fast data sampling.

1.3.2 Modern Cadastre System using GPS Technology

The old cadastral survey system in Singapore commenced around 1930. The system (known as the Cassini-Soldner System) used the method of “running survey” by which new surveys are propagated based on information of a “proven” reference line as the datum. The test for acceptance of datum used is by a comparison of the “original” distances and bearings of lines with the newly surveyed values. Over time, the datum for cadastral survey becomes inhomogeneous due to propagation of errors. The cadastral survey results were documented as “bearings and distances” measured. The direct measurements of “bearings and distances” were adopted as legal description of a land parcel. This method of documentation was mathematically weak and prone to conflict. It also caused a fundamental problem as the computed coordinates will never be unique. This is a major obstacle to automation.

These two primary problems have prompted the Singapore Land Authority (SLA) (formerly known as the Survey Department) to embark on a series of projects to modernise the cadastral survey system in Singapore. One of the main projects is to encourage the use of GPS for geodetic control of all surveying applications in Singapore. Subsequently, a new cadastre system based on the coordinated cadastre and geodetic control points was introduced. It is known as the SVY21 system. The new system incorporates the uses of GPS as the tool for data collection and supports automation of Singapore’s cadastre system.

Under the SVY21 system, the geodetic control network which is known as the Integrated Survey Network (ISN) is used as the survey control framework for all cadastral surveys. The SLA has taken over 4 years to establish approximately 4000 ISN marks on the ground for use by surveyors. Figure 1-2 shows the ISN distribution. Figure 1-3 shows a typical ISN mark.

However, the geodetic framework of the ISN suffers high attrition due to rapid development. Many of the ISN marks were destroyed or damaged. This has prompted the Authority to consider using an active control network of permanent GPS reference stations as the primary survey control framework. Nevertheless, the conventional high precision GPS system based on carrier-phase measurement has

limitation over long distances. Hence, a multiple-reference-station system is desired for Singapore specifically for the cadastral survey application. This permanent GPS-reference-station network will also serve as the national geodetic infrastructure for other surveying applications in Singapore.

Figure 1-2: Integrated Survey Network (ISN) array

Figure 1-3: ISN mark installation on ground

1.4 Research Objectives and Scope of Work

Conventionally, the single-base RTK positioning has limitation of baseline length. Carrier-phase-based multiple-reference-station algorithm was introduced to overcome this limitation. Hypothetically, the multiple-reference-station method is also able to improve the RTK positioning performance. Field tests carried out by other investigators were done in experimental environment and most of them were at mid-latitude locations. Hence, this research project has the following specific aims:

- (a) To investigate the feasibility of an operational real-time carrier-phase-based multiple-GPS-reference-station-network system for Singapore.
- (b) To examine and analyse the performance of the multiple-GPS-reference-station network both in real-time and post-processing modes for different GPS survey techniques.
- (c) To investigate the performance of using rapid-static method with virtual reference station technique in a grid-layout to support the cadastral survey system in Singapore.

The main objective of this research project is to investigate the feasibility of an operational real-time carrier-phase-based multiple-GPS-reference-station-network system in Singapore based on the algorithm proposed by Han & Rizos (1995). This algorithm will be implemented in a real-time environment in Singapore which is located near to the equator (low latitude region) and is affected by high ionospheric delay error. To be able to demonstrate and achieve the objectives, a multiple-GPS-reference-station-network infrastructure is designed, set up and implemented. This infrastructure with its system is novel and innovative as it involves multiple GPS receivers and antennas connected in a network configuration utilising state-of-the-art internet and wireless communication technology. A control centre was developed which include the implementation of a database system for the storage and management of raw GPS data to accommodate various GPS

research needs. The multiple-reference-station infrastructure will serve as the modern geodetic infrastructure for the purpose of providing the survey control facility and the reference frame for the management of spatial data in Singapore.

The second aim of the project involves field tests to examine and analyse the performance of the multiple-GPS-reference-station network both in real-time and post-processing modes for different GPS survey techniques. The field tests are conducted at various locations of Singapore to demonstrate the feasibility of the system. The performance parameter of RTK survey such as the time taken to fix the carrier-phase ambiguity (known as the time-to-fix, TTF) and positioning accuracy are investigated. The field tests also include comparisons with conventional methods.

The third aim of the project is to investigate the feasibility and performance of using rapid-static GPS survey method with a grid-layout virtual reference station technique. This novel process is introduced to support the cadastral survey application in Singapore. Various tests are carried out to establish the feasibility and performance of the proposed method. They include tests on different duration of observation and performance comparison with conventional method.

1.5 Contributions of the Research

The project started in 1999 and has been executed over 4 years. When the project commenced it was innovative and new. Over the years since, a few commercial systems have been developed that have achieved all the functionality of the system developed.

The project establishes an operational system that is designed and adapted from the multiple-reference-station algorithm proposed by Han and Rizos (1995). Little has been reported on the distribution of the network correction to real-time users. This is an integral part of GPS network-RTK positioning and it must be adequately addressed before practical realization of a Network-RTK system. The issues related the generation of Network-RTK correction data and the adaptation of

the Network-RTK correction data for the usage of conventional RTK users have not been resolved by Han and Rizos (1995).

The system has the following attributes which are novel and distinct from other systems.

- (a) The implementation of a Control Centre to manage GPS data;
- (b) the implementation of a database using SQL for GPS data archive;
- (c) the transmission of DGPS correction to the rover users via IP (the Internet); and
- (d) the implementation of multiple-reference-station algorithm using the conventional RTK correction format enabling existing RTK user to use the system.

The contributions of this research project can be summarised as follows:

- (a) The research project has led to the establishment of a GPS-reference-station network with network solution capability, which serves as the main component of Singapore's geodetic infrastructure. This infrastructure is the zero-level survey control infrastructure for all kinds of surveying and mapping applications.
- (b) The GPS-reference-station infrastructure was incorporated as the reference frame for the new cadastral survey system (SVY21) implemented by the Singapore Land Authority. It has become a major component in the cadastre system of Singapore. The infrastructure is significant as the SVY21 system is based on the concept of a coordinated cadastre.
- (c) The infrastructure can serve as an "open air" laboratory for more high precision GPS-related research. It is especially important as Singapore is situated in the equatorial region (low latitude). The testing of new GPS surveying techniques will be made possible using this infrastructure.

- (d) The infrastructure is also a test-bed for the implementation of a novel multiple-reference-station-network algorithm that supports network solution both in RTK and rapid-static techniques. The reference station network, developed based on open standards and formats, will allow many other applications to take advantage of the infrastructure, for examples, structural monitoring and navigation applications. The example referred to in this research is for cadastral surveying.

1.6 Challenges

The main challenge of this research project is how to implement the network solution using carrier-phase measurements for real-time operations for high precision positioning. The two challenges highlighted here are firstly, the setting up of the GPS-reference-station network is a networking challenge to transmit the GPS data back to a central server and; secondly, the data and corrections dissemination process, especially for real-time applications. The challenges are elaborated in the following sections.

1.6.1 The GPS Multiple-Reference-Station Network

The main component of the proposed system is the reference stations network with communication links and a central server/processor. The implementation of the communication network is an IT challenge.

The system must function automatically, continuously and reliably. The raw GPS data is transmitted instantaneously from the receivers at each reference station location to the central server via high speed leased lines. Once the data is transferred to the central server, several processing steps are carried out. The data will be archived in a particular format, or the data will be processed immediately and correction messages sent to appropriately equipped users. Alternatively, the data is made available to other processes at the central server, each of which runs a dedicated program, e.g. to handle real-time requests via the Internet.

1.6.2 Supporting Real-time GPS Positioning over the Internet

One of the challenges in supporting a real-time DGPS system is in the selection of the data communication link for the transmission of the differential data. A variety of technical, economical and administrative aspects need to be considered. The mode of operation, whether it is simplex or duplex, is an important factor in deciding on the communication link. Data latency is also a challenge for many real-time applications. The data latency is normally caused by the data transmission and the data processing.

The Internet is becoming the primary data communication link option for “corrections” dissemination. (Rizos & Han, 2003). This research project will look into two aspects of the correction data dissemination, both in real-time and post-processing. The GPRS technology using mobile communication via the Internet will be used as the communication link for the real-time applications, while the Internet itself will be used to support the post-processing applications.

1.7 Outline of the Thesis

This thesis consists of seven chapters. The contents of each chapter are briefly outlined as follows:

This chapter introduces the project and provides an overview of the GPS positioning techniques so as to set the background for the research. The motivation, the challenges, the objectives and the contributions are also discussed.

Chapter 2 reviews related research work, provides some fundamental background on GPS observables and measurements. It introduces the Differential GPS technique, which is the underlying technique for high precision positioning. The chapter also describes the multiple-reference-station-network or network-based RTK techniques and its development.

Chapter 3 describes the multiple-reference-station-network processing algorithms, which served as the fundamental algorithms in this research work. The basic functional model for the network is presented. The correction-generation functions are also described in the chapter.

In Chapter 4, the implementation of the Singapore multiple-GPS-reference-station-network is described. Details of the infrastructure implementation, design, software and hardware considerations, and problems faced are also presented.

Chapter 5 deals with the real-time kinematic (RTK) survey using the Singapore GPS multiple-reference-station-network. Various field tests were carried out, and the results and analyses are presented.

In Chapter 6, the rapid-static post-processing method using the GPS multiple-reference-station-network is discussed. A new method of rapid-static survey using the virtual reference station concept is proposed and the results of various tests are presented.

Chapter 7 summarises the project and the investigations, draws conclusions from the research and makes recommendations. The chapter also highlights the benefits of the multiple-reference-station-network, especially for Singapore.

The attached appendices contain detailed information about the GPS reference station network and its various components.

Chapter 2

Literature Review

2.1 Overview

This chapter provides the background information for the implementation of a multiple-reference-station-network using the carrier-phase-based GPS positioning technique. The primary goal of this research is to demonstrate the technical feasibility of setting up a real-time multiple-reference-station network DGPS system in Singapore.

The Differential GPS (DGPS) technique is the principle approach used in all high precision positioning and surveying. A discussion on this topic is given in this chapter. It includes: DGPS systems and services available today; their accuracy and limitations; different modes of DGPS; carrier-phase-based DGPS, its data processing techniques; etc. The multiple-reference-station-network approach is elaborated and research projects of a similar nature undertaken by other researchers are also discussed. The reviews concentrate on carrier-phase-based algorithms.

GPS principles and the theoretical bases of GPS signals, GPS observables, GPS error sources and GPS surveying can be found in Wells *et al.* (1986), Leick (1995), Hofmann-Wellenhof *et al.* (1992) and Rizos (1997).

2.2 Differential GPS (DGPS)

Differential GPS (DGPS) is a technique that significantly improves the accuracy and integrity of the GPS system (Parkinson *et al.*, 1995). The most common version of DGPS is illustrated in Figure 2-1. It uses a pair of GPS receivers that observe simultaneously (preferably tracking the same satellites on both receivers) at two locations. The measurement errors common to both receivers can be mitigated and hence the obtainable positioning accuracy will be higher. A typical DGPS system uses a single reference station to derive range “corrections” for each satellite in view.

Figure 2-1: Differential GPS setup

The DGPS technique can be employed in either one of two modes - the post-processing or the real-time mode. The post-processing mode is simpler. It involves collection of GPS data simultaneously at two locations as described above, and no communication devices are needed. The GPS observations collected from the two

locations will be processed to compute a set of parameters known as the “baseline” between the two locations. One of the receiver locations is referred to as the reference station (with known coordinates) and the other one is referred to as the rover station. The more complex mode of DGPS is real-time DGPS. The corrections are broadcasted to the roving user equipped with an appropriate communications device. Further discussion of the communication options for the distribution of DGPS corrections is given below.

Differential GPS techniques can be classified according to

- ❑ type of GPS measurement, e.g. code or carrier-phase,
- ❑ post-processed or real-time, and
- ❑ static or kinematic.

The classification of the DGPS techniques and some of their characteristics are given in Table 2-1.

Table 2-1: Classification of DGPS techniques

Measurement Type	Real-time or Post-processing	System Type	Accuracy	Coverage Area
Code	Post-processing	Post-processed DGPS, post-processed LADGPS or post-processed WADGPS	from < 1 m to ~10 m	From several 10 km to several 1000 km
Code	Real-time	DGPS, LADGPS or WADGPS	from < 1 m to ~10 m	From several 10 km to several 1000 km
Carrier-phase	Post-processing	Kinematic, rapid-static or static	from < 1 cm to several cm	From several km to several 1000 km
Carrier-phase	Real-time	Real-time kinematic	from < 1 cm to several cm	From several km to several 10 km

Code differential techniques use the GPS pseudo-range measurement, which is obtained by locking onto the pseudo-random code for a given satellite and measuring the time difference between transmit and receive time, in order to determine the satellite range. The code measurement is an absolute range

measurement, which provides a value of the true range between the satellite and the receiver, after removal of clock errors and other error sources. It is relatively easy to implement differential GPS for code measurements, because it is an absolute measurement of distance.

Carrier-phase-based differential techniques rely upon a measurement of the accumulated phase of the GPS carrier signal. It is not an absolute distance measurement, because the number of carrier-cycles at the start of the accumulation period (known as the phase ambiguity) is not known. Due primarily to the different wavelengths of the code and carrier-phase measurements (about 290 m for C/A code and 0.2 m for carrier-phase), carrier-phase measurements are much more precise. However, to use carrier-phase measurements for positioning, the integer values of the phase ambiguities must be first determined. This process is known as the “Ambiguity Resolution”.

The objective of this research project is to implement a real-time DGPS service, utilising the phase measurement (carrier-phase-based differential GPS), which yields high accuracy.

2.2.1 Permanent GPS Reference Stations

The basic requirement of the DGPS techniques is a reference station. It is the location where the coordinates are accurately determined. Hence, to practice DGPS for high accuracy positioning, one needs two GPS receivers, and operate two survey parties for each job. This is both time consuming and incurs high cost. Today, many organisations - both private and public - are setting up GPS reference stations at permanent locations. These GPS receivers operate “24/7” and the data are systematically archived. The GPS data are collected at a centralised system to be distributed to GPS users. There will also be a data dissemination system for DGPS users. Some even provide real-time access to the corrections to enable real-time high accuracy positioning. These facilities and infrastructures are collectively known as “Permanent GPS Reference Stations”. Some may refer to these facilities as the “Continuously Operating Reference Stations” or CORS in short. The CORS are also known as “active GPS reference stations network”. On the other hand, the

“passive GPS reference station network” is referred to simply as the control network surveyed using GPS technology.

Permanent GPS reference stations are being increasingly established all over the world. These permanent reference stations are developed in a network environment and operate continuously. They are mainly used to support two categories of applications - the geodetic and the differential GPS (DGPS) applications (Rizos, 2002). Besides that, the data sets are also used in other scientific research such as atmospheric, meteorology, and climatologic studies. Geodetic research includes determination of earth rotation parameters, monitoring of crustal motion, and computation of the International Terrestrial Reference Frame (ITRF, a global reference datum system).

For many years, networks of GPS reference stations were used for the determination of crustal motion on a variety of spatial scales. On a global scale, the International GPS Service (IGS- now known as the International GNSS Service) network was developed especially for crustal motion research. In Europe, the EUREF (European Reference Frame) Permanent Network has 30 participating countries. It has the function similar to the IGS but on a continental scale (Refer to <http://www.epncb.oma.be/>). Networks have also been established to study local ground deformation due to tectonic faulting. Two examples of such networks are the Southern California Integrated GPS Network (SCIGN), and the Geographical Survey Institute's (GSI) network in Japan. Refer to their web sites for more information (SCIGN, 2000; GSI, 2000).

The CORS are being used extensively for DGPS applications, either in “real-time” or “post-processing” mode. These services may span many hundreds of kilometres and are able to achieve accuracies of the order of a few metres using the code measurements. The DGPS corrections to pseudo-range data are determined at groups of permanent GPS stations, which may service continental or oceanic regions. The corrections are transmitted to users via a variety of communication links, including geostationary communication satellites. This technique is known as Wide Area DGPS (WADGPS). One example of such service is the Fugro's OmniStar DGPS service, which delivers an accuracy of a few metres.

A GPS reference station network can be categorised in terms of its spatial scale. The IGS network is a Continuously Operating Reference Station network that operates on a global scale. It comprises of a few hundred of CORS. These CORS operate independently, managed by various land and geodesy agencies. GPS data are uploaded to one or more data centres on a daily basis, and made available via the Internet to GPS users. On a continental scale, there is the Australian Fiducial Network (AFN), which comprises less than ten GPS receivers. The distances between stations are over one thousand kilometres. Such networks also collect and archive carrier phase data on a daily basis.

The National Geodetic Survey (NGS) operates and manages about 190 CORS sites in United States (US) (Snay, 2000). The agency collects, processes, and distributes data from the CORS to support high accuracy 3-dimensional positioning activities throughout the United States. This NGS CORS network meets post-processing requirements of positioning and meteorological users, among others, by providing (GPS) code and carrier-phase observational data.

Presently, there is great interest in employing a regional reference network to perform precise positioning using GPS carrier-phase measurements. As already mentioned, this is the focus of this research project.

2.2.2 DGPS Data Link / Communication Options

Real-time DGPS positioning requires the reception of code and carrier-phase correction data. Observations or observation corrections from a single reference station are transmitted for single base DGPS. In the case of network-based DGPS the observations of several reference stations are pre-processed at a central computing facility, and network corrections are then made available to the user.

Presently, a few common modes of communication are used to transmit the correction. Hence, DGPS services can be categorised based on the transmission mode used as follow:

- ❑ radio beacon DGPS
- ❑ satellite DGPS

- ❑ FM sub-carrier DGPS
- ❑ Cellular Digital Packet Data (CDPD)
- ❑ Internet

The radio beacon DGPS system is very reliable, high quality, has high availability and is of low cost. It is the most widely used DGPS method. In total, there are over 160 stations operational worldwide, with over 140 sites proposed to come online within the next two years (CSI, 1999). In United States, the US Coast Guard (USCG) and the Army Corps of Engineers operate a network of beacon stations that service the entire length of both the east and the west coasts and the Great Lakes area. The advantages of using the beacon DGPS include:

- ❑ free access to DGPS correction;
- ❑ long-range signal which travels over the horizon;
- ❑ high quality differential correction which are monitored for integrity; and
- ❑ relatively inexpensive user equipment.

The second technique utilises communication satellites for the transmission of the correction terms. Although this method has worldwide coverage, it is expensive and less reliable due to interference with ground-based microwave transmission. Two systems that use this technique are StarFire by NavCom (StarFire, 2007) and Omnistar by Fugro (Omnistar, 2007).

FM sub-carriers are another method for transmitting differential corrections. This technique has short broadcasting range and suffers similar propagation problems experienced by conventional FM radios.

The CDPD technique has become more popular as the cost of cellular communication has become cheaper. This method is unique because it allows two-way communication between the user and the reference station.

In recent years the transfer of real-time data over Internet Protocol (IP) capable communication channels has gained importance.

2.3 DGPS Systems and Services

Currently, there are many agencies and authorities around the world that operate GPS reference stations that provide DGPS services to GPS users. Figure 2-2 shows the DGPS service coverage worldwide. The concentrations are along busy maritime routes near coastal areas. Each of the reference stations has a coverage of approximately 200km. These reference stations generally broadcast the corrections in the Radio Technical Commission for Maritime Services, Special Committee 104 (RTCM-SC104) format, which is widely accepted by the GPS industry and can be interpreted by all commercial GPS receivers that are differential-ready. Typically, code differential techniques are used and an accuracy of 1 to 5 metres is achieved. These services have been widely used in marine navigation. Other applications such as mapping and land navigation, which requires less accuracy, also make use of the systems.

Figure 2-2: Global DGPS corrections coverage (adapted from Fugawi, 2001)

The major DGPS systems generally available today are broadly categorised as follow:

- ❑ Local Area Differential GPS (LADGPS) - The system uses a single reference station to derive pseudo-range corrections. Ground-based beacon transmitters are used to broadcast DGPS corrections in the Radio Technical Commission for Maritime Service (RTCM) format. Beacons typically have a broadcasting range of 100 to 200km and the real-time DGPS accuracy is in the range of one to ten metres.
- ❑ Wide Area Differential GPS (WADGPS) – This system uses a number of reference stations (a few ten to hundreds) to derive vector corrections for each satellite. The algorithms used are able to account for the spatial de-correlation of GPS errors over longer distances (a few thousand kilometres). The corrections are typically supplied in real time by way of a geostationary communications satellite or through a network of ground-based transmitters. It supported real-time accuracy in the range of one to ten metres.
- ❑ Carrier-Phase Differential GPS (CDGPS) – This technique uses carrier-phase observations for high precision positioning (cm-level), and therefore involves an “ambiguity resolution” procedure. In kinematic mode, this technique is known as Real-Time Kinematic (RTK).

2.3.1 Existing DGPS Services in Singapore

In Singapore, two DGPS services are in operation essentially for maritime navigation and national security. However, some GPS users are using the services for GIS mapping and vehicle navigation.

The Maritime and Port Authority of Singapore (MPA) has set up facilities to broadcast differential GPS (DGPS) signals in 1997. The system provides the DGPS broadcast service to enhance navigational safety in the Singapore Straits, its approaches and the port waters. The service is free-of-charge to the shipping community, and to the public using appropriate equipment. The DGPS corrections

from the MPA are broadcasted in the Medium Frequency (MF) band at 298kHz frequency, at a transmission speed of about 100bps. The message format is RTCM SC-104 Version 2.0. The types of broadcast messages include Type 9-3, Type 16, Type 3, Type 5 and Type 7. It has a coverage range of about 200km and a positioning accuracy of ± 5 m to sub-metre, depending on the type of receivers used. The DGPS signal can also be received inland of Singapore, hence offering some benefits to land-based GPS users. Figure 2-3 shows the MPA's DGPS reference station located on one of the southern islands of Singapore.

The Singapore Navy also operates another service which has a transmission frequency of 310kHz. Details of the service are not available as the service is only intended for the Singapore Navy.

Figure 2-3: DGPS reference station near Raffles Lighthouse, southern island of Singapore

2.4 Real-Time Kinematic (RTK) Technique

Real-Time Kinematic (RTK) is a technique where the GPS signal corrections are transmitted from a reference receiver at a known location to one or more rover receivers. The rover stations combine locally collected measurements with those from the reference station to obtain position results at a centimetre-level. The use of an RTK-capable GPS system can compensate for atmospheric delay,

orbital errors and other variables in GPS geometry, resulting in high positioning accuracy. Used by engineers, surveyors and other professionals, RTK is a technique employed in applications where precision is paramount. RTK is used also in navigation and automatic machine guidance and in dredging and civil engineering applications. It provides advantages over other traditional positioning and tracking methods in terms of productivity and accuracy. The RTK process begins with an initial ambiguity resolution. This is a crucial aspect of any kinematic system, particularly in real-time where the velocity of a rover receiver should not degrade either the achievable performance or overall reliability of the system.

In traditional RTK GPS, developed in the early 1990s, a stationary reference receiver is located at a known point and the position of the moving receiver (the rover), is determined. This differential GPS method needs at least four common satellites to be tracked simultaneously at both sites and also good satellite geometry. The known coordinates of the reference station are used to calculate the corrections to the observations, which are transmitted via some form of communication link to the rover. So it is possible to calculate the position of the rover receiver with more accuracy than in the single point positioning mode.

The first commercial RTK GPS system was launched in the early 1990s. The computation of coordinates in real-time thus allows the use of GPS positioning for engineering work such as staking out, etc. Shortly after the introduction of the first single-frequency system, a dual-frequency version of the RTK-GPS system appeared, opening up the widespread use of GPS in surveying. Initialisation period of up to 30 seconds are needed for ambiguity resolution. If the signal lock to at least four satellites is maintained by both the reference receiver and the rover after the initialisation, cm-level accuracy can be achieved continuously.

2.5 Network-based RTK

The multiple-reference-station carrier phase-based RTK technique is also referred to as the network-RTK technique. The concept of a network-RTK service has been around for many years, however, the issues related to the real-time resolution of integer ambiguities within the network, the optimal network correction

parameterization and their dissemination to users within the network coverage area are recent challenges for real-time applications. The accurate and reliable resolution of integer ambiguities for the baselines between reference stations of the network in real-time is essential for network-RTK. Papers with detailed discussions of this topic include those by Raquet (1998); Sun *et al.* (1999) and Dai *et al.* (2001). A comprehensive investigation of the different correction parameterization schemes has been carried out by Dai *et al.* (2001).

However, little has been reported on the distribution of the network corrections to real-time users. This is an integral part of GPS network-RTK positioning and it must be adequately addressed before a practical realization of the multiple-reference-station-network concept can be implemented. A natural extension of the network-RTK implementation is the Virtual Reference Station (VRS) concept. This was first addressed by Lynn & Anil (1995) for code-based DGPS. Recently, the use of the VRS concept has been proposed by researchers as a feasible approach for relaying network correction information to the network-RTK users (Wanninger, 1999; Marel, 1998; Vollath *et al.*, 2000; Cannon *et al.*, 2001; Euler *et al.*, 2001). At the XXII FIG (the International Federation of Surveyors) International Congress in April 2002, there was a special session presenting the status of VRS systems (Cruddace *et al.*, 2002; Higgins, 2002).

As in the case of conventional RTK, the VRS RTK-GPS technique has great potential for precise navigation and surveying applications. This approach does not require an actual physical reference station equipped with GPS receiver and data link. Instead, it allows the user to access data from a “virtual” reference station at any location within the network coverage area (Marel, 1998; Vollath *et al.*, 2000; Cannon *et al.*, 2001; Euler *et al.*, 2001). Also, the VRS approach is more flexible in terms of permitting users to use their current receivers and software, without requiring any special software to manage simultaneous transmitted corrections from a network of reference stations.

High accuracy RTK-GPS positioning is one of the most widely used surveying techniques nowadays, but its use is restricted by many GPS errors, including ionosphere and troposphere effects, which create systematic errors in the

raw data. In practice, this means that the distance between a rover (mobile) receiver and its reference station has to be quite short ($< 10\text{-}15\text{ km}$) in order to work efficiently and provide good quality results with relatively short observation sessions.

The establishment of a multiple-reference-station-network offers an enhanced opportunity for high accuracy RTK surveys. The multiple-reference-station-network is an integrated system of GPS hardware, software and communication links that uses data from several permanent reference stations to model GPS errors throughout the network region.

2.6 Multiple-reference Carrier-phase-based Algorithm and Data Processing Techniques

2.6.1 Han's Method

Han (1997) introduced an enhanced multiple-reference-station data processing technique. The technique utilises a linear combination functional model. It requires that the reference stations data be first processed in order to generate correction terms. These correction terms, when applied to standard baseline determination software, mitigate the effects of satellite orbit error, ionospheric and tropospheric biases, multipath and observation noise. This technique has been tested in several experiments across the Sydney area (Chen *et al.*, 1997, Han and Rizos, 1997). In these experiments, single epoch OTF ambiguity resolution was demonstrated. In addition, high accuracy baseline results could be obtained even when using single-frequency GPS receivers. As reported, the results of the algorithm were very preliminary and no firm conclusions could be drawn. Hence many tests and experiments have had to be carried out to identify potential problems as well as applications. Figure 2-4 illustrates a three-station multiple-reference-station configuration.

Figure 2-4: Multiple-reference-station configuration

The single-differenced carrier phase observations from a user receiver (u) to multiple reference receivers (i) are formed as follow (Han, 1997):

$$\Delta\phi_i = \Delta\rho_i + \Delta dp_i - c \cdot \Delta dT_i + \lambda \cdot \Delta N_i - \Delta d_{ion,i} + \Delta d_{trop,i} + \Delta d_{mp,i}^\phi + \epsilon_{\Delta\phi_i} \quad (2-1)$$

where,

$\Delta(\cdot)_i = (\cdot)_u - (\cdot)_i$, is the between-receiver differencing operator, i indicates the reference station, and u the user station;

ϕ is the carrier-phase observation (m);

λ is the wavelength of the carrier-phase;

N is the integer ambiguity;

$\rho = \|X^S - X\|$ X^S is the satellite position vector, X is the station position vector;

d_{mp}^ϕ is the phase multipath error;

ϵ_ϕ is the carrier-phase observation noise;

c is the speed of light (m/sec);

dT is the receiver clock error (sec);

dp is the satellite orbital error component in the range direction (m);

d_{ion} is the ionospheric error (m); and

d_{trop} is the tropospheric error (m).

A set of parameters α_i can be determined, based on the conditions given in Han and Rizos (1997):

$$\sum_{i=1}^3 \alpha_i = 1 \quad (2-2)$$

$$\sum_{i=1}^3 \alpha_i \cdot \Delta \vec{X}_i = \vec{X}_u - \alpha_1 \cdot \vec{X}_1 - \alpha_2 \cdot \vec{X}_2 = 0 \quad (2-3)$$

where $\vec{X}_u$ and $\vec{X}_i$ are the position in the Gauss plane coordinate system. (i=1, 2, 3)

Equation (2-3) above can be written as:

$$\begin{bmatrix} x_u \\ y_u \end{bmatrix} = \begin{bmatrix} x_1 & x_2 \\ y_1 & y_2 \end{bmatrix} \begin{bmatrix} \alpha_1 \\ \alpha_2 \end{bmatrix} \quad (2-4)$$

α_1 and α_2 can be computed as:

$$\begin{bmatrix} \alpha_1 \\ \alpha_2 \end{bmatrix} = \begin{bmatrix} x_1 & x_2 \\ y_1 & y_2 \end{bmatrix}^{-1} \begin{bmatrix} x_u \\ y_u \end{bmatrix} \quad (2-5)$$

The linear combination of the single-differenced observations can be formed as:

$$\begin{aligned} \sum_{i=1}^3 \alpha_i \cdot \Delta \phi_i &= \sum_{i=1}^3 \alpha_i \cdot \Delta \rho_i + \sum_{i=1}^3 \alpha_i \cdot \Delta d\rho_i - c \cdot \sum_{i=1}^3 \alpha_i \cdot \Delta dT_i + \lambda \cdot \sum_{i=1}^3 \alpha_i \cdot \Delta N_i \\ &- \sum_{i=1}^3 \alpha_i \cdot \Delta d_{\text{ion},i} + \sum_{i=1}^3 \alpha_i \cdot \Delta d_{\text{trop},i} + \sum_{i=1}^3 \alpha_i \cdot \Delta d_{\text{mp},i}^{\phi} + \epsilon_{\sum_{i=1}^3 \alpha_i \cdot \Delta \phi_i} \end{aligned} \quad (2-6)$$

The orbit bias term has been shown to be (Han, 1997):

$$\sum_{i=1}^3 \alpha_i \cdot \Delta d\rho_i \approx 0 \quad (2-7)$$

The ionospheric delay term can be represented as (ibid, 1997):

$$\sum_{i=1}^3 \alpha_i \cdot \Delta d_{\text{ion},i} = d_{\text{ion},u} - d_{\text{ion},3} - \begin{bmatrix} \alpha_1 \\ \alpha_2 \end{bmatrix}^T \begin{bmatrix} d_{\text{ion},1} - d_{\text{ion},3} \\ d_{\text{ion},1} - d_{\text{ion},3} \end{bmatrix} = 0 \quad (2-8)$$

This equation can be rewritten as below considering Equation (2-5):

$$\sum_{i=1}^3 \alpha_i \cdot \Delta d_{\text{ion},i} = d_{\text{ion},u} - d_{\text{ion},3} - \begin{bmatrix} x_u & y_u \end{bmatrix} \begin{bmatrix} x_1 & y_1 \\ x_2 & y_2 \end{bmatrix}^{-1} \begin{bmatrix} d_{\text{ion},1} - d_{\text{ion},3} \\ d_{\text{ion},1} - d_{\text{ion},3} \end{bmatrix} = 0 \quad (2-9)$$

The tropospheric delay term can be represented in a similar manner to the ionospheric delay:

$$\sum_{i=1}^3 \alpha_i \cdot \Delta d_{\text{trop},i} = d_{\text{trop},u} - d_{\text{trop},3} - \begin{bmatrix} x_u & y_u \end{bmatrix} \begin{bmatrix} x_1 & y_1 \\ x_2 & y_2 \end{bmatrix}^{-1} \begin{bmatrix} d_{\text{trop},1} - d_{\text{trop},3} \\ d_{\text{trop},1} - d_{\text{trop},3} \end{bmatrix} = 0 \quad (2-10)$$

The multipath term can be written as:

$$\sum_{i=1}^3 \alpha_i \cdot \Delta d_{\text{mp},i}^{\phi} = d_{\text{mp},u}^{\phi} - \sum_{i=1}^3 \alpha_i \cdot d_{\text{mp},i}^{\phi} \quad (2-11)$$

The standard deviation of the one-way carrier-phase observation can be approximated as a function of the elevation angle. The elevation angle of a satellite is approximately the same for all the surrounding reference stations due to the fact that these stations are located within a region of less than 100 km across.

$$\sigma_{\sum_{i=1}^3 \alpha_i \cdot \Delta \phi_i} = \sqrt{1 + \alpha_1^2 + \alpha_2^2 + \alpha_3^2} \cdot \sigma^j \quad (2-12)$$

The single-differenced carrier-phase observation functional model (Equation 2-6) can be simplified as:

$$\sum_{i=1}^3 \alpha_i \cdot \Delta \phi_i = \sum_{i=1}^3 \alpha_i \cdot \Delta \rho_i - c \cdot \sum_{i=1}^3 \alpha_i \cdot \Delta dT_i + \lambda \cdot \sum_{i=1}^3 \alpha_i \cdot \Delta N_i + \varepsilon_{\sum_{i=1}^3 \alpha_i \cdot \Delta \phi_i} \quad (2-13)$$

The above Equation can be rewritten as:

$$\begin{aligned} \Delta\phi_{u,3} - [\alpha_1 \cdot \Delta\phi_{1,3} + \alpha_2 \cdot \Delta\phi_{2,3}] &= \Delta\rho_{u,3} - [\alpha_1 \cdot \Delta\rho_{1,3} + \alpha_2 \cdot \Delta\rho_{2,3}] - c \cdot \sum_{i=1}^3 \alpha_i \cdot \Delta dT_i \\ &+ \lambda \cdot \Delta N_{u,3} - [\alpha_1 \cdot \Delta N_{1,3} + \alpha_2 \cdot \Delta N_{2,3}] + \varepsilon_{\sum_{i=1}^3 \alpha_i \cdot \Delta\phi_i} \end{aligned} \quad (2-14)$$

Hence, the residual vectors can be defined as:

$$V_{1,3} = \nabla\Delta\phi_{1,3} - \nabla\Delta N_{1,3} - \nabla\Delta\rho_{1,3} \quad (2-15)$$

$$V_{2,3} = \nabla\Delta\phi_{2,3} - \nabla\Delta N_{2,3} - \nabla\Delta\rho_{2,3} \quad (2-16)$$

The double-differenced observation model can be written as:

$$\nabla\Delta\phi_{u,3} - [\alpha_1 \cdot V_{1,3} + \alpha_2 \cdot V_{2,3}] = \nabla\Delta\rho_{u,3} + \lambda \cdot \nabla\Delta N_{u,3} + \varepsilon_{\sum_{i=1}^3 \alpha_i \cdot \nabla\Delta\phi_i} \quad (2-17)$$

Residual vectors can be determined using the known coordinates of the reference stations and known integer ambiguity.

The residual vector can be represented by:

$$\begin{bmatrix} V_{12} \\ V_{13} \\ \vdots \\ V_{1n} \end{bmatrix} = \begin{bmatrix} \nabla\Delta\phi_{12} - \nabla\Delta\rho_{12} - \nabla\Delta N_{12} \\ \nabla\Delta\phi_{13} - \nabla\Delta\rho_{13} - \nabla\Delta N_{13} \\ \vdots \\ \nabla\Delta\phi_{1n} - \nabla\Delta\rho_{1n} - \nabla\Delta N_{1n} \end{bmatrix} = \begin{bmatrix} \Delta X_{12} & \Delta Y_{12} \\ \Delta X_{13} & \Delta Y_{13} \\ \vdots & \vdots \\ \Delta X_{1n} & \Delta Y_{1n} \end{bmatrix} \cdot \begin{bmatrix} a \\ b \end{bmatrix} \quad (2-18)$$

a and b are coefficients which can be determined using least squares adjustment.

2.6.2 NetAdjust Method

Raquet (1998) proposed an algorithm known as NetAdjust. The differential correction generated improves the ability to perform carrier-phase ambiguity resolution at the rover receiver. The NetAdjust method proposed is based upon a linear minimum error variance estimator. It is an effective means of using a reference receiver network to estimate and remove uncorrelated and correlated differential errors for both code and phase measurements, and for improving

ambiguity resolution performance. If the double-differenced errors are zero-mean and Gaussian, then the NetAdjust algorithm provides the optimal error estimates (in the sense that the sum of the corrected measurement error variances is minimised). At the heart of the NetAdjust algorithm is the differential error covariance matrix. This matrix describes the error variance and cross-correlation for all of the measurements made by the network reference receivers and the measurements that would be received by a mobile receiver at a predefined computation point. A perfectly correct error covariance matrix guarantees optimality (as described above). The degree to which the implemented error covariance matrix matches the true error covariance matrix is the degree to which the NetAdjust algorithm, as implemented, is optimal with respect to the defined criterion. The prediction equations used to compute the corrections to the carrier-phase observables are:

$$\delta \hat{\mathbf{l}}_r = \mathbf{C}_{\delta \mathbf{l}_r, \delta \mathbf{l}} \mathbf{B}^T (\mathbf{B} \mathbf{C}_{\delta \mathbf{l}} \mathbf{B}^T)^{-1} (\mathbf{B} \bar{\phi} - \lambda \Delta \nabla N) \quad (2-19)$$

$$\delta \hat{\mathbf{l}} = \mathbf{C}_{\delta \mathbf{l}} \mathbf{B}^T (\mathbf{B} \mathbf{C}_{\delta \mathbf{l}} \mathbf{B}^T)^{-1} (\mathbf{B} \bar{\phi} - \lambda \Delta \nabla N) \quad (2-20)$$

where,

$\delta \hat{\mathbf{l}}_r$ is the correction vector to carrier-phase observables collected at the user receiver (m);

$\delta \hat{\mathbf{l}}$ is the correction vector to carrier-phase observables collected at the reference stations (m);

$\mathbf{C}_{\delta \mathbf{l}_r, \delta \mathbf{l}}$ is the cross-covariance matrix between the carrier-phase observables collected at the user receiver and the reference station;

$\mathbf{C}_{\delta \mathbf{l}}$ is the covariance matrix of the carrier-phase observables collected at the reference station;

λ is the carrier-phase wave length;

$\bar{\phi}$ is the measurement-minus-range carrier-phase observable ($\bar{\phi} = \phi - \rho$) (m), assuming that the reference station coordinates are known in order to compute the geometric range ρ ;

$\mathbf{B}$ is the double-differenced matrix ($\mathbf{B} = \frac{\partial \Delta \nabla \bar{\phi}}{\partial \phi}$); and

$\Delta\nabla N$ is the double-differenced ambiguity vector between the reference stations (cycles).

2.7 Network-based RTK Services

A multiple-reference DGPS system enables various combinations of static and kinematic positioning in either real-time or post-processed mode. Users need not own and operate the reference station infrastructure. They need only a single receiver for high precision positioning. This will significantly reduce the cost of the survey.

A network-based RTK (Real-Time Kinematic) service has been introduced in Japan (Petrovski *et al.*, 2000). The system implements a Virtual Reference Station algorithm by the GPS manufacturer Trimble; internet-based reference station network and TV sound multiplexed sub-carrier data link. It is the first of its kind and has been developed and tested in Tokyo. It covers an area of approximately 100 km in radius.

The core engine of the system utilises the multiple-reference-station algorithm developed at the University of Calgary (Raquet, 1998). A number of tests were conducted at different locations within the network. The results yield root mean square errors of about three centimetres.

The State survey offices of Germany have also implemented a differential correction service for geodetic and land surveying applications (Martin, 1999). The service broadcasts code and phase corrections in the VHF-band using the RTCM version 2.1 (Radio Technical Commission for Maritime Service) format. The accuracy was improved using a numbers of reference stations connected together to form a “High Precision Positioning Network”. This network-based solution is intended to effectively model the orbit and calculate the atmospheric errors. Corrections can be computed as a set of “area correction parameters”. These corrections are transmitted in the RTCM Type 59 message. Test results show that ambiguities can be resolved within one to two minutes for a baseline up to 30 to 40 km length resulting in an accuracy of about ± 1 cm.

During the Institute of Navigation (ION) 2000 conference in Salt Lake City, USA, Spectra Precision Terrasat announced a new package of hardware and software for GPS network-based reference station infrastructure known as the Virtual Reference Station (VRS) system (Vollath *et al.*, 2000). The VRS software package manages the collection of GPS data from a distributed network of reference stations. This system includes data archiving and the control of one or more reference stations via modem or IP networking. The system has the capability to generate RTK correction terms in RTCM and CMR (Compact Measurement Record) format. CMR is a standard communications protocol used in Trimble RTK systems to transmit GPS carrier-phase and code observations from a reference station to one or more rover stations. It also has the capability for cycle slip detection and repair, as well as alarm generation in case of failures and subsequent notification of operators via email or Short Message Service (SMS). The VRS software has the basic functionality of processing and quality control analysis of code and carrier-phase data in a differential method for the complete network of reference stations. The VRS system has comparable performance to standard RTK/On-the-fly (RTK/OTF) systems at greater distances from reference stations with improvements in both accuracy and initialisation time. The reported horizontal position error is 10 to 30 mm at distances of approximately 50 km between the reference stations.

Spectra Precision Terrasat has installed the VRS software, *GPS-Network* in a three-station network in areas surrounding Helsinki, Finland. The software was installed at one of the three reference stations, which acts as the control centre. Continuous leased line connections between the control centre and all reference stations were also set up. Data is transmitted continuously to the centre. At the control centre, the *GPS-Network* performs a continuous computation of the following by analysing double-differenced quantities:

- ❑ ionospheric errors,
- ❑ tropospheric errors,
- ❑ ephemeris errors, and
- ❑ carrier-phase ambiguities for L1 and L2.

From these parameters *GPS-Network* can compute the interpolated effect on a rover within the reference station network. To allow this interpolation, the rover must provide its approximate position to the *GPS-Network*. This is done via a GSM connection with the standard NMEA (National Marine Electronics Association – a Standard for Interfacing Marine Electronics Devices) message, which all receiver manufacturers supported. The *GPS-Network* calculates optimised RTCM messages and transmits them to the rover via the GSM connection. With these optimised RTCM messages, improved RTK positioning can be achieved within the reference station network.

2.8 Single-reference-station and Multiple-reference-station Approaches

Carrier-phase-based multiple-reference-station DGPS offers several advantages over the standard single baseline approach. Firstly, the multiple-reference-station DGPS service has increased reliability and availability compared to a single-reference-station DGPS service. There are usually more than two reference stations in a multiple-reference-station network. The utilisation of more than two stations actually allows for redundancy. If one of the reference stations fails (e.g. power failure), its contribution to the correction term can be removed. The network will still be able to function, retaining the availability of service. In addition, the use of a network approach allows the quality of the corrections generated from each reference station to be checked with the remaining corrections. Thus, if a particular reference station is generating erroneous corrections, the network permits the possible detection and elimination of outliers from the final solution.

Secondly, distance-dependent or spatially-correlated errors (e.g. ionospheric, tropospheric and satellite orbit effects) can be modelled in the network approach. By combining observations from a number of permanent reference stations (with known coordinates), the effect of the above-mentioned distance-dependent errors can be reduced through various modelling techniques as described in Section 2.6. The modelling of the spatially-correlated errors improves the resolution of the

carrier-phase ambiguities, which are required for centimetre-level positioning. Moreover, the improvement in ambiguity resolution over longer baselines allows greater inter-station distances between the network reference stations. Hence, fewer stations are needed to cover an area. This is illustrated in Figure 2-5. The inter-station baseline lengths increase from a maximum of few tens of kilometres to a few hundred kilometres using the multiple-reference-station approaches.

Figure 2-5: Area of coverage for single-reference-station (a) versus multiple-reference-station (b) approaches

Lastly, the multiple-reference-station-network approach enables the generation of observations for a virtual reference station (VRS). The data is generated for a fictitious reference station situated very close to the user station, resulting in an improved DGPS positioning. Note, this approach does not require a receiver to be physically located at the reference site. Also, the use of the VRS RTK approach is more flexible in terms of permitting users to utilise their current receivers and software, without requiring any special carrier-phase software to deal with simultaneously transmitted corrections from a series of reference stations.

Despite the advantages, the multiple-reference-station approach has some drawbacks. With the increased in the number of reference stations there is a

possibility of increased data transmission load to the rover users, and thus higher communication bandwidth is needed. To date, the standard format for the multiple reference correction has not been defined. So each service provider has introduced its own format and uses a different approach at the rover site in order to make use of the network-generated correction.

Several methods of carrier phase-based multiple-reference-station solution have been developed for the past few years by various researchers. The correction generation algorithms and processing methodology can be categorised as follows (Fotopoulos, 2000):

1. Partial derivative algorithms,
2. Linear interpolation algorithms (Gao *et al.*, 1997; Han 1997),
3. Condition adjustment algorithm (Raquet, 1998), and
4. Virtual reference station methodologies.

The first three methods deal with the actual generation and subsequent parameterization of the carrier-phase-based corrections. However, these techniques are still undergoing algorithmic development and fine-tuning. The last method deals with a 'parameterization' in a virtual reference station framework.

Other multiple-reference-station methods are categorised and given in Chen (2001) and Wanninger (2002).

2.9 Applications of High Precision Multiple-reference Carrier-phase-based DGPS

GPS is a precise and reliable tool in a wide range of surveying applications. GPS applications are fast growing since the Selective Availability was turned off on 2 May 2000. For the establishment of a geodetic control network, GPS is the most economical and efficient surveying tool. In this case, a static observation of more than half an hour and extensive post-processing in the office is tolerable. Other applications, on the other hand, require short observation time so that more points

can be surveyed in the same time span. The introduction of RTK enabled users to economically perform a survey using short observation times at each point.

The largest group of GPS applications require medium- and low-order accuracy positioning (Parkinson *et al.*, 1995). High precision applications only represent a small portion of the total GPS positioning usage. Some of the high precision GPS positioning applications are as follows:

- ❑ building, dam and landslide monitoring;
- ❑ engineering work such as setting-out;
- ❑ machine guidance and control; and
- ❑ surveying work which includes establishing geodetic control and cadastral surveying.

One objective of this research project is to demonstrate the multiple-reference carrier-phase-based DGPS technique for cadastral surveys. This includes both the real-time and post-processing mode of operation.

GPS has become the preferred positioning technology for geodetic control and mapping surveys in the last two decades. However, for a number of reasons, including the high capital cost of the technology and its comparatively low productivity, GPS has not been generally used for cadastral surveys.

On the other hand, Total Station technology has been almost exclusively used for cadastral surveys, and any surveys concerned with the development of land. Cadastral surveying in particular has always been the responsibility of registered or professional surveyors who must operate in accordance with the local land laws. In addition, there are also cadastral survey standards and specifications, or regulations, that they have to follow.

However, over the last few years considerable R&D has been invested by manufacturers to overcome those GPS technology constraints that were considered to be unnecessarily restrictive for cadastral surveying. Present state-of-the-art GPS systems, together with the availability of high precision DGPS infrastructure, have the following capabilities:

- ❑ able to be used even when the receiver is moving,
- ❑ require comparatively short observation times at each point being coordinated, and
- ❑ capable of real-time operation through the provision of a communication link between two GPS receivers.

Therefore GPS is now generally considered to be a viable tool for surveying that challenges the traditional EDM-theodolite-traverse methodology. However, there is no readily available cadastral methodology of tracing the GPS measurements back to a recognised value standard. This concept is known as legal traceability. Hence, proper guidelines and equipment testing facility are needed before the integration of GPS coordinated land parcel into the cadastre system (Tor, 2001).

Many countries are making progress in implementing the Coordinated Cadastral System (CCS) to replace the conventional "bearing-distance" system. They include Australia, Malaysia and Singapore. One of the most important issues of implementing CCS is the issue of legal traceability. It has been identified that a set of recommended practices or guidelines regarding the use of GPS for cadastre survey in a country need to be developed (Ses *et al.*, 1999).

There will be a lot of advantages if the land authority of a country operates a real-time, reliable and high accuracy DGPS system. Such a system is proposed and implemented in this research project.

Chapter 3

Correction Generation for SIMRSN (Singapore Integrated Multiple Reference Station Network)

3.1 Overview

The purpose of this study is to assess the technical feasibility of setting up an operational multiple-reference-station-network. It aims to demonstrate real-time GPS positioning using the multiple-reference-station framework. The network will enable users to stretch their baseline length to more than 10 km and still obtain RTK accuracy. As discussed in previous chapter, this technique is generally known as the Network-RTK technique. In some cases, it is also known as the multiple-reference-station solution.

The network of GPS reference stations provides GPS data to generate correction terms, which are to be broadcast to the rover users. As explained in section 2.5, there is no standard format to disseminate the network-RTK correction. The network-RTK will be implemented in the conventional way using the virtual reference station (VRS) technique. This technique practically is similar to the single-based RTK and there is no additional software and hardware required for the rover user. These correction terms are computed in real-time to mitigate the effect of ionospheric and tropospheric delay errors on GPS observations. It will improve the efficiency of ambiguity resolution with the Network-RTK technique at the rover receiver, when situated within the coverage area.

This chapter introduces the algorithms used in the Singapore Multiple Reference Station Network (SIMRSN) to generate the corrections for Network-RTK. The VRS parameterization of the correction terms is used. This Network-RTK solution is described in this report as SIMRSN-RTK.

3.2 SIMRSN Correction Generation Algorithm

SIMRSN's multiple-reference-station corrections are generated using the VRS technique. VRS data is not raw GPS data made by a GPS receiver. It is generated from real GPS observations acquired by a network of GPS reference stations. The VRS data resembles fundamentally the data of a real GPS receiver would have acquired at the location specified for the VRS. Because VRS data are computed from several actual stations of the network, errors can be spatially modelled. The user benefits from data of all GPS reference stations in the network, without the burden of complicated processing. The generation of VRS data is described in this section, which focuses on:

1. real-time ambiguity resolution of the baselines between the reference stations in the network;
2. correction generation scheme; and
3. VRS data generation, with emphasis on real-time implementation.

3.2.1 Real-time Ambiguity Resolution of the Network

Numerous methods for the resolution of carrier phase ambiguities have been developed (for both real-time and post-processing modes). These are typically known as on-the-fly (OTF) techniques when the receiver is moving (Frei and Beutler, 1990; Hatch, 1990; Chen & Lachapelle, 1995; Teunissen, 1993). There is also a technique to resolve ambiguities in the case of longer inter-station distances (Blewitt, 1989). In order to generate the network corrections for the user, dual-frequency carrier-phase ambiguities of the baselines between the reference stations of the network must first be fixed to their integer values in real-time.

A pre-requisite to implementing this correction methodology is the provision of accurate reference stations coordinates of the network. These could be provided by the local survey authority, a permanent reference network or obtained through a static survey of each station using conventional static GPS techniques. However, even with precisely known coordinates it is not easy to resolve ambiguities between reference stations of the network in real-time, especially for satellites with low elevation angles.

A method is proposed as follows: the wide-lane ambiguities are first resolved, then the L1 and the relative tropospheric zenith delay (RTZD) are estimated using the ionosphere-free observables via an adaptive Kalman filter. When the estimated (float) L1 ambiguity meets certain criteria, this ambiguity will then be fixed (Sun *et al.*, 1999; Chen *et al.*, 2000). In order to help the network ambiguity resolution process, the orbital error de-correlation can be reduced or eliminated using the IGS UltraRapid Predicted Orbit instead of broadcast orbits. The precise ephemeris can be obtained from the International GNSS Service (IGS).

The double-differenced carrier phase observable can be expressed as (Hofmann-Wellenhof *et al.*, 1992; Leick, 1995; Han, 1997):

$$\lambda_k \nabla \Delta \phi_k = \nabla \Delta \rho + \lambda_k \nabla \Delta N_k + \nabla \Delta d_{trop} - \alpha_k \nabla \Delta I + \varepsilon(\nabla \Delta \phi_k) \quad (3-1)$$

Where $\nabla \Delta$ is the double-differencing operator, $\nabla \Delta \phi_k$ is the double-differenced carrier-phase observable expressed in units of cycles; λ_k is the wavelength of the carrier wave k ; $\nabla \Delta \rho$ is the double-differenced geometric satellite-to-receiver distance; $\nabla \Delta N_k$ is the double-differenced integer ambiguity; $\nabla \Delta d_{trop}$ is the double-differenced tropospheric delay; $\nabla \Delta I$ is the double-differenced ionospheric delay parameter (α_k for L1 and L2 carrier-phase $\alpha_1 = f_2^2 / (f_1^2 - f_2^2)$, $\alpha_2 = f_1^2 / (f_1^2 - f_2^2)$ respectively); f_k is the frequency of the carrier wave k), and $\varepsilon(\nabla \Delta \phi_k)$ is the double-differenced carrier-phase observation noise.

The double-differenced widelane ($\nabla\Delta\phi_{1,-1}$) and ionosphere-free ($\nabla\Delta\phi_{77,-60}$) combination measurements can be written as (Han, 1997; Chen *et al.*, 2000):

$$\lambda_{1,-1}\nabla\Delta\phi_{1,-1} = \nabla\Delta\rho + \lambda_{1,-1}\nabla\Delta N_{1,-1} + \nabla\Delta d_{trop} + \alpha_{1,-1}\nabla\Delta I + \varepsilon(\nabla\Delta\phi_{1,-1}) \quad (3-2)$$

$$\lambda_{77,-60}\nabla\Delta\phi_{77,-60} = \nabla\Delta\rho + \lambda_{77,-60}\nabla\Delta N_{77,-60} + \nabla\Delta d_{trop} + \varepsilon(\nabla\Delta\phi_{77,-60}) \quad (3-3)$$

The widelane integer ambiguity ($\nabla\Delta N_{1,-1}$) can be resolved first due to its wavelength of 86.4 centimetres using a search method or a sequential estimation approach (Blewitt, 1989; Euler & Landau, 1992; Sun *et al.*, 1999). Details of these algorithms will not be presented here.

If the widelane integer ambiguity can be fixed, the ionosphere-free ambiguity ($\nabla\Delta N_{77,-60}$) can be represented by:

$$\nabla\Delta N_{77,-60} = \frac{60i + 77j}{i + j} \nabla\Delta N_{1,-1} + \frac{17}{i + j} \nabla\Delta N_{i,j} \quad (3-4)$$

where if $i=1$ and $j=0$, then

$$\begin{aligned} \lambda_{77,-60}\nabla\Delta\phi_{77,-60} &= \nabla\Delta\rho + \nabla\Delta N_{1,0}(17\lambda_{77,-60}) + \nabla\Delta N_{1,-1}(60\lambda_{77,-60}) \\ &+ \nabla\Delta d_{trop} + \varepsilon(\nabla\Delta\phi_{77,-60}) \end{aligned} \quad (3-5)$$

In Equation (3-5) the ionosphere-free ambiguity is replaced by a combination of the widelane integer ambiguity ($\nabla\Delta N_{1,-1}$) and the L1 ambiguity (here the effective wavelength of the ionosphere-free observation is 10.7 cm). Then the ionosphere-free combination can be used to resolve the L1 integer ambiguity with an effective wavelength of 10.7 cm using the above relationship if the widelane ambiguities are first resolved (Sun *et al.*, 1999; Chen *et al.* 2000). Using the known coordinates of the reference stations, L1 ambiguity resolution is only affected by the residual tropospheric delay, multipath disturbance and observation noise. The multipath effect can be reduced by careful selection of reference station sites and using GPS hardware with multipath rejection capabilities, such as choke-ring antennas (Hofmann-Wellenhof *et al.*, 1992; Leick, 1995). The challenge

therefore is to mitigate the residual tropospheric delay and reduce the observation noise.

The double-differenced residual tropospheric delay can be approximately expressed as a function of relative tropospheric zenith delay (RTZD) and a mapping function with respect to the elevation angle (Zhang & Lachapelle, 2001):

$$\nabla \Delta d_{trop}^{xy} = RTZD \cdot [MF(\varepsilon^x) - MF(\varepsilon^y)] \quad (3-6)$$

Where ε^x and ε^y are the average elevation angles of the two receivers for satellites x and y, here $MF(\cdot) = \frac{1}{\sin(\cdot)}$. Hence, Equation (3-5) can be rewritten as:

$$\begin{aligned} & \lambda_{77,-60} \nabla \Delta \phi_{77,-60} - \nabla \Delta \rho - \nabla \Delta N_{1,-1} \cdot (60 \lambda_{77,-60}) \\ &= \nabla \Delta N_{1,0} \cdot (17 \lambda_{77,-60}) + RTZD \cdot [MF(\varepsilon^x) - MF(\varepsilon^y)] + \varepsilon(\nabla \Delta \phi_{77,-60}) \end{aligned} \quad (3-7)$$

In order to estimate RTZD as well as the double-differenced L1 integer ambiguities in real-time, an adaptive Kalman filter was developed to process each baseline between the master reference station and the other reference stations, using the following models (Mohamed & Schwarz, 1998; Chen *et al.*, 2000; Hu *et al.*, 2002a):

$$\begin{aligned} Z_k &= H_k X_k + V_k \quad V_k \sim N(0, R_k) \\ X_k &= \Phi_{k,k-1} X_{k-1} + W_k \quad W_k \sim N(0, Q_k) \end{aligned} \quad (3-8)$$

Where R_k is the covariance matrix of observation noise.

The observation vector is

$$Z_k = \begin{bmatrix} \lambda_{77,-60} \nabla \Delta \phi_{77,-60}^{12} - \nabla \Delta \rho^{12} - \nabla \Delta N_{1,-1}^{12} \cdot (60 \lambda_{77,-60}) \\ \lambda_{77,-60} \nabla \Delta \phi_{77,-60}^{13} - \nabla \Delta \rho^{13} - \nabla \Delta N_{1,-1}^{13} \cdot (60 \lambda_{77,-60}) \\ \vdots \\ \lambda_{77,-60} \nabla \Delta \phi_{77,-60}^{1n} - \nabla \Delta \rho^{1n} - \nabla \Delta N_{1,-1}^{1n} \cdot (60 \lambda_{77,-60}) \end{bmatrix} \quad (3-9)$$

Here, superscript 1 refers to the reference satellite, 2 to n refer to others satellites. The state vector is defined as:

$$X_k = [RTZD, \nabla \Delta N_1^{12}, \nabla \Delta N_1^{13}, \dots, \nabla \Delta N_1^{1n}]^T \quad (3-10)$$

and the design matrix is:

$$H_k = \begin{bmatrix} MF(\varepsilon^1) - MF(\varepsilon^2) & 17\lambda_{77,-60} & 0 & \dots & 0 \\ MF(\varepsilon^1) - MF(\varepsilon^3) & 0 & 17\lambda_{77,-60} & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ MF(\varepsilon^1) - MF(\varepsilon^n) & 0 & 0 & \dots & 17\lambda_{77,-60} \end{bmatrix} \quad (3-11)$$

Here, RTZD is assumed to be a first-order Gauss-Markov process, and the L1 ambiguities are assumed to be white noise with very small variance. Then the state transition matrix and corresponding covariance matrix are defined as:

$$\Phi_{k,k-1} = \begin{bmatrix} e^{-\Delta t / \tau} & 0 & \dots & 0 \\ 0 & 1 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & 1 \end{bmatrix} \quad (3-12)$$

$$Q_k = \begin{bmatrix} \frac{\tau}{2}(1 - e^{-2\Delta t/\tau})q & 0 & \cdots & 0 \\ 0 & 1e^{-16} & \cdots & 0 \\ 0 & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 1e^{-16} \end{bmatrix} \quad (3-13)$$

Where q is the variance of the RTZD process noise for the correlation time τ , and Δt is the sampling rate.

The conventional Kalman filter procedure should provide reasonable values for covariance matrices of measurement noise and system noise (R_k and Q_k) based on a priori information. In practice, however, the true statistical properties of measurement and system noise are never known (Wang *et al.*, 2002). Incorrect values will lead to inaccurate results and even divergence. On the other hand, the network-RTK method generally requires six or more satellites with corrections and does not tolerate interruptions (Edwards *et al.*, 1999). To overcome this problem, a residual-based adaptive procedure (Mohamed & Schwarz, 1998; Hu & Ou, 1999) is adopted to improve the reliability of the Kalman filter.

$$X_{k,k-1} = \Phi_{k,k-1} X_{k-1,k-1} \quad (3-14)$$

$$P_{k,k-1} = \Phi_{k,k-1} P_{k-1} \Phi_{k,k-1}^T + Q_{k-1} \quad (3-15)$$

$$J_k = P_{k,k-1} H_k^T (H_k P_{k,k-1} H_k^T + R_{k-1})^{-1} \quad (3-16)$$

$$X_k = X_{k,k} = X_{k,k-1} + J_k (L_k - H_k X_{k,k-1}) \quad (3-17)$$

$$P_k = P_{k,k} = (I - J_k H_k) P_{k,k-1} \quad (3-18)$$

$$R_k = C_{v_k} - H_k P_k H_k^T \quad (3-19)$$

$$Q_k = J_k C_{v_k} J_k^T \quad (3-20)$$

where,

$$C_{v_k} = \frac{1}{N} \sum_{i=i_0}^k v_i v_i^T \quad (3-21)$$

and the residual sequence:

$$v_k = L_k - H_k X_k \quad (3-22)$$

where $i_0 = k - N + 1$ is the first epoch inside the estimation of a moving window with size N . Here optimal width of this window is 25 epochs (Mohamed & Schwarz, 1998; Wang *et al.*, 2002), $X_{k,k-1}$, $P_{k,k-1}$ are predicted state vector and its covariance matrix respectively, $X_{k,k}$, $P_{k,k}$ are the estimated ones, and J_k denotes gain matrix.

Here, covariance matrices of measurement noise and system noise (R_k and Q_k) are estimated from previous epochs. Through the adaptive Kalman filter recursive formula, RTZD and the double-differenced L1 float ambiguities can be estimated together with corresponding covariance matrix $P_{k,k}$. Then the double-differenced L1 integer ambiguity search was conducted using the LAMBDA method (e.g., Teunissen, 1993; Teunissen, 1995).

This is a process that occurs each time a new satellite appears above the horizon (or at a specified elevation angle) or a cycle slip or long data gap occurs. Given that reference stations are usually located in areas of low signal masking, only a few ambiguities (newly risen satellite and re-gained satellite after a cycle slip or long data gap) will be estimated by the filter. With increasing epochs, the ambiguity estimates will become better and better. The RTZD will also be precisely estimated and then applied to the newly risen satellites. Due to the recursive nature of the adaptive Kalman filter, this method can run in real-time automatically (Chen *et al.*, 2000; Hu *et al.* 2002a).

3.2.2 Correction Generation Scheme

When the double-differenced integer ambiguities are fixed to their integer values, there are many methods to formulate corrections for the user (see, for example, Wanninger, 1995; Wübbena *et al.*, 1996; Han & Rizos, 1996; Gao *et al.*, 1997; Raquet, 1998). Dai *et al.* (2001) showed that the performance of all the methods is similar.

The purpose of the corrections is to reduce the influence of the spatially-correlated errors. This means that when the corrections are applied to the raw code and phase observations made by the user receiver, the influence of the double-differenced atmospheric biases and other errors will be reduced. This results in improved positioning performance. Since the corrections for the user in reality are an estimate of the residual errors (i.e. after the double-differenced integer ambiguities associated with the reference stations have been fixed to their correct values, corrections can then be estimated from the residuals in the L1 and L2 carrier phase measurements for each satellite and epoch). A distance-based linear interpolation algorithm was adopted here (Wübbena *et al.*, 1996; Han & Rizos, 1996; Gao *et al.*, 1997). The advantage of this method for real-time use is that interpolations are performed on an epoch-by-epoch and satellite-by-satellite basis. By using this method, the orbit biases and ionospheric delay can be eliminated and, in addition, the tropospheric delay, multipath and the observation noise can be reduced (Han, 1997). In order to apply this method in real-time, a modified 2-dimensional linear interpolation model, which uses the user's horizontal coordinates as parameters, is employed (Wanninger, 1995; Han & Rizos, 1996; Chen *et al.*, 2000).

The residual vector V can be represent by a two-dimensional linear model which uses the user's horizontal coordinate as input parameters:

$$\begin{bmatrix} V_{12} \\ V_{13} \\ \vdots \\ V_{1n} \end{bmatrix} = \begin{bmatrix} \lambda_k \nabla \Delta \phi_{12} - \nabla \Delta \rho_{12} - \lambda_k \nabla \Delta N_{12} \\ \lambda_k \nabla \Delta \phi_{13} - \nabla \Delta \rho_{13} - \lambda_k \nabla \Delta N_{13} \\ \vdots \\ \lambda_k \nabla \Delta \phi_{1n} - \nabla \Delta \rho_{1n} - \lambda_k \nabla \Delta N_{1n} \end{bmatrix} = \begin{bmatrix} \Delta X_{12} & \Delta Y_{12} \\ \Delta X_{13} & \Delta Y_{13} \\ \vdots & \vdots \\ \Delta X_{1n} & \Delta Y_{1n} \end{bmatrix} \cdot \begin{bmatrix} a \\ b \end{bmatrix} \quad (3-23)$$

Here $\nabla\Delta\phi$ is the double-differenced carrier-phase observable expressed in unit of cycles; $\nabla\Delta\rho$ is the double-differenced geometric satellite-to-receiver distance; λ is the wavelength of the carrier wave; 1 represents the master reference station; 2 to n for the other reference stations in the network. ΔX and ΔY are the plane coordinate differences referred to the master reference station; and a and b are the coefficients for ΔX and ΔY . As can be seen from Equation (3-23), a minimum of three reference stations is required for this process. In cases where more than three reference stations are available, the coefficients a and b can be estimated by a least squares adjustment on an epoch-by-epoch, satellite-by-satellite basis, which also has the benefit of mitigating the effects of multipath through averaging (Han, 1997), as:

$$\begin{bmatrix} a \\ b \end{bmatrix} = (A^T A)^{-1} A^T V \quad (3-24)$$

$$\text{where } A = \begin{bmatrix} \Delta X_{12} & \Delta Y_{12} \\ \Delta X_{13} & \Delta Y_{13} \\ \vdots & \vdots \\ \Delta X_{1n} & \Delta Y_{1n} \end{bmatrix}, V = \begin{bmatrix} V_{12} \\ V_{13} \\ \vdots \\ V_{1n} \end{bmatrix} = \begin{bmatrix} \lambda_k \nabla\Delta\phi_{12} - \nabla\Delta\rho_{12} - \lambda_k \nabla\Delta N_{12} \\ \lambda_k \nabla\Delta\phi_{13} - \nabla\Delta\rho_{13} - \lambda_k \nabla\Delta N_{13} \\ \vdots \\ \lambda_k \nabla\Delta\phi_{1n} - \nabla\Delta\rho_{1n} - \lambda_k \nabla\Delta N_{1n} \end{bmatrix}.$$

Then the corrections for a certain user location within the coverage of the network can be computed on epoch-by-epoch, satellite-by-satellite basis as:

$$V_{1u} = a \cdot \Delta X_{1u} + b \cdot \Delta Y_{1u} \quad (3-25)$$

Where 1 represents the master reference station, u for the user station. ΔX_{1u} and ΔY_{1u} are the plane coordinate differences between the user station and the master reference station. The model can be applied to both the L1 and L2 carrier-phase and pseudo-range measurements.

With real-time generated corrections from the network, the errors that are dependent on distance in the reference station and user data are reduced. This allows users to increase the distance between their receiver and the nearest reference station. It also increases the reliability of the system and the accuracy of the positioning, and reduces the RTK initialisation time.

3.2.3 SIMRSN RTK Data Generation

In order to generate VRS data, the carrier-phase and pseudo-range observations from the master reference station must be altered by applying the corrections of the network according to the user's approximate position, i.e. the VRS position.

Let x^s be the satellite position vector, x^r the master reference station position vector and x^v the VRS position vector. At epoch t , the geometric range between satellite and master reference station receiver is:

$$\rho_r^s(t) = \|x^s - x^r\| \quad (3-26)$$

and the geometric range between satellite and VRS is:

$$\rho_v^s(t) = \|x^s - x^v\| \quad (3-27)$$

The change in the geometric range can be applied to all observations to 'displace' the phase and pseudo-range observations from the master reference station to the VRS position. After the geometric correction, a standard troposphere model, such as Saastamoinen model (Saastamoinen, 1973), can be used to correct for tropospheric delay effects to the VRS data. The resulting VRS data is converted to RTCM or CMR (Compact Measurement Record) format (Talbot, 1996) and transmitted to the user.

3.3 Summary

A novel technique for high precision Network-RTK algorithm has been developed using the active multiple-reference-station network in Singapore. A summary of the methodology is given below:

1. Data from the network receivers are transferred to the Control Centre.
2. The carrier-phase ambiguities are resolved for the network baselines and the relative troposphere zenith delay (RTZD) is estimated using the adaptive Kalman filter.
3. The residuals in the L1 and L2 carrier-phase measurements are used to compute the correction coefficients.
4. The corrections are computed for a certain user location on a satellite-by-satellite, epoch-by-epoch basis.
5. VRS data are generated for the user as RTCM or CMR messages, and broadcast to the user for RTK positioning.

This technique overcomes limitations of single-base RTK positioning. It allows positioning to be performed more efficiently, at longer ranges from a reference station than the standard RTK. In this way, the user benefits from the reliability, availability and accuracy of a multiple-reference-station-network, without having to invest in new RTK software or their own reference station.

Chapter 4

Implementation of the Singapore Integrated Multiple Reference Station Network

4.1 Overview

A major part of this research project involved the implementation of a GPS reference station network as high precision GPS infrastructure in Singapore. The infrastructure will also serve as the country-wide geodetic control network. This network of GPS reference stations will complement the passive ISN (Integrated Survey Network) control points as the key geodetic infrastructure.

The network provides the main infrastructure as well as an “open air research laboratory” for high precision positioning applications. It is the most critical component in this research project as it provides the platform for the implementation of the concept and algorithm. It is also a challenge to build a real-time GPS reference station network based on the availability and affordability of the local communications infrastructure, communication devices and off-the-shelf GPS equipment.

This chapter provides a description of the GPS reference station network. It also discusses various considerations in the development and implementation of the network infrastructure.

4.2 Implementation of the GPS Reference Station Network

The GPS reference station network is the core of the entire system. It was implemented with the assistance of the Survey Department of Singapore (now known as the Survey Services, Singapore Land Authority) over a period of about 9 months. The GPS reference station network was given the name “Singapore Integrated Multiple Reference Station Network” or in short “SIMRSN”.

The SIMRSN implementation includes:

- ❑ Sourcing for reference stations sites,
- ❑ acquisition of hardware (suitable GPS receivers and antennas),
- ❑ setting up infrastructure (putting up antennas and installation of equipment boxes),
- ❑ setting up the real-time networking devices, and
- ❑ implementing the GPS database.

SIMRSN is a high quality, multi-functional GPS reference station network. It utilises state-of-the-art devices for networking and data communication. It aims to serve the needs of real-time precise positioning for surveying, civil engineering, precise navigation, road pricing, etc. The SIMRSN also aims to serve off-line non-real-time users via the Internet.

It is important that the design of this network is based on common data formats and exchange protocols. This ensures that the exciting scientific and operational potential of real-time GPS networks is fully realised. The network has “open system” architecture with no constraints on specific GPS receiver manufacturers. Standard protocols and data formats are used as much as possible. Equipment is commercial-off-the-shelf (COTS) products. Most of the software is self-developed to ensure smooth system integration, flexibility and robustness.

4.3 Configuration and Components of SIMRSN

The implementation of SIMRSN involves the setting up of infrastructure at the permanent GPS reference stations and at the control centre. All of the reference

stations are of the permanent Continuously Operating Reference Station (CORS) variety operating and tracking GPS satellites 24 hours a day. The stations are strategically chosen; four stations are placed at the four extreme corners of the main island of Singapore in order to cover as wide an area as possible, while the fifth station is placed in the centre of the island to minimize the baseline length. The effects of the de-correlate atmospheric refraction on the GPS signal limits the use of the RTK positioning up to distances of 10-15 km from the reference station. In low latitude region (i.e. Singapore), the distance is further reduced to about 5 to 10 km. With the multiple-reference-station-network approach, precise RTK positioning capability may be extended for a much larger area. During the initial stage of SIMRSN, 4 reference stations were established. Initial field tests revealed that RTK was difficult when a user is located in the middle of Singapore. The fifth station in the middle of Singapore was established to strengthen the network.

The effective implementation of Han's method required the user's rover location to be encompassed by a minimum of 3 reference stations (refer to section 2.6.1). The user's location will be used to generate the corrections in the network-DGPS. This prompted us to locate the reference station at the extreme corners of Singapore.

The selection of the GPS reference stations sites is a challenging and progressive process. It took a period of over 2 years to complete. Firstly, it is the identification of the location based on available resources and information such as the street directory and digital database. Sites visits were carried out on the identified locations and if they are suitable, a discussion with the owner of the property was conducted. Once it is finalised, the authority will enter into a tendency agreement to lease the roof area for the reference station.

Generally, the following criteria were used in the selection of the reference station site:

- a. location of reference station sites to be at the extreme corners of Singapore (except NYPC) so to maximise area of coverage for network solution (this will ensure the effectiveness of Han's method);
- b. good sky view i.e. minimum blockage of satellite signals;

- c. location with minimum multipath effects and other microwave disturbance such as the GSM station;
- d. access to the reference station and antenna;
- e. security of the site; and
- f. existing power supply and communication infrastructure (to cut down on the cost of site preparation).

The layout of the network array is shown in Figure 4-1. The circles show the coverage of 10 km radius for each reference station. The inter-station distances are given in Table 4-1 below. The longest baseline of 21.7 km is between KEPC and LOYA, while the shortest baseline is 10.5 km between NYPC and SEMB. Overall, the average spacing between the CORS is about 17 km. The reference station at NTU0 also operates as a Control Centre for the network.

Table 4-1: Inter-station distances of the SIMRSN CORS (km)

	NTU0	SEMB	LOYA	KEPC	NYPC
NTU0	---	20.7	32.6	16.6	19.1
SEMB	20.7	---	20.0	22.4	10.5
LOYA	32.6	20.0	---	21.7	13.7
KEPC	16.6	22.4	21.7	---	13.2
NYPC	19.1	10.5	13.7	13.2	---

Figure 4-1: Singapore Integrated Multiple Reference Station Network (SIMRSN)

The addresses of the five CORS are shown in Table 4-2. The CORS are located at public sites and buildings such as schools, factories and recreational clubs. Detail location maps and location descriptions are given in Appendix A. The physical location of the Control Centre can be located at any place with appropriate network and server facilities. During development stage, there is a frequent need to have direct access to the servers for database, software and server configuration. Hence, it is practical to host the Control Centre at NTU.

Table 4-2: Location of the five CORS in SIMRSN

No.	CORS	Address
1	Nanyang Technological University (NTU0)	Spatial Information Laboratory School of CEE Nanyang Technological University Nanyang Avenue
2	Sembawang (SEMB)	SAF Yacht Club Sembawang Camp 43 Admiralty Road West Singapore 759962
3	Keppel Club (KEPC)	Keppel Club, Bukit Chermin Rd Singapore 109918
4	Loyang (LOYA)	Jurong Town Corporation 30 Loyang Way Singapore 508769
5	Nanyang Polytechnic (NYPC)	Block S1, Engineering Block, Nanyang Polytechnic, 180 Ang Mo Kio Avenue 8

The network configuration and components of SIMRSN are as shown in Figure 4-2. Each of the reference station is connected to the control centre at NTU via a 64 kbps leased line. A Local Area Network (LAN) is created with TCP/IP protocol for networking. These will enable the GPS data to be transmitted back to control centre in real-time. At the control centre, the GPS data will be archived and distributed. A corrections generation ‘engine’, running at the Control Centre, processes the GPS data in real-time. Appendix B illustrates the SIMRSN network configuration and its possible applications.

Figure 4 - 2: Network configuration and components of the SIMRSN

Figure 4-3 : Equipment cabinet at KEPC

4.3.1 GPS Reference Stations Installation

The configuration at the reference station comprises of a dual-frequency geodetic-grade GPS receiver and a choke-ring antenna with auxiliary hardware such as a device server, a router and a network terminal unit. The GPS antenna is situated at the top of the building in order to have a good sky view for maximum GPS signal reception. The GPS receiver and the auxiliary hardware are housed in a ventilated steel cabinet. These equipment cabinets are situated near to the GPS antenna. Figure 4-3 and Figure 4-4 show the GPS reference station at the Keppel Club, Bukit Chermin Road. The GPS antenna is mounted to the wall of a building. Different antenna frames were designed to cater for different requirements of the locations. The setting up of

the GPS reference station sites, running of antenna cables and the decision to locate the auxiliary equipment required much planning. The planning involved processes such as the decision on the running of the power cable; where to run the communication cables; where to locate the antenna pole; logistic during the installation; etc. A site installation plan was created and submitted to the owner of the building for approval. Photographs of each of the GPS reference station are given in Appendix C.

Figure 4-4 : GPS antenna and equipment cabinet at KEPC

4.3.2 Control Centre

The Control Centre is situated in the Spatial Information Laboratory, School of Civil and Environmental Engineering, Nanyang Technological University (NTU). The Control Centre is the heart of the SIMRSN. It is located at NTU where the development of the system took place as the direct access to the server is important during this stage.

The major components at the Control Centre are the Windows NT servers and other networking peripherals. The system software are designed to be implemented separately on several servers as well as sharing a server. The decision is based on the capacity of the server and the usage of the system. The functions of the Control Centre are as follows:

- ❑ It receives, processes and generates correction terms;
- ❑ all GPS data are archived here;
- ❑ serves as the Control Centre to manage other reference stations;
- ❑ a specially designed database is situated here; and
- ❑ it has a web server to cater for web-based applications.

The implementation of SIMRSN is on 3 physical servers which are known as:

- ❑ GPS server;
- ❑ Database server (SQL server); and
- ❑ Web server + FTP server + SIMRSN MRC server.

The functions of each server are described in Section 4.6. The leased lines that come from each reference station are connected to four network terminal units. Each of the network terminal unit is wired to a router via four V.35 cables. The router is linked to a hub with a 10/100 Tbase cable. The three servers used in the system are linked up to the hub. The main port of the hub is connected to NTU's network backbone (See Figure 4-2). Figure 4-5 shows the server rack in NTU that houses the three servers, hub, router, uninterruptible power system (UPS) and the network terminal units. NTU is both a GPS reference station as well as the Control Centre for the network.

Figure 4-5: SIMRSN Control Centre located at NTU

4.4 Coordinate Determination of the SIMRSN Reference Stations

Coordinates of the reference stations in the SIMRSN must be determined to very precise level. One GPS survey campaign was conducted simultaneously on known primary Singapore Integrated Survey Network (ISN) control points (Base7, BED, CSE, PRP, SAR, SENO, SENT1) on 24 August 2001. All stations logged GPS raw data at 15 seconds interval from 8:30am to 14:00pm (local time). Trimble Geomatics Office version 1.50 software was used to do the baseline processing and network adjustment together with SIMRSN reference stations' data. The coordinates of the five reference stations, which have been transformed to local datum SVY21, are shown in Table 4-3. Details of the coordinates in WGS 84 are given in Appendix D.

Table 4-3: Coordinates of the SIMRSN CORS in SVY21

Reference Station ID	Northing (SVY21) (m)	Easting (SVY21) (m)	Height above Ellipsoid (WGS-84) (m)
NTU0	36435.856	10931.929	76.257
SEMB	50143.261	26466.730	30.900
LOYA	39406.335	43394.281	51.153
KEPC	27727.849	25087.183	37.445
NYPC	40121.066	29717.586	55.645

4.5 Network Infrastructure and Design

One of the most important issues to address in this research is the network link between the GPS reference stations and the Control Centre. It is a networking challenge to create a system that must function automatically, continuously and reliably. The GPS data has to be transferred to the Control Centre instantaneously so that real-time corrections can be generated. In this situation, reliable networking devices must be sourced and most importantly a high-speed data link is needed. It was decided to use the 64kbps dedicated leased line service provided by one of the telecommunication companies in Singapore. The networking protocol used was the TCP/IP, a common protocol for the Internet. A Local Area Network (LAN) has been created using the static 192.168.10.X IP addresses schema set. This IP set is designated for private usage. All the CORS has been given two IP numbers on the device server and router located at the CORS. The IP addresses and other CORS information for each reference station of the SIMRSN are given in Appendix E.

Besides enabling the GPS data to be transmitted back to NTU in real-time, the leased line connections also allow the Control Centre to monitor and maintain the CORS remotely. With the link, operators can monitor and reinitialise the GPS receivers from the Control Centre, reducing maintenance time and cost.

4.6 Hardware Considerations

The hardware equipment used in the SIMRSN are listed below:

- ❑ 5 units of GPS receivers,
- ❑ 4 units of terminal server or device server,
- ❑ 5 units of routers,
- ❑ 4 units of network terminal units,
- ❑ 1 hub, and
- ❑ 3 computer servers.

The device servers are used at the GPS reference station to replace the computer as a network node in the SIMRSN configuration. The specification of the device server used is given in Appendix F. The equipment are connected in a network environment (Figure 4-2) so that the GPS data can be relayed back to the Control Centre at NTU. The GPS receiver chosen for SIMRSN meets the following criteria:

- ❑ Dual-frequency, L1 and L2 with carrier phase and pseudo-range output;
- ❑ 12 channels;
- ❑ data measuring rate of 1 Hz (one epoch per second);
- ❑ choke-ring antenna (except at NTU0 which uses a Trimble Micro Centred Compact Geodetic Antenna with ground plane).

The SIMRSN uses three different makes of GPS receivers. The specifications of the receivers can be found in the manufacturers' web sites.

- ❑ Trimble 4700 with choke-ring antenna;
- ❑ Leica CRS1000 with choke-ring antenna;
- ❑ Ashtech Z-surveyor FX with D/M choke-ring antenna.

The reason for using different brands of receiver is that it will create an opportunity to compare the reliability of the receivers. The GPS receivers chosen are able to track up to 12 satellites in carrier phase and pseudo-range on both the L-band frequencies. It is essential to eliminate multipath as much as possible at a reference

station. Hence, choke-ring antennas were used because of their ability to mitigate multipath errors.

The configuration of the SIMRSN requires at least three servers running at the Control centre. One of the servers is primarily used to receive GPS data and log the GPS data binary files. The second server runs the correction generation software to support the real-time users. This server also is used as the Internet host for offline users. The third server is used to store the database. The database is located at the third server because continual updating of the database uses a large amount of CPU time. This updating process affects the performance of a server.

The routers, the network terminal units and the hub are used to facilitate the network connection. IP addresses are given to each router and device server (terminal server) so that the server at NTU is able to communicate with them.

The device server from Lantronix is used to connect to the GPS output, which is a serial interface. The device server is able to convert the serial interface to an Ethernet network using the TCP/IP protocol. It has a network interface speed of 10-Mbit/s. The Lantronix CoBox-E2 has two serial interfaces, 1xRS-232/RS-422 DB25 and 1xRS-232 DB9. It is used to connect to two separate serial devices. In this case, two types of data can be transmitted back to the Control Centre separately.

4.7 Database Development

Besides serving real-time users, the SIMRSN system is also developed to serve off-line GPS users. Non-real-time applications include positioning tasks as well as other research activities. A substantial database has been developed to accommodate this demand. Users are able to access the database via the World Wide Web.

A database enables accelerated access to specific data. It provides an organised method to archive and distribute large amounts of data. A Relational Database Management System (RDBMS) allows users to access data via the Internet. Web-based programmes can be developed for specific applications. A front-end client can be easily built with off-the-shelf components such as Visual Basic, C++, Java and many other languages. Listed below are some of the advantages of MS SQL Server 7:

- ❑ Seamless integration with the Microsoft NT Server and the Windows 2000 operating system;
- ❑ well integrated with the Microsoft Internet Information Server 4.0 (IIS) for Web-based database application;
- ❑ relatively low cost; and
- ❑ database administration and maintenance made easy through the Enterprise Manager.

Updating the database is a very intensive process (high CPU-time consuming), hence it is very important to keep the database separated from the GPS server. After much consideration, the database was installed on the Web Server. The database is updated with new data every 15 minutes.

Several alternatives for the design of the database schema were investigated. The data model is suited for use in several RDBMS: IBM DB2 Universal Database, Informix, Microsoft Access, Sybase SQLServer, Oracle8 Server, UniSQL and MS SQL Server 7. The data model describes the table and indexes used to store GPS data from multiple reference stations. The table structure is designed to allow changes to be made if required. Appendix G provides the details of the table structure, including a database schema diagram that shows the relationships between the tables in the entire database.

The database of the SIMRSN is designed with the following considerations:

- ❑ The table structure should be as portable as possible to enable it to be used with different database software, such as Oracle, Informix or SQL Server.
- ❑ The table structure is designed in a way that it can cater for a wide range of scientific research activities.
- ❑ All table names are less than 18 characters. Maximum number of characters in the table name allowable in Informix is only 18.
- ❑ The data type of each field must be appropriately defined to keep the size of the database as small as possible.
- ❑ Indices must be created for fast retrieving of data.

The architecture of the SIMRSN database, organised in four data groups, is illustrated in Figure 4-6. The groups are connected via the relevant key fields. Several tables are designed under each group to archive the appropriate data (Figure 4-7). The groupings are based on the source of data and their roles. Figure 4-6 shows the relevant input (data source) to each of the group. Table 4-4 lists each table in the GPS database and the function of each table. The input to the SIMRSN database is done via several different software developed in this project.

Figure 4-6: SIMRSN database architecture

Figure 4-7: Relationship between the four tables under the GPS Base Station Information group

Table 4-4: Function for each table in the SIMRSN database

	Table Group	Table Name	Function
1	GPS Base Station Information	SAT_RECEIVER	Stores GPS receiver information
		SAT_SITE	Stores site particulars e.g. location, X, Y, Z
		SAT_ANTENNA	Stores antenna information
		SAT_REC_ANT	Stores sites, receivers and antenna in used
2	GPS Raw Data	SAT_DATA	Stores raw GPS data e.g. L1, L2, C1, P2
		SAT_EPOCH	Stores information of each epoch e.g. no. sat.
		SAT_NAV	Stores navigation messages for each satellites
		SAT_INTERVAL	Stores interval if any.
		SAT_LEAPSECONDS	Stores leap seconds information
3	Precise Ephemeris	SAT_PRECISE_HEADER	Stores header information of precise orbit
		SAT_PRECISE_ORBIT	Stores precise ephemeris orbit data
4	Almanac and Meteorological Data	SAT_ALMANAC *	Stores almanac of the satellite constellation
		MET_HEADER *	Stores Meteorological data header
		MET_SENSOR_TYPE *	Stores meteorological sensor information
		MET_DATA *	Stores meteorological data

* Not implemented

The data types determine the amount of storage needed. For example, a “DATETIME” format (used in MS SQL) requires eight bytes while a “SMALLDATETIME” type requires only four bytes. The amount of data stored in the database depends on various factors such as:

- ❑ data rate,
- ❑ elevation mask,
- ❑ number of observables such as L1, L2 carrier-phase, CA pseudo-range, etc.,
- ❑ number of sites (GPS reference stations), and
- ❑ number of days of data kept in the database.

Table 4-5 provides an approximate guide on the number of rows occupied and the storage space needed for daily GPS data and precise ephemeris. It has been decided to keep only 10 days of GPS data in the database. This decision is based on the storage space available. Old data will be converted to RINEX format and archived onto DVD on a monthly basis.

Table 4-5: Number of rows needed per day for the five main tables in the SIMRSN database.

Table	Number of rows in 1 day for 4 reference stations (based on 7 satellites and 1 second data rate)
SAT_DATA	2,592,000
SAT_EPOCH	86,400
SAT_NAV	468
SAT_PRECISE_HEADER	1
SAT_PRECISE_ORBIT	2880

4.8 Software Development

Software development is a major aspect in the implementation of the SIMRSN. Part of the research goal is to investigate an efficient and robust method to compute and distribute corrections to RTK users. To accomplish this task, a few software ‘engines’ are developed to handle:

- ❑ the transmission of GPS raw data back to the Control Centre;
- ❑ the generation of the corrections; and
- ❑ the distribution of the corrections to users.

This section describes the software development work carried out to support the operations of the integrated reference station network.

Software for the project is developed under the Windows platform. Four applications programmes were identified in the development:

- ❑ software that runs at GPS reference stations and transfers raw GPS data to the Control Centre;
- ❑ software that runs at the Control Centre that collects GPS data, generates correction terms for real-time application, and computes rover position for near-real-time applications;
- ❑ database management software that archives GPS data for post-processing applications; and
- ❑ real-time and near-real-time applications software running at user sites.

The developed software is divided into two major groups; the post-processing and real-time applications. The details about the programmes are given in Appendix H. Based on the above requirements, the following modules (or applications) were developed:

1. *SIMRSN RS Connector* (RS – Reference Station);
2. *SIMRSN DB Server* (DB – Database);
3. *SIMRSN DB Manager*;
4. *SIMRSN EPH Server* (EPH – Ephemeris);
5. *SIMRSN RS Monitor*;

6. *SIMRSN DB2RINEX*;
7. *SIMRSN RINEX Generator*;
8. *SIMRSN MRC Server* (MRC – Multiple Reference Corrections);
9. *SIMRSN MRC Generator*;
10. *SIMRSN MRC Manager*;
11. *SIMRSN VRS* (VRS – Virtual Reference Station) and *SIMRSN VRS CE*; and
12. *SIMRSN SMS Server* (SMS – Short Messaging System).

Appendix I shows the architecture of the SIMRSN real-time correction system. It shows the flow of the GPS data and the MRC corrections. The appendix also shows how real-time users connect to the SIMRSN system.

4.9 Wireless Data Communications

Wireless data communications are used to distribute the correction terms to the rover users. There are several well-established wireless data networks available in Singapore. These networks include the Mobitex, the DataTAC and the GSM/GPRS network. One advantage of these networks is the capability for two-way (duplex) communication. The research used GSM/GPRS, as it is the most reliable and widely used network. Furthermore the network has full coverage of the whole Singapore.

Listed are some considerations in selecting the wireless network:

- ☐ data transfer rate,
- ☐ latency,
- ☐ data integrity,
- ☐ network coverage,
- ☐ usage charges, and
- ☐ availability.

4.10 Summary

GPS reference station networks are becoming more essential to providing high precision positioning solutions all over the world.

SIMRSN, a real-time city-scale GPS reference-station-network infrastructure for positioning, has been established in this research project. The network consists of five permanent GPS reference stations connected via high-speed leased line to a central control centre. The GPS raw data are transmitted to the Control Centre in real-time. SIMRSN was designed specifically to suit the requirements of Singapore. Tests were carried out to monitor the functionality and reliability of the network.

Chapter 5

Real-Time Kinematic Survey with the SIMRSN

5.1 Overview

One of the objectives of this study is to assess the technical feasibility of setting up an operational multiple-reference-station-network infrastructure for real-time high precision positioning. SIMRSN is designed and built to support high precision positioning using carrier-phase in Singapore. To demonstrate the capabilities and potential of the SIMRSN, various experiments and tests were carried out. The tests were conducted to evaluate:

- ❑ the accuracy attainable using dual-frequency phase-measuring receivers;
- ❑ the performance of the SIMRSN compared to a commercially available system;
- ❑ the effectiveness of the corrections generated from the SIMRSN;
- ❑ the enhancement in time-to-fix and accuracy for Real-time Kinematic (RTK); and
- ❑ the SIMRSN-RTK latency.

This chapter describes the experiments and tests carried out to assess and evaluate the SIMRSN in the real-time mode. Analyses of the results are also presented here.

5.2 Real-Time Kinematic Survey with SIMRSN

SIMRSN Real-time Kinematic (RTK) is carried out in a similar way to conventional single-based RTK.

To realise the network-RTK, the Virtual Reference Station (VRS) concept is employed. This concept allows the multiple-reference-station corrections to be computed and integrated into the observation of a “virtual reference station” that is very near to the location of a rover user. For more information on the technical background of VRS see, for example, Marel (1998), Wanninger (1999), Vollath *et al.* (2000), Petrovski *et al.*, (2000), Hu *et al.* (2002b), Hu *et al.* (2002c). SIMRSN supports two types of data link:

- ❑ GSM direct dial-up via modem, and
- ❑ Internet connection via GPRS or GSM.

In the GSM direct dial-up mode, a user will dial directly into the SIMRSN server via a modem. As the direct dial-up is a one-to-one connection, many modems are needed to support the number of users simultaneously. The user RTK receiver which is connected to a GSM modem, sends its approximate position to the SIMRSN Control Centre. The software at the Control Centre will choose the nearest reference station to the user as the master reference station. The raw data from that reference station is then enhanced by applying the corrections of the SIMRSN according to the approximate position of the user, and transmitted as RTCM or CMR messages to the user receiver via a GSM with data rate of 9,600 bps. Figure 5-1 illustrates the SIMRSN GSM data link model.

For the Internet connection, a user can choose to use GPRS or GSM services. In both cases, a user has to dial-up to a service provider first, before accessing the SIMRSN server via a TCP/IP socket.

Figure 5-1: SIMRSN GSM RTK model

In the second mode of operation, a user dials up to an Internet service provider using either GPRS or GSM. User will need to use SIMRSN rover software to connect to the SIMRSN server. Before the RTK data is generated for a user, authentication will be carried out. Conceptually, the system broadcast the correction onto an IP (or Internet). The connection to the correction is via IP addresses. Hence, the system supports any means that enabled a user to access the Internet both wired or wireless. These include broadband and 3G services. The Internet connection software running on a Pocket PC is illustrated in Figure 5-2. The SIMRSN GPRS model is illustrated in Figure 5-3.

Figure 5-2: SIMRSN Internet connection software running on a Pocket PC

Figure 5-3: SIMRSN GPRS RTK model

5.2.1 SIMRSN-RTK Format and Data Link

The performance of a Real-Time Kinematic (RTK) system is highly dependent on the data link component between the reference (base) and the rover. Each manufacturer has developed proprietary protocols for communicating reference station data to the rover station(s). The RTK data transmission standard used in the SIMRSN is the CMR (Compact Measurement Record) format. The CMR format contains packet framing and message types for raw L1 and L2 carrier-phase and pseudo-range data, plus reference station location information and description messages. This format only requires half the bandwidth of the equivalent RTCM-SC104 messages. The RTCM messages have a large framing overhead and do not include significant data compression algorithms to make them practical for many data link options. See Talbot (1996) for more information about CMR, and RTCM SC-104 (1994) for information about RTCM. The performance of a RTK data link can be judged based on the following parameters:

- ❑ cost;
- ❑ data link range and coverage;
- ❑ transmission bandwidth / latency;
- ❑ error checking and correction; and
- ❑ licensing issues.

Listed below is the data link options commonly used for RTK data transmission:

- ❑ Radio / modem,
- ❑ cellular phone (via GSM or GPRS),
- ❑ FM sub-carrier, and
- ❑ satellite link.

The data link should be chosen to match the operating conditions for the project. For example, in open undulating terrain, a one-Watt output, spread spectrum radio/modem set-up in the 900MHz band would provide appropriate coverage up to a few kilometres. For greater coverage, users can employ radio repeaters. In built-up areas, near line-of-sight radio coverage may be difficult and cellular phone networks would be better. Commercial operations have taken advantage of available data bandwidth on FM radio station transmissions and broadcast GPS reference station data on FM sub-carrier bands. Many cities around the world have had FM sub-carrier reference stations for metre-level differential GPS. In remote locations a satellite link provides excellent radio coverage, even though it is expensive compared to other systems.

For the SIMRSN, the intended coverage area is about 20 X 40 km (the size of the Singapore island). Radio/modem is not a good choice as the radio transmission regulations are tight and a suitable transmission station has to be identified. FM sub-carrier is also not suitable in this case as the SIMRSN needs the approximate coordinate of the rover to be sent back to the Control Centre (requires two-way communication). Cellular phone was thus chosen for its coverage and availability in Singapore.

The introduction of GPRS (General Packet Radio Service) service in Singapore provided another option for the RTK transmission. The Internet can be used as a communication option for RTK. The greatest advantage of GPRS for mobile subscribers lies in the possibility to have continuous connectivity to the Internet, the corporate Intranet or a WAP portal, for fast access to new content-rich services. However, one of the critical characteristics of the Internet is the

unexpected transfer latency, which will have a great effect on RTK positioning accuracy. Hence, there is a need to carry out tests to assess the quality of the GPRS data link option.

5.2.2 SIMRSN-RTK Latency

As discussed in previous chapters, the SIMRSN is able to generate "correction terms" for the RTK technique. These "correction terms" can be transmitted in either the RTCM or the CMR format. On average, about 252 bytes are used to transmit the "correction terms" of about 9 satellites using the CMR format (Talbot, 1996) as compare to about 500 bytes used in the RTCM format. The CMR format is thus more economical if the charges for transmitting data are based on data volume.

Software has been written to measure the latency of the Internet for transmissions of RTK messages to users. One version of the programme is running on Windows PC and another version is running on the Pocket PC operating system. Figure 5-4 shows the test programme running on a Pocket PC.

The latency tests were carried out by transmitting a packet size of 252 bytes from the user device to the server at the SIMRSN Control Centre and back to the user device. The RTK transfer latency is simply half of the round trip time taken for the packet to travel from user to server and back to user. We are only measuring time on the user device. The Windows 2000 operating system used in the tests is able to measure time to a precision of 10 ms (milliseconds) according to the specifications. The 252 bytes packet was chosen to be as near (similar) to the actual size of the 1 Hz RTK messages used in the SIMRSN.

The average results of the latency tests using different devices are tabulated in Table 5-1. The average latency of all the devices is 759 milliseconds. It is observed that differences in latency using various devices are small and can be ignored. Figure 5-5 shows the test results using a laptop with Bluetooth connection to a GPRS phone.

Figure 5-4: Pocket PC program for RTK latency test

Table 5-1: Internet RTK latency using different devices (average of each test)

	Test 1 (ms)	Test 2 (ms)
Laptop with Bluetooth Connection to GPRS phone	756	760
Pocket PC with Bluetooth Connection to GPRS phone	723	742
Pocket PC with Wireless Ipaq GPRS	804	767

Figure 5-5: Test results using laptop with Bluetooth connection to GPRS phone

5.3 Real-time Kinematic (RTK) Positioning Tests

A number of real-time field tests were conducted at different locations in Singapore during January and February 2002. The tests were carried out primarily to assess the stability and correctness of the software created. The tests were used also to demonstrate the connection to the SIMRSN Control Centre.

The two most important criteria in determining the performance of a RTK system are the positioning accuracy and the time required for ambiguity fixing. Tests were carried out to determine:

- i) whether centimetre accuracy can be achieved; and
- ii) the average time-to-fix ambiguity for RTK initialisation at rover users.

The Test 8, 9 and 11 were used in the accuracy and TTF analysis. The time and venue of the tests are listed in Table 5-2. The location of each test point is shown in Figure 5-6.

Table 5-2: RTK positioning tests timetable and locations

Test No.	Time (local time)	Venue	Point ID
1	1100 h ~1600 h, 22 Jan 2002	Woodlands Avenue 5	WLA5
2	1206 h ~1547 h, 23 Jan 2002	Lower Peirce Reservoir	LOPR
3	1100 h ~1609 h, 25 Jan 2002	Jalan Pemimpin	GPSL
4	1000 h ~1700 h, 28 Jan 2002	Jalan Pemimpin	GPSL
5	1000 h ~ 1500 h, 1 Feb 2002	Woodlands Avenue 5	WLA5
6	1121 h ~ 1610 h, 4 Feb 2002	Jalan Pemimpin	GPSL
7	0900 h ~ 1740 h, 14 Feb 2002	NTU	NTU1
8	0900 h ~ 1600 h, 15 Feb 2002	NTU	NTU1
9	1120 h ~ 1600 h, 19 Feb 2002	Lower Peirce Reservoir	LOPR
10	1500 h ~ overnight, 22 Feb 2002	Jalan Pemimpin	GPSL
11	1000 h ~ overnight, 26 Feb 2002	Jalan Pemimpin	GPSL
12	1000 h ~ overnight, 27 Feb 2002	Jalan Pemimpin	GPSL
13	1100 h ~ 1600 h, 28 Feb 2002	Woodlands Avenue 5	WLA5

Figure 5-6: Locations of test points

Only 3 tests were reported in the thesis. The earlier tests (test no. 1 to 7) were only used to assess and ascertain the functionality and stability of the communication configuration and software developed. The earlier tests were also meant for the fine tuning of the software and algorithm during the development of SIMRSN. The data collected for earlier tests was not complete for analysis. These initial tests and results were repeated and similar in nature to the 3 tests reported.

- i.) Test 8 at NTU1 (15 February 2002),
- ii.) Test 9 at LOPR (19 February 2002), and
- iii.) Test 11 at GPSL (26 February 2002).

All the test locations were selected because they have the following criteria:

- i.) Good sky view i.e. minimum blockage of satellite signals;
- ii.) location suitable for long hours of observation i.e. minimum disturbance by public; and
- iii.) location with minimum multipath effects and other microwave disturbance.

The location encompassed by the 4 reference stations located at the extreme corners, the NTU0, SEMB, LOYA and KEPC, forms the SIMRSN network coverage area. WLA5 is located far from the master reference station, NYPC. This point represents points situated at the fringe of the SIMRSN network. LOPR is located near to the master reference station and it represents points located around the central area of Singapore. GPSL was selected because the location is on the roof-top of a building and there were power supply and a secure office for continuous overnight 24-hour data collection. NTU1 was selected as the point representing location outside the SIMRSN network coverage. The multiple-reference-station algorithm is most effective and works well if the user location is within the coverage area of the reference stations as reported by Chen (2001). However, correction can be calculated for a location outside the multiple-reference-station area.

Figure 5-7 is a photograph of the portable computer used to log the RTK data and results. Figure 5-7 and Figure 5-8 show the typical test set-up. A GSM PCMCIA card is used to dial into the Control Centre to acquire the RTK

corrections. All NMEA GKG outputs from the receivers are logged into the portable computer.

Position errors are calculated based on the “true position” of the test point. The “true position” is determined by at least half-an-hour of static GPS survey. These errors indicate how accurate the system is. Besides the positioning accuracy, the crucial factor in the operational use of RTK-GPS is the speed at which it can initialise (i.e. solve for integer ambiguities), and is expressed as TTF (Time-to-Fix) or TTFA (Time-To-Fix-Ambiguities) value (Edwards *et al.*, 1999; Wübbena *et al.* 2001; Hu *et al.*, 2002b). The TTF of RTK refers to the observation time required to resolve integer ambiguities in real-time after re-initialisation. A programme was written to monitor the status of the receiver’s positioning mode. Five seconds after each successful fixing or three minutes at the latest (if no fixing occurred), the GPS receiver’s RTK ‘engine’ will be completely reset. This is referred to as re-initialisation. For the testing purpose, it is determined that three minutes is the maximum time to wait for a time-to fix. The time-to-fix is affected by many factors such as the number of satellites observed, their DOP values (indicating the satellite geometry), multipath conditions and the latency of the RTK message transmission.

Figure 5-7: The portable computer being used in the test (left photo). The hand phone, the GSM card and the TSC1 used to dial into the Control Centre (right photo)

Figure 5-8: Typical test set-up with GSM PC card being used to dial into the SIMRSN Control Centre

5.3.1 Test 8: RTK accuracy and TTF analysis

This test was conducted on the rooftop of the Block N1 in NTU, from 0100 h to 0940 h UTC (0900 – 1740 h local time), using NYPC as the master reference station, 19.1 km away from the rover. The rover was a Trimble 5700 dual-frequency receiver with Zephyr antenna. Using the VRS concept, a representative sample of the differences between epoch-to-epoch coordinates in local datum SVY21 obtained by RTK positioning at the rover, NTU, and the known coordinates are shown in Figure 5-9. The standard deviations of the easting, northing and height components are 0.009 m, 0.005 m and 0.0149 m respectively. Figures 5-10, 5-11 and 5-12 show the histograms of the easting, northing and height errors, respectively. It can be seen from these figures that the position accuracy in the easting, northing and height components are 27mm, 18mm and 37mm respectively at the 99% confidence level.

Test Name: Test 8
Test Date/Local Time: 15 February 2002 0900 h – 1600 h local time
Location: Nanyang Technological University
Point ID: NTU1
Known Position: N 39105.628 m E 27203.667 m
Known Height: 25.231m
Receiver Type: Trimble 4700
Antenna Type: Trimble Micro-centre L1/L2 w/Groundplane

Figure 5-9: Position error in easting, northing and height

Figure 5-10: Histogram of position error of the easting component

Figure 5-11: Histogram of position error of the northing component

Figure 5-12: Histogram of position error of the height component

The TTF for RTK vs. PDOP value and number of satellites is shown in Figure 5-13. Distribution plot of the TTF is shown in Figure 5-14. It can be seen that the TTF for RTK with the SIMRSN corrections was within 80 seconds at the 90% confidence level. The overall averaged TTF was 47 seconds.

Figure 5-13: The TTF for RTK vs. PDOP value and number of satellites

Figure 5-14: Analysis of TTF for RTK at NTU0

5.3.2 Test 9: RTK accuracy and TTF analysis

This RTK test was carried out on 19 Feb 2002 in the vicinity of the Lower Peirce Reservoir (LOPR, see Figure 5-6 for the location of this test point). The location of this test is especially chosen to be in the middle of Singapore and also approximately in the centre of the SIMRSN coverage. This test point is 2.7 km from the NYPC, which is used as the master reference station in the test. This is an outdoor point where all equipment is powered by batteries. The details of the tests are tabled below.

Test Name:	Test 9
Test Date/Local Time:	19 February 2002 1120 h – 1600 h local time
Location:	Lower Peirce Reservoir
Point ID:	LOPR
Known Position:	N 39105.628 m E 27203.667 m
Known Height:	25.231m
Receiver Type:	Trimble 4700
Antenna Type:	Trimble Micro-centre L1/L2 w/Groundplane

The horizontal (easting and northing) error is generally less than three centimetres. The standard deviations are 0.010 m, 0.007 m and 0.018 m for the easting, northing and height component respectively. Figure 5-15 shows the position error for the easting, northing and height components.

Figure 5-15: Position error for easting, northing and height

Figure 5-16 shows the three-dimensional positioning error over a period of 2000 seconds. Generally, three-dimensional errors are less than 0.1 metres.

Figure 5-16: 3-D positional error

Figure 5-17 shows the TTF information from the tests. The TTF is plotted together with the PDOP and number of satellites. These two parameters are important in determining the TTF. It is observed that during the test period from 1230 h to 1600 h local time, all the TTF are less than 180 second (cut-off time).

Figure 5-17: Time-to-fix

Figure 5-18 depicts the error distribution. It indicates that 99% accuracy to be within 17 mm, 18 mm and 49 mm for northing, easting and height components, respectively.

Figure 5-18: Histogram of position error of the easting component

Figure 5-19: Histogram of position error of the northing component

Figure 5-20: Histogram of position error of the height component

5.3.3 Test 11: RTK accuracy and TTF analysis

This test was carried out on 26 February 2002 (GPS week 1155, Day of year 57), approximately between 0250 h and 0817 h UTC (1050 h -1617 h local time), using a Trimble 4700 dual-frequency receiver with Zephyr antenna at the GPSL station. Similar to Test 8 and 9, NYPC is used as the master reference station. Figure 5-21 shows the differences between coordinates obtained by RTK at each epoch and the known coordinates (computed from a 6 hours static survey). The standard deviations of the easting, northing and height components are 0.007 m, 0.008 m and 0.016 m respectively. Figures 5-22, 5-23 and 5-24 show the histograms of the positional error for the 3 components. Results indicate that for 99% of the time, positional accuracy was better than 29 mm, 27 mm and 44 mm for the easting, northing and height components, respectively.

Figure 5-21: Position error in the easting, northing and height at GPSL

Figure 5-22: Histogram of position error of the easting component

Figure 5-23: Histogram of position error of the northing component

Figure 5-24: Histogram of position error of the height component

Figure 5-25 shows the TTF for RTK carried out at GPSL. The TTF is plotted against PDOP value and the number of satellites. It can be seen that the TTF for RTK with the SIMRSN corrections was within 100 seconds at the 90% confidence level. The overall averaged TTF was 72 seconds during the test (see Figure 5-26).

Figure 5-25: TTF, PDOP and number of satellites

Figure 5-26: Analysis of TTF for RTK at GPSL

5.3.4 SIMRSN-RTK Test using Leica System 500

This series of test was carried out to assess the compatibility of the SIMRSN CMR messages for use with Leica equipment. The standard CMR format used by the SIMRSN is meant to support a variety of GPS hardware.

The results (Figures 5-27 and 5-28) show that the horizontal accuracy is better than 23 mm for Easting and 28 mm for Northing, 95% of the time. The average TTF is 55 seconds. This RTK equipment is able to achieve a very stable TTF. Most of the time, RTK fixes are obtained in less than 26 seconds (See Figure 5-29).

Listed below is the detail of the first test:

Test Name:	Leica 530 Test	
Test Date/Local Time:	31 July 2002	1030 h – 1530 h
Location:	Spatial Information Lab, CEE, NTU	
Point ID:	NTU1	
Known Position:	N 36439.288 m	E 10930.396 m
Known Height:	76.252m	
Receiver Type:	Leica 530	
Antenna Type:	Leica AT502

Figure 5-27: Histogram of easting error, using Leica 530 at NTU1

Figure 5-28: Histogram of northing error, using Leica 530 at NTU1

Figure 5-29: Time-to-fix using Leica

5.3.5 SIMRSN-RTK Test using Different Master Reference Station

SIMRSN's RTK corrections are distributed in standard CMR format. This format only supports the single-reference station RTK mode. Hence for the distribution of the SIMRSN multiple-reference corrections, a master reference station has to be selected. The corrections will be applied to the GPS observations of this master reference station and transmitted to the rover. Hitherto there was no transmission format for network-RTK. Hence, the concept of integrating multiple reference station corrections into a single master reference station GPS observation is known as Virtual Reference Station (VRS) concept.

This test was carried out to determine if the distance to the master reference station would affect the time-to-fix of the SIMRSN-RTK.

Two master reference stations were chosen, NYPC, which is about 19 km from the rover, and NTU0 which is only about 2 metres from the rover. Figure 5-30 shows the comparison of TTF for both scenarios. Generally, it is faster to fix using NTU0 as the master reference station. Out of the 100 samples measured, NTU0 produced a faster TTF in 63 samples; the same in 15 samples; and slower than NYPC in 22 samples.

Figures 5-31 and 5-32 give the TTF versus the number of satellites and PDOP; practically the same for the two master reference stations used.

Test Name:	Master Reference Station Test	
Test Date/Local Time:	29 July 2002	1330 h – 1600 h
Location:	Spatial Information Lab, CEE, NTU	
Point ID:	NTU1	
Known Position:	N 36439.288 m	E 10930.396 m
Known Height:	76.252m	
Receiver Type:	Trimble 4700 and Trimble 4800	
Antenna Type:	Microcentred for Trimble 4700

Figure 5-30: Comparison between NYPC and NTU0 as master reference station

Figure 5-31: RTK time-to-fix using NYPC as master reference station

Figure 5-32: RTK time-to-fix using NTU0 as master reference station

Figure 5-33 shows the results of a second similar test. For the 100 samples measured, NTU0 produced 61 samples with faster TTF, 11 with the same and 28 samples with slower TTF than that of NYPC. These results generally confirm that it is easier to get fixed ambiguities when the master reference station is nearer to the user location.

Figure 5-33: Comparison between NYPC and NTU0 as master reference station

5.4 Comparison between SIMRSN-RTK and Standard RTK

SIMRSN-RTK is carried out based on the network solution as explained in section 5.2. The Standard RTK is based on a single reference station. The test was carried out from 11 am to 3 pm on 7 November 2000, during the period of high ionospheric influences. The location of the rover (test point BB01) was at the Bukit Batok Heavy Vehicle Park, which is about 6 km from the reference station NTU0. The distance was chosen to be less than 10 km so that the standard RTK technique is still effective. For the SIMRSN-RTK solution, only 3 reference stations were used (SEMB, NTU0 and LOWD) in the test. Subsequently, LOWD was replaced by KEPC during the last quarter of 2001 as the school site of LOWD was undergoing a major renovation for expansion. The setup of the test is shown in Figure 5-34. The equipment includes a laptop computer, a VHF radio transmitter and a RTK-GPS receiver. The configuration of the test is not the usual one because the laptop served as the relay component. During the tests, only three of the four reference stations in the SIMRSN were used to generate the “corrections”. Figure 5-35 shows the test point BB01 and the three reference stations used, and their respective baseline lengths. SEMB was designated as the master reference station, to which all the computations involving the reference stations were related.

Figure 5-34: The radio link-GSM set-up (right) and the RTK test set-up (left)

Figure 5-35: SIMRSN reference stations and the test point at Bukit Batok (BB01)

This test was carried out earlier than the other tests in year 2000. During that time, only 3 reference stations were in operation. The objective was to compare the SIMRSN-RTK and the standard RTK. We are able to do that base on 3 reference stations. However, for effective standard RTK, we need a location which is between 5 to 8 km from any one reference station. The location at Bukit Batok (BB01) was chosen as it is about 6.4km from NTU0. The two tests, SIMRSN-RTK and Standard RTK were not carried out at the same time. They were done 30 minutes apart. The number of satellites available during the Standard RTK test period is more but the average TTF is slower then SIMRSN-RTK.

Table 5-3 summarises the results of the TTF test for the standard RTK and SIMRSN-RTK. Figure 5-36 and Figure 5-37 show the TTF using SIMRSN-RTK and standard RTK, respectively. Figure 5-38 gives the performance comparison of the two methods in terms of the time-to-fix. The 50% mark of the samples gives the typical TTF and the 90% mark indicates the typical maximum time. As TTF is dependent on the baseline length, the result presented here is for the baseline length of about 6 km.

Table 5-3: Comparison of TTF between SIMRSN-RTK and standard RTK

Type of RTK	Average TTF	Minimum TTF	Maximum TTF
Standard RTK	62 seconds	15 seconds	183 seconds
SIMRSN-RTK	32 seconds	15 seconds	119 seconds

The results of the test can be summarised as below:

SIMRSN-RTK	50%	-	22 seconds
	90%	-	97 seconds
Standard RTK	50%	-	46 seconds
	90%	-	125 seconds

Hence, the SIMRSN-RTK yields a better result compared to the standard RTK technique.

Figure 5-36: Time-to-fix (TTF) using SIMRSN-RTK

Figure 5-37: Time-to-fix (TTF) using standard RTK

Figure 5-38: Time-to-fix

5.5 Comparison of SIMRSN-RTK with Trimble VRS System

This RTK test was carried out on the 26 Feb 2002 at a location approximately in the centre of the SIMRSN network (the point is known as GPSL). The aim of this experiment is to assess the performance of the SIMRSN against a comparable commercial real-time multiple-reference-station system. Results show that the SIMRSN-RTK is comparable in terms of TTF and positioning accuracy with the Trimble VRS system.

The Trimble VRS RTK and SIMRSN-RTK positioning is carried out simultaneously as shown in Figure 5-39. The GPS observations come via the same antenna, hence eliminating antenna and location-dependent biases.

Figure 5-39: The test configuration for simultaneous Trimble VRS and SIMRSN-RTK using one antenna

Figures 5-40 and 5-41 show the comparison of time-to-fix between Trimble VRS and SIMRSN-RTK at the same location over two periods of time (2 sessions) on the same day. Figure 5-42 is the distribution plot of the TTF for the 1st session. The plot show that most of the time (75 out of 94 times), SIMRSN-RTK achieved ambiguity fixes in less then 180 seconds (the cut-off time). It also suggests that half of the ambiguity fixes by SIMRSN-RTK are below 30 seconds (39 out of 75). Compared to the Trimble VRS which achieved 22 times of TTF below 180 seconds. For the 2nd session (as shown in Figure 5-39), 40 comparison was recorded. For SIMRSN-RTK achieved 36 fixes below 180 seconds while Trimble VRS only managed 22. This shows that the SIMRSN system is comparable in terms of TTF performance with the Trimble VRS system.

**Figure 5-40: TTF comparison between Trimble VRS and SIMRSN-RTK
(11am –3pm, 26 Feb 2002)**

Figure 5-41: TTF comparison between Trimble VRS and SIMRSN-RTK (3pm-7pm, 26 Feb 2002)

Figure 5-42: Distribution plot of TTF for Trimble VRS (left) and SIMRSN-RTK (right)

5.6 Corrections Availability

Initially, there were four GPS reference stations in the SIMRSN, and SEMB was used as the master reference station. A few tests had been carried out and the results indicated that the ambiguities between the 4 reference stations are difficult to resolve due to the distances between SEMB and the rest of the reference stations. When this happened, only corrections of those satellites that have had their ambiguities fixed will be sent out to rover users. At the rover, the availability of RTK fixes, which require at least five corrections, will be affected.

Because of the difficulty in resolving the ambiguity is due to the long inter-station distances, a fifth station was established, in the centre of Singapore, during the 4th quarter of 2001. By introducing an additional station, it can reduce the distances between the reference stations and increase the number of corrections. An assessment was carried out on 7 March 2002 to determine if the introduction of the fifth station helps to increase the number of VRS corrections that are generated. The results are shown in Figures 5-43 and 5-44. During the same period of time, the 5-reference-station SIMRSN was able to generate more corrections compared to the 4-reference-station configuration. Figure 5-45 gives the distribution chart of the comparison. The results show that 94.6% of the time, the 5-reference-station SIMRSN generated 5 or more corrections, while the 4-reference-station SIMRSN only achieves 83.6%.

Figure 5-43: Corrections generated using five-reference-station SIMRSN

Figure 5-44: Corrections generated using four-reference-station SIMRSN

Figure 5-45: Numbers of corrections distribution chart for 4 and 5 reference-station-SIMRSN

5.7 Summary

An active multiple-reference-station network (SIMRSN) has been established in Singapore. The use of a multiple-reference-station network can improve RTK positioning accuracy performance. RTK positioning will no longer be performed relative to one single reference station but will make use of a network of GPS reference stations.

This chapter presents the results of performance tests for RTK positioning with the SIMRSN corrections in real-time. It is shown that 3D-position accuracy of

a few centimetres can be achieved within initialisation times of 3 minutes, often even within 80 seconds. The use of the SIMRSN corrections results in a significant performance gain for RTK positioning. These results show that the SIMRSN has the potential to support reliable RTK positioning. More satellites will result in better PDOP and subsequently better TTF. To effectively use RTK, guidelines for appropriate field procedure and equipment usage need to be developed.

Chapter 6

Rapid-static Survey with the SIMRSN

6.1 Overview

GPS positioning and surveying in urban areas face the problems of increased incidence of cycle slips and fewer tracked satellites. This is due to the obstruction of satellite signals by high-rise buildings. As a result, ambiguity resolution for carrier-phase may not be possible and incorrect positioning may occur. Besides, other signal disturbance such as multipath error might be serious in urban areas. This problem is more prevalent in RTK surveys, as RTK needs a minimum of 5 satellites to resolve the ambiguities during “initialisation” (El-Mowafy, 2000; Van Diggelen, 1997; Lau & Mok, 1999).

The SIMRSN infrastructure was developed to support both real-time and post-processing survey techniques. The RTK method (or Network-RTK if the multiple-reference-station-network algorithm is used) was discussed extensively in previous chapters. Although Network-RTK technique is the most efficient technique, the technique does not work under all conditions. Hence, it is essential to consider also the implementation of the multiple-reference-station algorithm using the post-processing mode suitable for static and rapid-static surveys.

In this chapter, the technique of rapid-static surveying using the corrections generated from the SIMRSN is investigated. The concept of a grid-based VRS network for cadastral surveys in Singapore is also described.

6.2 Rapid-static Survey Technique

The rapid-static survey technique is a GPS surveying technique (post-process) which requires relatively short observation times, of 5 to 20 minutes, to achieve centimetre-level accuracy. The field procedures are much like a conventional static GPS survey except that the occupation times are shorter. This technique is also known as “fast static” or “quick static” by some GPS manufacturers. The positioning accuracy is a function of the baseline length, the number of satellites tracked and the satellite geometry.

Different GPS manufacturers recommend different hardware requirements for rapid-static surveys. The other basic requirement of this technique is the ability of the software to resolve the ambiguities using a very short observation data. Different techniques of ambiguity resolution (AR) have been developed (Chen & lachapelle, 1995; Frei & Beutler, 1990; Teunissen, 1993, 1995). The observation period depends on the following factors:

- ❑ Baseline length;
- ❑ number of satellites;
- ❑ satellite geometry (DOPs); and
- ❑ level of ionospheric disturbance (varies with the time and location of the receiver measurement period).

Baseline length is the most critical factor in the rapid-static survey. As observation time and accuracy are mainly a function of baseline length, it is highly recommended that baseline lengths should be kept to a minimum. The approximate guide to baseline lengths and observation times for static and rapid-static survey (for mid-latitude locations) is given in Table 6-1. The author failed to find any literature that recommends the maximum baseline length for rapid-static surveys carried out at low-latitude locations. However, the baselines should be comparatively shorter and the observation time should be longer compared to those recommended for mid-latitude locations. It is not in the scope of this research to establish the relationship of baseline lengths and observation time for this region.

The work will require many controlled tests and in-depth knowledge of the algorithm for rapid-static baseline processing.

Table 6-1: Approximate guide to baseline lengths and observation times for mid latitudes locations (adapted from the Leica GPS System 500 user manual)

Observation Method	No. Satellites GDOP ≤ 8	Baseline Length (kilometre)	Approximate observation time (minutes)	
			By day	By night
Rapid Static	4 or more	Up to 5	5 to 10	5
	4 or more	5 to 10	10 to 20	5 to 10
	5 or more	10 to 15	Over 20	5 to 20
Static	4 or more	15 to 30	60 to 120	60
	4 or more	Over 30	120 to 180	120

There is a “data quantity gamble” element in the rapid-static GPS surveying technique (Rizos, 1997). One will never know if the data collected (based on the length of observation time) is enough to produce quality baselines, because the time taken for reliable AR is not known a priori with precision.

6.3 Rapid-static Survey with the SIMRSN

While scientific and high accuracy applications require the highest possible accuracy and long observation times, surveyors, by the nature of their work, prefer short observation sessions. The RTK technique, which required short observation times, is the best option for surveyors. However, if the urban environment is an obstacle to the use of the RTK technique, alternative technique needs to be explored and developed.

Due to high multipath and urban canyon effects, there are instances where the initialisation needed for the RTK survey is hard to obtain. Rapid-static surveying is the next best option available for the cadastral survey application. However, the rapid-static survey requires short baseline lengths. Hence, the implementation of the multiple-reference-station algorithm in the rapid-static survey mode is essential in order to gain accuracy from a limited number of permanent

GPS reference stations. The standard single-base technique would require a density of reference stations that is unrealisable for implementation in many countries due to the high cost.

There are 2 methods of applying the corrections for static and rapid-static surveying using SIMRSN. They are:

1. Rapid-static - Multiple Reference Correction (RS-MRC) method
2. Rapid-static - Virtual Reference Station (RS-VRS) method

In the RS-MRC method, corrections are applied directly to the raw observations of either the rover station or reference station. The approximate coordinates of the rover station are used in the computation of the correction terms. Then the correction terms are applied directly to the rover (or reference) observations. These corrected observations of the rover (or reference) is then paired up with the master reference station (or rover) used in the baseline processing.

In the RS-VRS method, a virtual reference station point is created using the network-generated corrections. The observations at the VRS can be estimated based on the observations of the master reference station. The rover is paired up with the VRS point created for the baseline processing. The VRS point is usually located near the rover point.

A software module known as *CorrTest*, which was developed using the algorithm described in Chapter 4, is used to generate correction coefficients on a epoch-by-epoch and satellite-by-satellite basis. The correction coefficients generated will be written into text files (ASCII format) for subsequent use. These correction coefficients files can be generated on hourly or daily basis.

To demonstrate the RS-MRC method, the correction coefficients must be computed first using the above mentioned module. Subsequently, the software module developed by Teo (2002), known as *AddCorr2Rinex*, was used to compute the corrections for a particular rover position. The computation is based on the algorithm described in Chapter 3. The software computes corrections based on the estimated rover's location and the known reference station location, and adds the corrections to the observations file of the rover station (RINEX format). These

rover observations will be paired up with a “master reference station” observation for baseline computations.

To implement the RS-VRS method, a software known as *GenerateVRSRinex* was developed. The correction coefficients for the area must be computed first. The *GenerateVRSRinex* module creates the observations for a VRS point; estimates the correction terms based on the coordinates given; and applies the correction terms to the observations of the VRS point.

The implementation of RS-MRC requires two-way communications. In the computation process, the approximate coordinates of the rover are needed. The RS-VRS method on the other hand is deemed easier to implement. This is due to the fact that VRS points can be pre-defined at certain locations. The number of VRS points can be pre-determined so as to cover the area of interest.

Both the methods, RS-MRC and RS-VRS, are investigated in the following sections.

6.3.1 Rapid-static using RS-MRC Method

Two tests were conducted, Test 1 on 30 Jan 2002 and Test 2 on 8 Feb 2002, to study the performance of rapid-static positioning using the RS-MRC method. Both tests compared the AR success rate with and without MRC corrections.

Test 1: Rapid-static using RS-MRC

In this test, the data set was collected at GPSL (see Figure 5-6) using a Trimble 5700 dual-frequency receiver during the time span 0440 h - 12:40 h UTC (1240 h – 2040 h local time). Reference station, LOYA (about 14.6 km away), was used as the master reference station in the correction coefficients computation using the *CorrTest* module. The observation corrections for the test point GPSL were then computed using the *AddCorr2Rinex* module. The time series of L1 and L2 carrier-phase corrections for satellite PRNs 02, 04, 08 and 11 are given in Figure 6-1.

PRN27 is the reference satellite. The corrections reach 14 cm for L1 carrier-phase and 18 cm for L2 carrier-phase.

Figure 6-1: L1 and L2 carrier-phase corrections at GPSL

To study the improvement in accuracy of positioning, data processing was divided into two parts. Firstly, the position of the GPSL was predetermined as a known precise position using the full set of static data. Then the SIMRSN MRC corrections were applied to the raw observations, and the observation files were divided into 15-minute and 30-minute sessions, to test whether centimetre-level accuracy could be achieved with the corrections (and compared to the case without

corrections). Figure 6-2 shows the differences between coordinates obtained in each session and the known coordinates, with and without the SIMRSN corrections.

Some 15-minute sessions cannot achieve centimetre-level accuracy without corrections. The results from Figure 6-2 indicate that a significant improvement has been obtained by applying the SIMRSN corrections for both the 15-minute and 30-minute sessions.

Figure 6-2: Differences between coordinates obtained in each session and the known coordinates with and without the SIMRSN corrections

Accuracy of a few centimetres for short observation times is only possible when the double-differenced phase ambiguities are resolved correctly. Once the integer double-differenced ambiguities have been successfully resolved, the positioning error drops from several decametres to a few centimetres. To test

whether the same integers as using historical data could be resolved with and without the corrections for each session, the estimated integer ambiguities were compared with those using historical data. The success rate was obtained by taking the ratio of the number of correct ambiguity sets and the total number of ambiguity sets, as shown in Table 6-2. From the table it can be seen that without the SIMRSN corrections it is difficult to successfully fix the ambiguities even when the session lengths are increased. After correcting the data with the SIMRSN corrections, the success rates increased considerably, with success rates of 90.7% and 98.3% for the 15-minute and 30-minute session, respectively.

Table 6-2: Ambiguity resolution success rates with and without the SIMRSN corrections applied

Observation Period	AR Success Rate (%)	
	Without MRC Corrections	With MRC Corrections
15-minute sessions	53.4%	90.7%
30-minute sessions	69.2%	98.3%

Test 2: Rapid-static using RS-MRC

A test was carried out using the NTU0 reference station as the “user”. The data set on 08 February 2002 over a whole daytime span was selected. This is to further examine the achievable improvements using the multiple-reference-station-network algorithm for rapid-static surveying.

The results using three baselines NTU0-KEPC (16.6km), NTU0-SEMB (20.7km), NTU0-LOYA (32.6km) were compared.

Figure 6-3 shows the sample time series of the corrections for the L1 and L2 carrier-phase corrections for satellite PRNs 01, 03, 22 and 25 (PRN31 is the reference satellite), where KEPC was the master reference station.

Figure 6-3: L1 and L2 carrier-phase corrections for NTU0

The observation files were also divided into 15-minute and 30-minute sessions, giving a total of 96 and 48 sessions respectively. The standard deviations of the differences between the coordinates obtained in each sessions and the known coordinates with the SIMRSN corrections, are summarised in Table 6-3 (excluding three 15-minute sessions and one 30-minute sessions, for which centimetre-level was not achieved due to poor geometry of satellites). A significant improvement is seen when the SIMRSN corrections were applied.

Table 6-3: Statistics of the positioning results

Baseline Length		Standard Deviation (metre)					
		15-minute sessions			30-minute sessions		
		Northing	Easting	Height	Northing	Easting	Height
NTU0-KEPC (16.6km)	without corrections	0.010	0.014	0.037	0.008	0.013	0.030
	with corrections	0.007	0.010	0.030	0.005	0.010	0.022
	improvement	30%	28%	19%	37%	23%	27%
NTU0-SEMB (20.7km)	without corrections	0.018	0.026	0.045	0.015	0.019	0.043
	with corrections	0.012	0.018	0.033	0.010	0.011	0.031
	Improvement	33%	31%	27%	33%	42%	28%
NTU0-LOYA (32.6km)	without corrections	0.021	0.031	0.063	0.015	0.027	0.049
	with corrections	0.018	0.021	0.048	0.010	0.018	0.034
	Improvement	14%	32%	24%	33%	33%	31%

Table 6-3 compares the ambiguity success rates for each of these baselines. After applying the corrections generated from the SIMRSN, the results in Table 6-4 shows that ambiguity resolution has improved from between 40.5% and 49.1% to 89.4% and 90.6% for the 15-minute sessions, and from between 64.9% and 68.7% to 95.3% and 97.7% for the 30-minute sessions.

**Table 6-4: Ambiguity resolution success rates with and without the SIMRSN
RS-MRC corrections applied**

Ambiguity success-rate	without corrections			with corrections		
	NTU0- KEPC (16.6km)	NTU0- SEMB (20.7km)	NTU0- LOYA (32.6km)	NTU0- LOWD (16.6km)	NTU0- SEMB (20.7km)	NTU0- LOYA (32.6km)
15-minute sessions	49.1%	46.7%	40.5%	90.6%	89.8%	89.4%
30-minute sessions	68.7%	65.4%	64.9%	97.7%	96.8%	95.3%

6.3.2 Rapid-static using RS-VRS Method

The data for the tests in this section was collected at Bishan Park GPS mini-test network (Pillar S4) on 5 October 2004; using a Trimble 4700 dual-frequency receiver operating over a period of 8 hours. The location of S4 is in central Singapore and is approximately 1.9 km from the NYPC reference station. The ‘true’ coordinates of S4 were pre-determined in a previous survey using 2 days of observation (Tor, 2001). All the baseline processing was carried out using the Trimble Geomatic Office (TGO) software.

The objective of these tests was to evaluate the positioning performance of the rapid-static survey technique using the RS-VRS method. By analysing the results of these tests, it may be possible to design the grid network (see section 6.4), and determine the rapid-static survey specifications for cadastral surveys in Singapore.

The first test was carried out to compare the performance of the RS-MRC and RS-VRS methods. The results in Table 6-5 indicate that the RS-VRS method gives slightly better accuracy compared to the RS-MRC method. This is due to the shorter baseline involved in the computation as the VRS stations are created near to the rover station.

Table 6-5: Comparison of the rapid-static methods based on different baseline lengths using 15 minutes observation

Rapid-static (RS) Method	Baseline length (approximate) (metre)	Statistics of horizontal distance errors of point S4 (based on 16 sets of data, NYPC is used as the master reference station)		
		Minimum (millimetre)	Maximum (millimetre)	Mean $\pm$ Std Dev (millimetre)
RS-VRS	1000	4	15	11 $\pm$ 5
RS-VRS	2500	8	22	15 $\pm$ 5
RS-MRC	17875 (to NTU0)	5	91	20 $\pm$ 20
RS-MRC	1940 (to NYPC)	5	15	10 $\pm$ 6
RS-MRC	11877 (to SEMB)	6	67	15 $\pm$ 15
RS-MRC	14733 (to LOYA)	8	76	19 $\pm$ 12
RS-MRC	11335 (to KEPC)	7	69	17 $\pm$ 14

The observation interval, or observation sampling rate, is a factor in determining the positioning accuracy. The lower the observation interval, the larger the number of data available for the computation. A test was carried out to determine how the observation interval influences the horizontal positioning using the RS-VRS method. The result of the tests is given in Table 6-6. For observation period of 15 minutes, the 1 second observation interval data sets yield better mean and standard deviation

There is a sharp increase in the mean horizontal distance error between data sets of 1-second and 5-second intervals. The RS-VRS method yields higher reliability compared to the RS-MRC method, as the standard deviation is lower. Although the differences in mean error are not great between the various observation intervals, it is recommended to adopt the 1 second observation interval for rapid-static surveys using 15-minute observation periods.

Table 6-6: Comparison of different observation interval versus observation period based on virtual reference station which is approximately 2500m from S4

Observation Period (minute)	Statistics of horizontal distance errors of point S4 (based on 16 sets of data, NYPC is used as the master reference station) Mean $\pm$ Std Dev (millimetre)			
	1 second observation interval	5 second observation interval	10 second observation interval	15 second observation interval
15	15 $\pm$ 5	18 $\pm$ 5	18 $\pm$ 5	20 $\pm$ 5
20	14 $\pm$ 3	18 $\pm$ 6	16 $\pm$ 7	20 $\pm$ 7
30	12 $\pm$ 3	16 $\pm$ 7	16 $\pm$ 7	17 $\pm$ 8

Teo (2002) has shown that 5 and 10 minutes of observation span in a rapid-static survey are too short to yield centimetre accuracy using single-frequency equipment. On the other hand, with 15 minutes of observation time one can always obtain centimetre-level accuracy. Hence, 15-minute sessions are used in the tests. Table 6-7 shows the horizontal errors caused by using different VRS points with various baseline lengths (from S4). The mean and standard deviation of the horizontal error for a baseline length of 5000 metre is (14 $\pm$ 8)mm, with the maximum error of 32mm and a minimum error of 6 mm. The results attained are better for baseline lengths shorter than 5000 metre. This shows that accuracy better than 30mm is attainable if the baseline length is kept to less than 5km.

Table 6-7: Comparison of different baseline length for rapid-static survey using RS-VRS method (NYPC used as master reference station)

Approximate distance of S4 from VRS (metre)	Minimum (millimetre)	Maximum (millimetre)	Mean $\pm$ Std Dev (millimetre) (based on 16 sets of data)
10	4	14	9 $\pm$ 4
100	4	14	9 $\pm$ 4
1000	4	15	11 $\pm$ 5
2500	8	22	15 $\pm$ 5
5000	6	32	14 $\pm$ 8

Table 6-7 shows the horizontal error of point S4 as computed with 15 minutes of observation data, and 1 second interval. 5 virtual reference stations were created based on different distances from S4 using NYPC as the master reference station (based on 16 sets of data).

Another test was carried out to investigate the effect of the choice of master reference station on the horizontal accuracy attainable. The observations for VRS points were created using the correction coefficients computed with NTU0 as the master reference station. Each of these VRS points is used in the rapid-static computation for point S4. The results are shown in Table 6-8. NTU0 is approximately 17.8 km away from the rover S4, whilst S4 is only about 1.9 km away from reference station NYPC.

Table 6-7 and Table 6-8 show that the standard deviations of the horizontal errors are slightly higher when NTU0 is used as the master reference station. The maximum horizontal errors are also obviously higher. Hence, the reference station which is nearest to the VRS point should be used as the master reference station in the computation of the VRS point.

Table 6-8: Comparison of different baseline length for rapid-static survey using RS-VRS method (NTU0 used as master reference station)

Approximate distance of S4 from VRS (metre)	Minimum (millimetre)	Maximum (millimetre)	Mean $\pm$ Std Dev (millimetre)
10	5	20	8 ± 9
100	5	32	10 ± 10
1000	5	40	16 ± 12
2500	2	94	20 ± 31
5000	5	61	20 ± 21

Table 6-8 shows the horizontal error of point S4 as computed with 15 minutes of observation data; and 1 second interval. Virtual reference stations were created based on different distances from S4 using NTU0 as the master reference station (based on 16 sets of data)

Chen (2001) has shown that there is no obvious difference in the quality of the results obtained using 3 or 4 reference stations. The number of reference stations used in the computation of the “corrections” depends on the size of the area covered and the location of the network.

6.4 Grid-based Virtual Reference Station Network in Singapore

A Grid-Based Virtual Reference Station Network (GB-VRSN) is proposed in this study for rapid-static survey applications in Singapore. This GB-VRSN provides a set of fixed virtual reference points, which has the advantage of “legal traceability”. The DGPS service provider (or the relevant authority) will maintain the GB-VRSN and generate all the data. The user-defined virtual reference point method is not desirable for cadastral surveying as the observation of the virtual reference point is created at the user site.

The GB-VRSN is a network of virtual reference points arranged in a grid frame as illustrated in Figure 6-4. Each virtual reference point has a fixed coordinate. The virtual reference point observations will be created based on the

coordinates, on a daily basis for all the points in the GB-VRSN. The virtual reference concept discussed above is used for the computation.

The GB-VRSN is implemented in this manner because it is simple and straightforward to the users. A user only needs commercially available software which can perform rapid-static baseline processing (minimum requirement). Based on the index, a GPS user can easily identify which is the nearest VRS point to use in his rapid-static survey. For the service provider, the VRS is a preferred method as there is only need for one-way communications. All the observations of the VRS points will be pre-computed and archived in an FTP server for downloading. The master reference station used to compute the VRS data will be based on the location of the VRS point. The nearest reference station will be used.

The GB-VRSN layout for Singapore is designed to coincide with the Cadastral Map Index (also known as the Standard Sheet Index), which is a map grid system adopted by the Singapore Land Authority. Each Cadastral Map has the size of 900 metre east-west by 600 metre north-south; and is identified by a four-digit index number (see Figure 6-4 and Figure 6-6). This index is widely used as a reference to a location in Singapore by land surveyors, lawyers and other professionals dealing with land development. Hence, the index is appropriate to be adopted for the GB-VRSN.

Figure 6-4: Cadastral Map Index of Singapore with the proposed VRS points (red triangles) located based on the map index

The baseline length of a rapid-static survey is recommended to be less than 5km. The tests conducted in section 6.3.2 have confirmed that the accuracy attainable using baselines of length less than 5km are adequate for rapid-static. Hence, the grids as displayed in Figure 6-5 are proposed. The grid size of 2700m east-west and 3000m north-south and the layout will ensure that any location on the main island of Singapore will be within 5 km from any 2 virtual reference stations and at least 3 km to any one station.

Figure 6-5: The layout of the Grid-based Virtual Reference Station Network proposed in Singapore

A total of 77 virtual reference stations will be created in a grid-based network as illustrated in Figure 6-5. Each of the virtual reference stations will be given an identification number from VRS01 to VRS77. The network covers the whole of the Singapore main island, and includes Jurong Island, Pulau Ubin and Sentosa island.

The RINEX files for all the 77 virtual reference stations can be created on a daily basis and uploaded onto the FTP site. GPS users can download the VRS RINEX files based on their location for rapid-static post-processing.

Figure 6-6: Zoom-in view of the cadastral map indexes and the VRS stations

Figure 6-6 illustrates an area in the Central Business District (CBD) of Singapore with the associate map grid index (the Cadastral Map Index). Using the GB-VRSN and some guidelines, a user will find it comparatively easy to perform the rapid-static processing. He can decide on which VRS point data to use as the reference station, based on the location of his rover point, referenced to the Cadastral Map Index. For example (see Figure 6-6), if the rover is located in 2187 (shown in the red-dotted rectangle), the two nearest VRS points are VRS56 and VRS65.

6.5 GB-VRSN Test

GB-VRSN test was carried out on 5 locations using the ISN control points. 5 test points were selected; 4 at the corners and 1 in the middle of Singapore. The GPS data used was collected by private surveyors during the static survey to establish the ISN control points. Each ISN point is established using 2 hours GPS observation data. The horizontal errors are computed by comparing the rapid-static survey results with the published coordinates of the ISN points. The two hours GPS observations are segmented to 8 sets of 15-minutes data. The baseline lengths to the VRS points vary from 538m to 2759m. Table 6-9 shows that the maximum horizontal error obtained is less than 20 mm. Figure 6-7 shows the location of the 5 test points.

Table 6-9: Test results of the GB-VRSN based on 5 ISN control points

Test Point (ISN control points)	VRS Point	Approximate baseline length (metre)	Horizontal errors (based on 8 sets of 15-minutes data)		
			Minimum (millimetre)	Maximum (millimetre)	Mean $\pm$ Std Dev (millimetre)
ISN No. 14191	VRS 05	1124	2	12	8 $\pm$ 5
ISN No. 14966	VRS 52	538	5	16	10 $\pm$ 8
ISN No. 14798	VRS 64	2759	10	15	13 $\pm$ 5
ISN No. 14491	VRS 42	802	9	19	15 $\pm$ 4
ISN No. 15493	VRS 31	1139	5	18	12 $\pm$ 4

Figure 6-7: Location of the 5 test points

6.6 Summary

The tests conducted showed that a GPS multiple-reference-station-network and its algorithm can improve the results of a rapid-static survey. The SIMRSN RS-MRC and RS-VRS are the two methods proposed for applying the corrections so generated. The RS-VRS method produces higher accuracy and reliability.

The grid-based virtual reference station network (GB-VRSN) concept is proposed for Singapore, to be used for cadastral surveys for the establishment of ISN control marks. The GB-VRSN has the following characteristics:

- ❑ location of VRS points based on the Cadastral Map Index;
- ❑ grid size of 2700m x 3000m;
- ❑ the nearest reference station used as the master reference station; and
- ❑ the correction coefficients are computed based on all 5 reference stations.

With the GB-VRSN, rapid-static survey using only 15 minutes of data is possible. The specification of rapid-static surveying based on the SIMRSN RS-VRS method (using the GB-VRSN) is proposed as below:

- ❑ Dual-frequency GPS receiver;
- ❑ 1 second sampling rate;
- ❑ minimum 15 minutes of observation; and
- ❑ minimum 6 tracked satellites.

Chapter 7

Conclusions and Recommendations

7.1 Summary

The multiple-reference-station concept proposed by Han and Rizos (1997) has been adapted and implemented in the Singapore Integrated Multiple Reference Station Network (SIMRSN) with enhanced features. The concept used in SIMRSN facilitates network solution RTK and rapid-static survey. The corrections for network solution are computed based on GPS observation from a number of GPS reference stations. The operational network of GPS reference stations successfully utilises state-of-the-art networking infrastructure for data collection and dissemination. SIMRSN supports network solution techniques both for RTK as well as rapid-static surveys.

There has been little research on the distribution of the network solution corrections to real-time users. This project proposed the dissemination of GPS data via Internet together with GPRS. Tests on the latency were carried out and the results showed that the communication mode is feasible for the transmission of DGPS corrections. In this project, the approach of dissemination network-RTK corrections using conventional RTK format (in the form of VRS) has been proposed and proven to be effective. Field tests were carried out and the results obtained ascertain the feasibility of such a system for the real-time high precision positioning needs of Singapore.

In post-processing mode, the SIMRSN is capable in providing multiple-reference-station corrections which enable rapid-static surveys to be carried out

using short observation spans. The project suggested 2 methods viz. RS-MRC and the RS-VRS, to draw on the network corrections for rapid-static, as described in Chapter 6 (Section 6.3). Test results showed that the RS-VRS method produces higher accuracy and reliability. The method is simple and easy to implement as end user will be able to process their observations using conventional software without any additional component.

To solve the problem of cycle slips and fewer tracked satellites in RTK survey, a new grid-based virtual reference station concept for rapid-static surveying using the SIMRSN infrastructure and the RS-VRS method is proposed in this project. The Cadastral Map Index is used as the grid for the creation of 77 virtual reference stations. With this new method, a user only need to know his approximate location and decide on the VRS point to use, based on the Cadastral Map Index. This approach is a simple and practical to implement the network-based carrier-phase DGPS in post-processing mode. Test results show that with the GB-VRSN proposed for Singapore, the rapid-static survey using only 15 minutes of data can yield an accuracy of about (15 ± 4) mm compared to the known coordinates.

Following the implementation of the new SVY21 cadastral survey system in August 2004, the SIMRSN was used operationally to establish ISN as part of the cadastral survey process. As the 5-year lifespan of the hardware (i.e. GPS receivers and other auxiliary equipment) used in SIMRSN was coming to an end in 2005, the Singapore Land Authority (SLA) decided to embark on a new system based on the lesson learned from the implementation of the SIMRSN. The new infrastructure launched in September 2006 is known as the Singapore Satellite Positioning Reference Network (SiReNT). The new infrastructure is to replace the SIMRSN. Similar to SIMRSN, the infrastructure consists of 5 GPS reference stations connected to a Data Control Centre (DCC). SiReNT system adopts the leading-edge technology of Network-DGPS (based on network solution) both for Real-Time Kinematic (RTK) and code-based DGPS technique. It uses the network software, GPSNet from Trimble Terrasat GmbH at the Data Control Centre which supports the Virtual Reference Station (VRS) technique.

The UNSW and the New South Wales Department of Lands (DoL) has worked together to implement a Network-RTK (known as the SydNET) in the state of New South Wales, Australia (Rizos et al., 2003). The implementation was modelled and designed base on the successful implementation of SIMRSN.

7.2 Conclusions

The SIMRSN project is potentially beneficial in many high accuracy positioning applications such as surveying, mapping, GIS, defence, intelligent transportation system, homeland security, atmospheric monitoring, structure monitoring, environmental monitoring, etc. Positioning tests carried out shown that network solution using SIMRSN yield a high quality results compared to the conventional single-base solution. The project has demonstrated the broadcasting of multiple-reference-station correction on IP and the usage of conventional RTK format (in the form of VRS) for multiple-reference-station correction. The project provides a reliable and high quality infrastructure for high precision DGPS positioning in Singapore. The tangible and intangible benefits of the SIMRSN can be outlined as follows:

1. From the geodetic perspective, the SIMRSN serves as the national geodetic reference frame for surveying and positioning. It is regarded as the “Zero” order geodetic control of Singapore, which is the reference frame for all mapping, positioning and surveying applications.
2. The SIMRSN infrastructure is the key component in the new SVY21 cadastral survey system, implemented in August 2004 by the Singapore Land Authority (Khoo, 2005). Under the new system, surveyors are required to use the SIMRSN data for the establishment of the Integrated Survey Network control marks for cadastral work. A guideline was introduced for the utilisation of the SIMRSN system. This ensures a homogeneous reference system for all cadastral surveys.

3. The SIMRSN is potentially an important requisite infrastructure in the growing field of Location Based Services (LBS) where specifically targeted information will be matched with positions and delivered in real-time to mobile users. Due to the open format development adopted in the SIMRSN project, many LBS applications can be developed and integrated into the SIMRSN system.
4. The SIMRSN GPS data are systematically archived and ready for scientific and atmospheric study applications.
5. The SIMRSN is also an infrastructure ready for many real-time applications such as fleet management, monitoring and tracking, both on land and in the port area of Singapore; structure monitoring; homeland security and public safety; etc.
6. In the implementation of the new SiReNT (Singapore Satellite Reference Station Network) system that replaced the SIMRSN, large amount of experiences were drawn and learned from the implementation and feasibility investigation carried out during this project.

Based on the investigations carried out to compare the network solution with the conventional single-base solution both for RTK and post-processing rapid-static techniques, the following conclusions can be drawn:

1. The results suggest that the network solution using multiple-reference-station algorithm implemented in the SIMRSN yields an improved performance compared to conventional single-base RTK. It is shown that the use of network-generated correction terms will improve productivity by:
 - ❑ shortening the convergence time for ambiguity resolution (time-to-fix);
 - ❑ increase the success rate of ambiguity resolution, and as a result enhance the reliability of real-time kinematic survey; and
 - ❑ increase the positioning accuracy using the VRS technique.

2. In the post-processing mode, the network solution using multiple-reference-station algorithm implemented in the SIMRSN also shows significant improvement as follows:
 - ❑ Rapid-static survey is possible using 15 minutes of data;
 - ❑ the application of correction terms using the RS-VRS method yields higher accuracy and reliability; and
 - ❑ the GB-VRSN is introduced as a service in the SIMRSN system for rapid-static surveying using a pre-defined virtual reference points arranged in a grid form.

7.3 Recommendations

The tests conducted in this research project suggested that the network-DGPS solution is feasible for a city-country like Singapore with a size of about 704 km². Listed below are some recommendations for further investigations:

1. The issue of "data quality" is of critical concern for many applications. It is important that the reference station data is reliable and of a consistently high quality. Hence algorithms for data "screening" to detect and repair cycle slips, mitigate multipath disturbances, and characterise variable data quality (whatever the source is) should be implemented.
2. The current development is concentrated on surveying applications. The system which is based on network solution has great potential for many other applications, including deformation monitoring, navigation, tracking etc. Hence, further investigations and development are needed to realise more applications.
3. Under the new SVY21 cadastre system, the data from the SIMRSN system is currently used for the establishment of the ISN marks using the post-processing technique. A cadastral survey will be carried out using the ISN

marks as the survey control. The usage of real-time SIMRSN directly on the boundary marks in Singapore needs further investigation. To use the network-RTK in cadastral survey effectively, guidelines for proper field procedures and system checks need to be developed.

4. The wireless internet communication option was recommended as the mode for data dissemination from the Control Centre. The broadcast through IP port allows for many simultaneous connections by many users. The infrastructure is only limited by the number of servers supporting the system. The IP broadcasting is a technology that could achieve extraordinary scalability. Hence, with the recent introduction of WiMAX (World Interoperability for Microwave Access), based on the IEEE 802.16 standard, it is expected to enable true broadband speeds over wireless networks at a cost point to enable mass market adoption. The technology is a feasible wireless communication option when the infrastructure can achieve nation-wide coverage.

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Appendix A

SIMRSN Reference Stations Location Maps

Location Map – GPS Reference Station SEMB,
Sembawang Yacht Club, Admiralty Road West

Location Map – GPS Reference Station NYPC,
Nanyang Polytechnic, Ang Mo Kio Avenue 8

Location Map – GPS Reference Station NTU0,
Block N1, School of CEE, Nanyang Technological University,
Nanyang Avenue

Location Map – GPS Reference Station KEPC,
Keppel Club, Bukit Chermin Road

Location Map – GPS Reference Station LOYA,
Block 30, JTC Factory, Loyang Way

Appendix B

SIMRSN Components and Configurations

Appendix C

SIMRSN Reference Stations Sites

GPS Reference Station KEPC – Antenna Location
Roof-top (above koi pond), Keppel Club, Bukit Chermin Road

GPS Reference Station KEPC – Equipment Cabinet
Roof-top (above koi pond), Keppel Club, Bukit Chermin Road

GPS Reference Station NTU0 – Antenna Location
Roof top Block N1, School of CEE, Nanyang Technological University,
Nanyang Avenue

GPS Reference Station NTU0 – Equipment Cabinet
Roof top Block N1, School of CEE, Nanyang Technological University,
Nanyang Avenue

Appendix C

GPS Reference Station NYPC – Antenna Location
Roof-top, Block S1, Nanyang Polytechnic, Ang Mo Kio Avenue 8

GPS Reference Station NYPC – Equipment Cabinet
Roof-top, Block S1, Nanyang Polytechnic, Ang Mo Kio Avenue 8

Appendix C

GPS Reference Station SEMB – Antenna Location
SAF Yacht Club, Admiralty Road West

GPS Reference Station SEMB – Equipment Cabinet
VIP Lounge, Top floor, SAF Yacht Club, Admiralty Road West

Appendix C

GPS Reference Station LOYA – Antenna Location
Roof-top, Block 30, JTC Factory, Loyang Way

GPS Reference Station LOYA – Equipment Cabinet
Roof-top, Block 30, JTC Factory, Loyang Way

Appendix D

SIMRSN Coordinates

SIMRSN Coordinates

Reference Station ID	Northing (SVY95) (m)	Easting (SVY95) (m)	Height above Ellipsoid (WGS-84) (m)
NTU0	36435.856	10931.929	76.257
SEMB	50143.261	26466.730	30.900
LOYA	39406.335	43394.281	51.153
KEPC	27727.849	25087.183	37.445
NYPC	40121.066	29717.586	55.645

Reference Station ID	X (WGS-84) (m)	Y (WGS-84) (m)	Z (WGS-84) (m)
NTU0	-1508022.5086	6195577.6654	148797.3207
SEMB	-1523020.9337	6191514.2528	162500.1192
LOYA	-1539521.7224	6187727.2632	151766.4896
KEPC	-1521810.8289	6192369.7612	140091.1359
NYPC	-1526242.9937	6191002.8603	152481.5673

Reference Station ID	Latitude (WGS-84)	Longitude (WGS-84)	Height above Ellipsoid (WGS-84) (m)
NTU0	1° 20' 44.81740" N	103° 40' 47.82595" E	76.257
SEMB	1° 28' 11.10813" N	103° 49' 10.34571" E	30.900
LOYA	1° 22' 21.53061" N	103° 58' 17.92939" E	51.153
KEPC	1° 16' 01.32664" N	103° 48' 25.72538" E	37.445
NYPC	1° 22' 44.81448" N	103° 50' 55.50848" E	55.645

Reference Station ID	Latitude (WGS-84, degree)	Longitude (WGS-84, degree)	Height above Ellipsoid (WGS-84) (m)
NTU0	1.3457826111	103.6799516528	76.257
SEMB	1.4697522583	103.8195404750	30.900
LOYA	1.3726473917	103.9716470528	51.153
KEPC	1.2670351777	103.8071459389	37.445
NYPC	1.3791151333	103.8487523556	55.645

Appendix E

SIMRSN Network and Hardware Information

Appendix E

No.	Station ID	Address.	Leased Line Diginet No.	Router & Host IP Address	Subnet Mask / Default Gateway	GPS Receiver	GPS Antenna
1	NTU0	Surveying & Mapping Laboratory, School of CEE Nanyang Technological University Nanyang Avenue	N/A	155.69.254.32 155.69.254.31	255.255.0.0 / 155.69.254.32	Trimble 4700 CORS S/N: 0220231090	Trimble Micro Centred Compact Geodetic with Ground Plane 33429.20+GP S/N: 0220226920
2	SEMB	SAF Yacht Club Sembawang Camp 43 Admiralty Road West Singapore 759962	0410956/ 0410958	192.168.10.2 192.168.10.3	255.255.255.248 / 192.168.10.2	Trimble 4700 CORS S/N: 0220214240	Trimble Choke Ring 29659.00 S/N: 0220214292
3	KEPC	Keppel Club, Bukit Chermin Rd Singapore 109918	0423269/ 0423270	192.168.10.9 192.168.10.10	255.255.255.248 / 192.168.10.9	Leica CRS1000 S/N: 30004	Leica AT504 D/M Element Choke Ring w/o Radome S/N: 475
4	NYPG	Block S1, Engineering Block, Nanyang Polytechnic, 180 Ang Mo Kio Avenue 8	0437109/ 0437110	192.168.10.25 192.168.10.26	255.255.255.248 / 192.168.10.25	Ashtech Z- Surveyor FX S/N: UX520005005	Ashtech D/M Choke Ring / Radome (SNOW) ASH700936.A S/N: CR520011204
5	LOYA	Jurong Town Corporation 30 Loyang Way Singapore 508769	0410954/ 0410955	192.168.10.17 192.168.10.18	255.255.255.248 / 192.168.10.17	Trimble 4700 CORS S/N: 0220210934	Trimble Choke-ring 29659.00 S/N: 0220214133

Appendix F

Device Server – Lantronix Cobox

CoBox® Device Server

CoBox Device Servers provide exceptional functionality for users with IP applications requiring two serial ports. An extensive software feature set and a variety of configurable hardware options make the CoBox one of the most flexible network-enabling devices available today. The CoBox products support both Ethernet and Token Ring, making them a fit for most any networking environment.

- Easily network-enable any product
- Flexible, well-developed IP protocol implementation
- RS-232, RS-422, RS-485 serial standards supported
- DB25 and DB9 serial interfaces
- RJ45 (10BASE-T) and AUI Ethernet interfaces (CoBox-E2), STP/UTP Token Ring interfaces (CoBox-TR2)
- Serial speeds up to 115Kbps supported
- HTTP, Serial, Telnet and SNMP management
- Flash ROM for easy software upgrades

CoBox

Protocols Supported

ARP, UDP, TCP, Telnet, ICMP, SNMP, DHCP, TFTP, and HTTP

Device Support

Supports any RS-232/RS-422/RS-485 serial device requiring Ethernet access

Network InterfaceCoBox-E2
RJ45 (10BASE-T) and AUI
EthernetCoBox-TR2
STP(SubD9) and UTP(RJ45)
Token Ring, 4/16 Mbit ring speed
(selectable)**Serial Interface**DB25 RS-232/RS-422/RS-485
serial port DCE configuration
DB9 serial port DTE configuration**Data Rates**

Serial speeds up to 115Kbps

Modem Control

RTS, CTS, DSR, DCD, DTR

Serial Line FormatsCharacters: 7 or 8 data bits
Stop bits: 1 or 21
Parity: odd, even, none**Flow Control**XON/XOFF
Hardware flow control**Management**HTTP
SNMP (read only)
Serial login
Telnet login**Software**Flash ROM standard;
downloadable from a TCP/IP host
(TFTP) or over serial port**Diagnostic LEDs**CoBox-E2
Transmit Data
Receive Data
Good Link
Collisions
Channel status
Fault indicatorCoBox-TR2
Transmit Data
Receive Data
Good Link
Channel status
Fault indicator**Compatibility**CoBox-E2
Ethernet: Version 2.0/IEEE 802.3**CoBox-TR2**

Token Ring: IEEE 802.2 LLC

Power Requirements16VAC or DC 1000mA
(External adapter included)
Power Consumption: 9 Watts**Environmental**Operating Temperature
5° to 50°C (41° to 122°F)**Storage Temperature**

-40° to 66°C (-40° to 151°F)

Physical Dimensions (H x W x D)1.57 x 6.1 x 7.0 in
(4.0 x 15.5 x 18.0cm)
Weight: 1.1 lbs (.5Kg)**Shipping Dimensions (H x W x D)**2.75 x 13.25 x 6.75 in
(7.0 x 33.66 x 17.15cm)
Weight: 2.9 lbs (1.315 Kg)**Agency Approvals**

CE, FCC B (Ethernet), C/UL

Warranty

5-year limited warranty

Ordering Information**CoBox-E2-01**Device Server, 1 DB25
(RS-232/ RS-423/RS-485) serial
port, 1 DB9 (RS-232) serial port,
AUI (10BASE5) and RJ45
(10BASE-T) network ports,
diagnostic LEDs, Installation
Guide, external 110VAC
power supply**CoBox-E2-02**Same as above with 230VAC
power supply**CoBox-E2-03**Same as above with European
2-prong 230VAC power supply**CoBox-TR2-01**Device Server, 1 DB25
(RS-232/RS-423/RS-485) serial
port, 1 DB9 (RS-232) serial port,
STP (SubD9) or UTP (RJ45) Token
Ring ports, diagnostic LEDs,
Installation Guide, external
110VAC power supply**CoBox-TR2-02**Same as above with 230VAC
power supply

Specifications

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+31 76 565 8179 fax

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SIMRSN Database Design

Table **SAT_RECEIVER** – stores receiver type information

Column Name	Data Type		Description
RECEIVER_ID	Integer		GPS Receiver ID
WAVE_FACT_L1	Integer		Wavelength Factor L1
WAVE_FACT_L2	Integer		Wavelength Factor L2
RECEIVER_NO	Varchar		Receiver number
RECEIVER_TYPE	Varchar		Type of receiver
RECEIVER_VER	Varchar		Receiver version
L1	Integer		Observed (1) or not observed (0) - L1 Carrier phase
L2	Integer		Observed (1) or not observed (0) - L2 Carrier phase
CA	Integer		Observed (1) or not observed (0) - C/A Code Pseudorange observation on L1
P1	Integer		Observed (1) or not observed (0) - P - Code Pseudorange on L1
P2	Integer		Observed (1) or not observed (0) - P - Code Pseudorange on L2
D1	Integer		Observed (1) or not observed (0) - Doppler frequency on L1
D2	Integer		Observed (1) or not observed (0) - Doppler frequency on L2

Table **SAT_SITE** : stores reference station site information

Column Name	Data Type		Description
MARK_ID	Integer		Survey mark ID
MARKER_NAME	Varchar		Name of survey mark
POSITION_X	Integer		X position (metres)
POSITION_Y	Integer		Y position (metres)
POSITION_Z	Integer		Z position (metres)
OBSERVER	Varchar		Name of Observer
AGENCY	Varchar		Name of Agency
COMMENTS	Varchar		Comment
TIME_ZONE	Integer		Time zone
ENTRY_DATE	Date		Date the data was entered into the database

Table **SAT_ANTENNA** : stores GPS antenna type and specification information

Column Name	Data Type		Description
ANTENNA_ID	Integer		Antenna ID
ANTENNA_NO	Varchar		Antenna serial number
ANTENNA_IDENT	Varchar		Antenna identification
ANTENNA_TYPE	Varchar		Antenna description
L1_OFFSET_E	Double		L1 Antenna Offset Easting (metres)
L1_OFFSET_N	Double		L1 Antenna Offset Northing (metres)
L1_OFFSET_U	Double		L1 Antenna Offset Up (metres)
L1_PHASE_90	Double		L1 phase at 90 degrees elevation (mm)
L1_PHASE_85	Double		L1 phase at 85 degrees elevation (mm)
L1_PHASE_80	Double		L1 phase at 80 degrees elevation (mm)
L1_PHASE_75	Double		L1 phase at 75 degrees elevation (mm)
L1_PHASE_70	Double		L1 phase at 70 degrees elevation (mm)
L1_PHASE_65	Double		L1 phase at 65 degrees elevation (mm)
L1_PHASE_60	Double		L1 phase at 60 degrees elevation (mm)
L1_PHASE_55	Double		L1 phase at 55 degrees elevation (mm)
L1_PHASE_50	Double		L1 phase at 50 degrees elevation (mm)
L1_PHASE_45	Double		L1 phase at 45 degrees elevation (mm)
L1_PHASE_40	Double		L1 phase at 40 degrees elevation (mm)
L1_PHASE_35	Double		L1 phase at 35 degrees elevation (mm)
L1_PHASE_30	Double		L1 phase at 30 degrees elevation (mm)
L1_PHASE_25	Double		L1 phase at 25 degrees elevation (mm)
L1_PHASE_20	Double		L1 phase at 20 degrees elevation (mm)
L1_PHASE_15	Double		L1 phase at 15 degrees elevation (mm)
L1_PHASE_10	Double		L1 phase at 10 degrees elevation (mm)
L1_PHASE_05	Double		L1 phase at 05 degrees elevation (mm)
L1_PHASE_00	Double		L1 phase at 00 degrees elevation (mm)
L2_OFFSET_E	Double		L2 Antenna Offset Easting (metres)
L2_OFFSET_N	Double		L2 Antenna Offset Northing (metres)
L2_OFFSET_U	Double		L2 Antenna Offset Up (metres)
L2_PHASE_90	Double		L2 phase at 90 degrees elevation (mm)
L2_PHASE_85	Double		L2 phase at 85 degrees elevation (mm)

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L2_PHASE_80	Double		L2 phase at 80 degrees elevation (mm)
L2_PHASE_75	Double		L2 phase at 75 degrees elevation (mm)
L2_PHASE_70	Double		L2 phase at 70 degrees elevation (mm)
L2_PHASE_65	Double		L2 phase at 65 degrees elevation (mm)
L2_PHASE_60	Double		L2 phase at 60 degrees elevation (mm)
L2_PHASE_55	Double		L2 phase at 55 degrees elevation (mm)
L2_PHASE_50	Double		L2 phase at 50 degrees elevation (mm)
L2_PHASE_45	Double		L2 phase at 45 degrees elevation (mm)
L2_PHASE_40	Double		L2 phase at 40 degrees elevation (mm)
L2_PHASE_35	Double		L2 phase at 35 degrees elevation (mm)
L2_PHASE_30	Double		L2 phase at 30 degrees elevation (mm)
L2_PHASE_25	Double		L2 phase at 25 degrees elevation (mm)
L2_PHASE_20	Double		L2 phase at 20 degrees elevation (mm)
L2_PHASE_15	Double		L2 phase at 15 degrees elevation (mm)
L2_PHASE_10	Double		L2 phase at 10 degrees elevation (mm)
L2_PHASE_05	Double		L2 phase at 05 degrees elevation (mm)
L2_PHASE_00	Double		L2 phase at 00 degrees elevation (mm)

Table **SAT_REC_ANT** : stores relationship of receiver, antenna and reference station

Column Name	Data Type		Description
REC_ANT_ID	Integer		Receiver Antenna ID combination
NAME	Varchar		Description of GPS receiver, antenna, site combination.
IP_ADDRESS			IP address of site
RECEIVER_ID	Integer		Receiver ID
ANTENNA_ID	Integer		Antenna ID
MARK_ID	Integer		Site mark ID

Table **SAT_DATA** - Stores raw GPS (GPS time, pseudo-ranges, carrier-phase and doppler).

Column Name	Data Type		Description
REC_ANT_ID	Integer		GPS Receiver ID
GPS_TIME	Date		GPS week and GPS seconds converted into year, month, day, hours, minutes and seconds format. Time (only suitable for > 1second data. Oracle does not store 0.1 seconds)
PRN	Integer		Satellite number PRN
SAT_TYPE	Varchar		'G': GPS or 'R': Glonass or 'T': NNSS Transit
L1_LOSS_LOCK	Integer		Loss of lock indicator for L1 frequency
L2_LOSS_LOCK	Integer		Loss of lock indicator for L2 frequency
L1_SIGNAL_STRENGTH	Integer		L1 signal strength, range from 0 to 9 (Rinex specification)
L2_SIGNAL_STRENGTH	Integer		L2 signal strength, range from 0 to 9 (Rinex specification)
L1_SIGNAL_NOISE	Integer		L1 signal to noise ratio (dbHz)
L2_SIGNAL_NOISE	Integer		L2 signal to noise ratio (dbHz)
L1_CARRIER	Double		L1 Carrier phase (full cycles)
L2_CARRIER	Double		L2 Carrier phase (full cycles)
CA_PSEUDORANGE	Double		C/A Code Pseudorange observation on L1 (metres)
P1_PSEUDORANGE	Double		P – Code Pseudorange on L1 (metres)
P2_PSEUDORANGE	Double		P – Code Pseudorange on L2 (metres)
D1_DOPPLER	Double		Doppler frequency on L1 (Hz)
D2_DOPPLER	Double		Doppler frequency on L2 (Hz)
SV_CLOCKBIAS	Double		SV Clock Bias
SV_FREQUNCYBIAS	Double		SV relative frequency bias

Table **SAT_EPOCH** - Stores information about each epoch, such as satellites observed for a GPS receiver.

Column Name	Data Type		Description
REC_ANT_ID	Integer		GPS Receiver ID
GPS_WEEK	Integer		GPS Week
GPS_SECONDS	Double		GPS Seconds (seconds)
GPS_TIME	Datetime		GPS week and GPS seconds converted into year, month, day, hours, minutes and seconds format. Time (only suitable for > 1 second data. Oracle does not store 0.1 seconds)
SATS_OBSERVED	Integer		Satellites observed
EPOCH_FLAG	Integer		Epoch Flag, 0: OK, 1: power flag between previous and current epoch., etc. See Rinex specifications

Table **SAT_NAV** - Stores navigation messages for each satellite. This table will be continuously updated as new ephemeris data is sent from each satellite.

Column Name	Data Type		Description
PRN	Integer		Satellite PRN number
GPS_WEEK	Integer		GPS Week
EPOCH	Time		Time of Clock
SV_CLOCK_BIAS	Double		SV clock bias (seconds)
SV_CLOCK_DRIFT	Double		SV clock rate (sec/sec)
SV_CLOCK_DRIFT_RATE	Double		SV clock acceleration (sec/sec ²)
IODE	Integer		IODE Issue of Data Ephemeris
CRS	Double		Amplitude of the sine harmonic correction. Term to the orbit radius (metres)
DELTA_N	Double		Delta N (radians/sec)
M0	Double		Mean anomaly at reference time (radians)
CUC	Double		Amplitude of the cosine harmonic correction. Term to the argument of latitude (radians)
ECCENTRICITY	Double		Eccentricity
CUS	Double		Amplitude of the sine harmonic correction. Term to the argument of latitude (radians)

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SQRT_A	Double		Sqrt(A) (sqrt(m))
TOE	Double		Reference time of ephemeris (seconds in GPS week)
CIC	Double		Amplitude of the cosine harmonic correction. Term to the Angle of Inclination (radians)
OMEGA0	Double		Right ascension at reference time (radians)
CIS	Double		Amplitude of the sine harmonic correction. Term to the angle of inclination (radians)
I0	Double		Inclination angle at reference time (radians)
CRC	Double		Amplitude of the cosine harmonic correction. Term to the orbit radius(metres)
ARG_PERIGEE	Double		Argument of perigee (radians)
OMEGA_DOT	Double		Rate of right ascension (radians/sec)
IDOT	Double		(radians/sec)
CODES_ON_L2	Double		Codes on L2 channel
L2_P_DATA_FLAG	Double		
SV_ACCURACY	Double		(metres)
SV_HEALTH	Integer		0 = healthy, 1 = unhealthy
TGD	Double		(seconds)
IODC	Double		Issue of data clock
TRANS_TIME_MESS	Double		Transmission time of message
SV_CONFIGURATION	Integer		0 = block I satellites, 1 = block II satellites

Table SAT_LEAPSECONDS

Column Name	Data Type		Description
REC_ANT_ID	Integer		GPS Receiver ID
DATE	Date		Time the leap seconds occurred.
LEAP SECONDS	Integer		Number of leap seconds from 6 Jan 1980

Table SAT_INTERVAL

Column Name	Data Type		Description
REC_ANT_ID	Integer		GPS Receiver ID
INTERVAL	varchar		

Table **SAT_PRECISE_HEADER** : stores precise ephemeris header

Column Name	Data Type		Description
GPS_TIME	Datetime		GPS time. Can only store year, month, day, hours, minutes and seconds. Will not store decimal seconds
TIME_SECS	Double		Stores the decimal seconds of the time
DATA_USED	Varchar		
COORDINATE_SYS	Varchar		Coordinate System
ORBIT_TYPE	Varchar		Orbit type
AGENCY	Varchar		Agency that supplied the SP3 data
CLOCK	Double		
GPS_WEEK	Integer		GPS week
GPS_SECONDS	Double		Number of seconds in GPS week
EPOCH_INTERVAL	Double		Epoch interval of data
MOD_JUL_DAY	Integer		Modified Julian dates
FRACTIONAL_DAY	Double		
NUM_SATS	Integer		Number of satellites

Table **SAT_PRECISE_ORBIT** : stores precise ephemeris information

Column Name	Data Type		Description
GPS_TIME	Datetime		GPS time in year, month, day, hour, min, and seconds. (Note: does not store decimal seconds)
TIME_SECS	Double		Decimal secs
VEHICLE_ID	Integer		Satellite ID
X_COORDINATE	Double		X-Coordinate (kilometres)
Y_COORDINATE	Double		Y-Coordinate (kilometres)
Z_COORDINATE	Double		Z-Coordinate (kilometres)
CLOCK	Double		Clock (microsecs)
X_VELOCITY	Double		X-Velocity (dm/s)
Y_VELOCITY	Double		Y-Velocity (dm/s)
Z_VELOCITY	Double		Z-Velocity (dm/s)
CLOCK_RATE	Double		Clock rate of change (e^{-4} microseconds/second)

Table **SAT_ALMANAC**

Column Name	Data Type		Description
ION_ALPHA0	Double		Ionospheric delay parameter A0 of almanac
ION_ALPHA1	Double		Ionospheric delay parameter A1 of almanac
ION_ALPHA2	Double		Ionospheric delay parameter A2 of almanac
ION_ALPHA3	Double		Ionospheric delay parameter A3 of almanac
ION_BETA0	Double		Ionospheric delay parameter B0 of almanac
ION_BETA1	Double		Ionospheric delay parameter B1 of almanac
ION_BETA2	Double		Ionospheric delay parameter B2 of almanac
ION_BETA3	Double		Ionospheric delay parameter B3 of almanac
DELTAUTC_A0	Double		Almanac parameter A0 - terms of polynomial
DELTAUTC_A1	Double		Almanac parameter A1 - terms of polynomial
DELTAUTC_T	Double		Reference time for UTC data (seconds)
DELTAUTC_W	Integer		UTC reference week number (weeks)
LEAP_SECONDS	Double		Delta time due to leap seconds
COMMENTS	Varchar		Comment

Table **MET_HEADER**

Column Name	Data Type		Description
RECEIVER_ID	Integer		Receiver ID
COMMENTS	Varchar		Comment
MARKER_NAME	Varchar		Marker name
MARKER_NUMBER	Varchar		Marker number
MET_SENSOR_POS_X	Double		Met sensor position X
MET_SENSOR_POS_Y	Double		Met sensor position Y
MET_SENSOR_POS_Z	Double		Met sensor position Z
MET_SENSOR_POS_HT	Double		Met sensor ellipsoidal height

Table **MET_SENSOR_TYPE**

Column Name	Data Type		Description
SENSOR_ID	Integer		Sensor ID
MODEL	Varchar		Sensor model/manufacturer
TYPE	Varchar		Met sensor type
ACCURACY	Double		Accuracy
OBSERVATION_TYPE	Varchar		Observation type

Table **MET_DATA**

Column Name	Data Type		Description
SENSOR_ID	Integer		Met sensor ID
OBS_TIME	Time		Observation time (GPS time)
PRESSURE	Float		Pressure (mbar)
RELATIVE_HUMIDITY	Float		Relative Humidity (percent)
WET_ZENITH_PATH_DELAY	Float		Wet zenith path delay (millimetres)

Table **REF_STATION**

Column Name	Data Type		Description
MARKER_NAME	Varchar		Name of survey mark
MARKER_ID	Char		Survey mark ID
REC_ANT_ID	Tinyint		Receiver, antenna ID combination
MARKER_ADDRESS	Varchar		Address of the reference station
POSITION_X	Float		X position (metres)
POSITION_Y	Float		Y position (metres)
POSITION_Z	Float		Z position (metres)
IP_ADDRESS	Varchar		IP address of the device server (on site)
PORT_NO	Tinyint		Port number of the device server
OBSERVER	Varchar		Name of Observer
AGENCY	Varchar		Name of Agency
COMMENT	Varchar		Comment

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TIME_ZONE	Char		Time zone
RECEIVER_TYPE	Varchar		Type of receiver
RECEIVER_VERSION	Char		Receiver version
RECEIVER_NO	Char		Receiver serial number
WAVE_FACTOR_L1	Integer		Wavelength factor for L1
WAVE_FACTOR_L2	Integer		Wavelength factor for L2
ANTENNA_TYPE	Varchar		Antenna type
ANTENNA_NO	Char		Antenna serial number
ANTENNA_DH	Float		Antenna offset – Up
ANTENNA_DE	Float		Antenna offset – Easting
ANTENNA_DN	Float		Antenna offset – Northing
L1	Integer		L1 carrier phase (Observed = 1 ; not observed = 0)
L2	Integer		L2 carrier phase (Observed = 1 ; not observed = 0)
C1	Integer		C/A code pseudo-range on L1 (Observed = 1 ; not observed = 0)
P1	Integer		P-code on L1 (Observed = 1 ; not observed = 0)
P2	Integer		P-code on L2 (Observed = 1 ; not observed = 0)
D1	Integer		Doppler observation on L1 (Observed = 1 ; not observed = 0)
D2	Integer		Doppler observation on L2 (Observed = 1 ; not observed = 0)

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Appendix H

SIMRSN Software Development

SIMRSN RS Connector and SIMRSN DB Server

The functions of *SIMRSN RS Connector* and *SIMRSN DB Server* are to remotely control GPS receivers located at the GPS reference stations from the Control Centre. Communication between *SIMRSN RS Connector* and *SIMRSN DB Server* is via leased lines utilising the TCP/IP protocol. A schematic diagram of the connection between *SIMRSN RS Connector* and *SIMRSN DB Server* is shown in Figure 1.

Figure 2 shows the screen shot of *SIMRSN RS Connector*. It is a receiver independent programme, and has following functions:

- ❑ serial communication with GPS receiver (sends control command and receives data from GPS receiver);
- ❑ receive control command from remote computer through the Internet or Local Area Network (LAN); and
- ❑ send real time GPS data stream to multiple programme through the Internet or LAN.

On the other hand, *SIMRSN DB Server*, that runs at the Control Centre, is capable of receiving GPS data from the reference station. It works together with *SIMRSN RS Connector*. *SIMRSN DB Server's* main function is to manage the *RS Connector* and to insert (write) the GPS raw data into the GPS database at an interval of time. Interface for *SIMRSN DB Server* is presented in Figure 3. This programme is able to perform the following tasks:

- ❑ GPS data collection, management and archive;
- ❑ remote control GPS receivers at Control Centre;
- ❑ receive and decode real-time GPS data from multiple receivers through LAN; and
- ❑ archive real-time data to the database using multiple thread technology.

Figure 1: SIMRSN RS Connector and SIMRSN DB Server schematic diagram

Figure 2: SIMRSN RS Connector

Figure 3: SIMRSN DB Server running at the Control Centre

SIMRSN RS Monitor

This module allows users to monitor the observations at each CORS in real-time. It is connected to the *SIMRSN RS Connector* via TCP/IP and draws the raw data from there. Users will be able to view epoch-by-epoch GPS observations, autonomous position, etc., of each CORS. Figure 4 shows the interface of *SIMRSN RS Monitor*.

Figure 4: *SIMRSN RS Monitor*

SIMRSN RINEX Generator

This module's function is to generate RINEX observation and navigation files for post-processing and backup. When it is executed it will query the SIMRSN database and retrieve the required data and organize them in RINEX format. Users can specify the period of observations needed and the data rate. It can be programmed to do the task on a regular interval or on-demand, either using batch-processing or single-processing. Figure 5 shows the interface for this module.

Figure 5: *SIMRSN RINEX Generator.*

SIMRSN DB Manager

This programme is a Graphical User Interface (GUI) for the GPS reference station information tables in the SIMRSN's database. It allows users to update the GPS reference station details without using (knowing how to use) the MS SQL7 database management system. Four tables are used to store information of GPS reference station:

- ❑ SAT_RECEIVER,
- ❑ SAT_ANTENNA,
- ❑ SAT_SITE, and
- ❑ SAT_REC_ANT.

These four tables are not implemented; instead one table has replaced the four tables and keeps all the information. The REF_STATION has been used because of easy query and maintenance.

SIMRSN EPH Server

The function of *SIMRSN EPH Server* is to download automatically precise ephemeris (precise orbit – SP3 format) files from the IGS ftp site. IGS operates a few hundred permanent GPS reference stations all over the world. This daily tracked GPS data is used to compute the precise orbit of the GPS satellites. IGS provides 3 levels of accuracy of the precise orbit for Internet users.

The program reads the ASCII file (precise orbit file) and updates the relevant tables in the database. Two tables, the SAT_PRECISE_HEADER and SAT_PRECISE_ORBIT will be updated after each download. Figure 6 shows the screen shot of the software. The precise ephemeris/orbit is used in the correction generation.

Figure 6: Screen shot of the *SIMRSN EPH Server*

***SIMRSN DB2RINEX* - web-based RINEX generation program**

DB2RINEX is a web-based ‘engine’ (dynamic library link), which queries the GPS database and generates RINEX files. The ‘engine’ allows multiple access to the GPS database through the world-wide-web (www). *DB2RINEX* creates two files, the RINEX Navigation file and RINEX Observation file, based on the time period and data rate specified by the user. The web interface is shown in Figure 7 and Figure 8. A unique filename is created each time different users request a RINEX file. The filename is based on the server’s clock when the request is made. Once the two RINEX files have been created, *DB2RINEX* generates a HTML (Hyper Text Markup Language) file, which is sent back to the client (user). A link in the HTML is created to allow users to download the files directly. In addition, *DB2RINEX* with other’s web pages created provide an introduction to the SIMRSN and the updated GPS data and ephemeris data availability in the database.

Figure 7: Web interface for *DB2RINEX*.

Figure 8: SIMRSN web site

SIMRSN MRC Server

SIMRSN MRC Server is the most important programme for the real-time application. It generates the “correction coefficients” of the *SIMRSN*, based on the five CORS epoch-by-epoch and satellite-by-satellite on L1 and L2 pseudo-range and carrier-phase observations. The stability of this program is very important. It draws raw GPS data from the *SIMRSN RS Connector* directly and solves the integer ambiguities between the CORS before computing the “correction coefficients”. Each *MRC Server* computes a set of “correction coefficients” and passes them to *MRC Generator* when needed. The algorithm for this software is described in Chapter 3. Figure 9 shows the *SIMRSN MRC Server*.

Figure 9: *SIMRSN MRC Server*

SIMRSN MRC Generator

This module computes the differential corrections for each user and generates the CMR messages. It connects to the relevant *MRC Server*, depending on the selection of the rover users. One *MRC Generator* is designed to serve only one rover user at any one time. Hence, the number of *MRC Generator* running at the Control Centre depends on the number of users the SIMRSN intends to serve. Details of computation and algorithm are presented in Chapter 3 and Chapter 4. Figure 10 shows the interface of *SIMRSN MRC Generator*.

Figure 10: *SIMRSN MRC Generator*

SIMRSN MRC Manager

This module manages all the *MRC Generator*. When a *SIMRSN VRS* initiates a connection, *MRC Manager* will assign a *MRC Generator* to the user. This module also keeps track of the available *MRC Generator* and conducts authentication when a user initiates a connection. Figure 11 shows the interface of the *SIMRSN MRC Manager*.

Figure 11: *SIMRSN MRC Manager*

SIMRSN VRS and SIMRSN VRS CE

This is the software that enables the connection to the SIMRSN Control Centre. The module executes at the rover users' side. There are two versions of this module, one works on Window PC and the other one works on Pocket PC. Figure 12 and Figure 13 show the interface of both versions. Detail descriptions of the procedures of using this software are presented in Chapters 3 and 4. The basic functions of this software are:

1. Dial up via GSM to the SIMRSN or connect to the SIMRSN via GPRS;
2. Send rover coordinate back to SIMRSN Control Centre;
3. Choose the mode of operation, either Multiple Reference Station (MRS) or Single Reference Station (SRS) service;
4. Choose the master reference station in MRS mode; and
5. Choose the reference station used for SRS.

Figure 12: SIMRSN VRS in Microsoft Windows operating system

Figure 13: SIMRSN VRS CE in a Pocket PC operating system

Appendix I

Architecture of the SIMRSN Real-time Corrections System

SIMRSN Real-time Correction Service

--- System Architecture ---

SIMRSN Real-time Correction Service

Server Modules

SIMRSN Real-time Correction Service

--- Server Modules ---

MRC Manager

Keeps track of the status of all active **MRC Generator** server on socket port 999;
Validates users' log in request on socket port 1000;
Informs user of the IP address and Port number of an available **MRC Generator** server.

MRC Generator

Notifies **MRC Manager** of connection status (busy/idle) on socket port 999;
Accepts user connection on socket port 1001+;
Connects to appropriate **MRC Server** (on socket port 801+ & 901+) based on user's request;
Computes MRSN corrections (if necessary) based on user's approximate position;
Process and format reference station raw data from **MRC Server** into CMR messages and send to user (**SIMRSN VRS**).

SIMRSN Real-time Correction Service

--- Client Module ---

SIMRSN VRS

Connects to **MRC Manager** on socket port 1000 to log in to SIMRSN Correction Service;

Receives IP address and Port number of an available **MRC Generator** server;

Disconnects from **MRC Manager** and connects to **MRC Generator** server on given IP and Port;

Let user select single- or multiple- reference station survey;

Let user enter approximate position (Lat, Lon, Ht) if multiple-reference option is selected (user can also select Master reference station);

Sends user option (or position) to **MRC Generator**;

Performs checksum verification on CMR messages received from **MRC Generator** and sends CMR messages out to serial comms;

Let user view the name and coordinates of the reference station.