

Internet-based GPS VRS RTK Positioning with a Multiple Reference Station Network

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Received: 27 November 2002 / Accepted: 27 December 2002

Abstract. Multiple reference station networks have been established for high precision applications in many countries worldwide. However, real-time application is still a difficult task in practice. Virtual reference station (VRS) concept is an efficient method of transmitting corrections to the network users for RTK positioning. Today's challenge for VRS RTK positioning lies in adapting advance wireless communication technologies for real time corrections. With the availability of GPRS technology, an Internet-based VRS RTK positioning infrastructure via GPRS has been developed and tested. This paper discusses the VRS data delivery mechanism, and gives an overview on VRS data generation for RTK positioning. Field test results are presented to evaluate the performance of the proposed system. The results demonstrate that Internet-based VRS RTK positioning can be achieved to better than 4 centimeters accuracy in horizontal position. Height accuracy is in the range of 1 to 6 centimeters.

Key words: GPS, Accuracy, Networks, Errors.

1 Introduction

GPS Real Time Kinematic (RTK) positioning is becoming increasingly important for many precise GPS applications - surveying, construction, precision farming and high accuracy Geographic Information System (GIS). Traditionally, a user receiver requires a reference station within 10 kilometers to ensure centimeter level accuracy. More recently, multiple reference station networks have been installed in many countries to overcome the limitations of standard RTK systems.

During the past few years, different approaches have been tested to take advantage of the availability of multiple reference stations. The focus of most of the research has been on modeling the spatial behavior of the distance-dependent errors (especially ionospheric errors). However, little research has been conducted on the distribution of these corrections to potential GPS users located within, and surrounding the network coverage area in real time. This is an integral part of GPS RTK positioning and it must be adequately addressed before a practical realization of the multiple reference station network is implemented (Fotopoulos et al., 2001).

Recently, the use of VRS (Virtual Reference Station) concept has been proposed by many research groups as a more feasible approach for relaying network correction information to the network RTK users (see, Wanninger, 1997; Marel, 1998; Vollath et al., 2000; Cannon et al., 2001; Euler et al., 2001). This approach does not require an actual physical reference station. Instead, it allows the user to access data of a non-existent virtual reference station at any location within the network coverage area. Also, the VRS approach is more flexible in terms of permitting users to use their current receivers and software without involving any special software to manage simultaneously corrections from a series of reference stations. With VRS, users within the reference station network can operate consistently at greater distances without degrading accuracy. It is necessary, however, to provide a reliable data communication link for the transmission of VRS data from a control center to a user receiver.

There are several ways of transferring the GPS data for RTK positioning. Hiromune et al. (2000) have investigated GPS RTK positioning using TV audio data broadcast and evaluated its validity. Global differential corrections are already available currently for DGPS applications over the open Internet via a TCP server

running at JPL (<http://gipsy.jpl.nasa.gov/igdg>, 2002; Muellerschon et al., 2000). For certain wireless services, there are frequency and power restrictions which regulate the use of such data transmission devices. GSM, a widely available public service, can be used as a distribution channel for the VRS data (Vollath et al., 2000). Using GSM as the communication link is unfortunately relatively expensive. From an operational point of view, cost is a very important consideration (Petrovski et al., 2001). This cost may be reduced using GPRS (General Packet Radio Service).

Every wireless communication mode has its pros and cons but must in general be able to support VRS RTK data link with low data latencies, good mobile performance, inexpensive user equipment, and nationwide coverage. The objective of this paper is to demonstrate a new method referred to as Internet-based VRS RTK positioning via GPRS.

This paper describes the VRS data generation approach. The Internet-based VRS data communication method is also discussed and field test results are included to evaluate the performance of the proposed system.

2 Overview of VRS Data Generation Approach

An overview of the VRS data generation approach is given in this section. In order to create data of a virtual reference station from the observations of the network of real reference stations, several processing steps have to be performed. The first step is to resolve the double-differenced carrier phase ambiguities between stations in the network.

The double-difference carrier phase observable between stations can be expressed as (e.g. Hofmann-Wellenhof et al., 1994; Leick 1995; Teunissen and Kleusberg 1998; Han, 1997)

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

Where $\nabla \Delta$ is the double-differencing operator, $\nabla \Delta \phi_k$ is the double-difference carrier phase observable expressed in units of cycles; λ_k and f_k are the wavelength and frequency of the carrier wave; $\nabla \Delta \rho$ is the double-difference geometric satellite-to-receiver distance; $\nabla \Delta N_k$ is the double-difference integer ambiguity; $\nabla \Delta d_{trop}$ is the double-difference tropospheric delay; $\nabla \Delta I$ is the double-difference ionospheric delay parameter (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), and $\varepsilon(\nabla \Delta \phi_k)$ is the double-difference carrier phase

observation noise and residual errors, here we assumed that the multipath effect can be reduced by careful selection of reference stations and using GPS hardware with multipath rejection capabilities, and orbit bias and phase center variation have been reduced to the ignored level.

Examining Eq. (1), it can be seen that the double difference ambiguities between the reference stations must be known, along with precise coordinates for the reference stations. The coordinates of the reference stations may be provided by the local survey authority, in the case of a permanent regional reference network. Alternatively, they may be obtained through a static survey of each station over long periods using the traditional long-range static positioning procedure. However, even with precisely known coordinates, it is not easy to fix ambiguities between reference stations of the network in real-time.

In order to support RTK positioning, the double-differenced integer ambiguities between reference stations of the network must be resolved in real time, because these ambiguities should be recalculated instantaneously in case of cycle slips or new satellites arise or long data gap occurs. Here, a residual-based adaptive Kalman filter is proposed to resolve the double-differenced carrier phase ambiguities between stations of the network with real-time capability. This is based on data of previous epochs and not just from the current one (Chen et al. 2000, Hu et al. 2002). 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 (igu) instead of broadcast orbits. The precise ephemeris can be obtained from the International GPS Service (IGS) centres which includes one day's predicted ephemeris (Roulston et al., 2000).

After the double-differenced ambiguities associated with the reference stations have been fixed to their correct values, the so-called correction terms for the atmospheric biases and other errors can be generated from the residuals in L1 and L2 carrier phase measurements on a satellite-by-satellite, epoch-by-epoch basis. 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 of the user, the influence from the atmospheric errors and other errors will be reduced or eliminated. This results in improved positioning performance. 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. 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. The advantage of this model is to eliminate orbit bias because the coefficients are derived in the way that orbit bias can be removed. The ionospheric delay and the tropospheric delay can also be reduced to the same degree that the epoch-by-epoch and satellite-by-satellite ionosphere and the troposphere models can do. Multipath and measurements noises can be reduced if the user receiver is located within the figure formed by the reference stations so that the coefficients are less than one. Otherwise the multipath and noise may be amplified because the coefficients might be larger than one (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. A more detailed description of the approach is given in Chen et al. (2000) and Hu et al. (2002).

In the next step, VRS data for user receivers are generated as required. In order to generate VRS data as though there was a reference station at the user's location, the user's approximate position and the user's position relative to this VRS, the carrier phase and pseudorange observations from master reference station has to be displaced geometrically and improved by applying the corrections of the network according to user's approximate position, i.e. VRS position. User's approximate position can be obtained by absolute GPS-code-positioning or output in NMEA format.

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

$$\rho_r^s(t) = \|x^s - x^r\| \quad (2)$$

and the geometric range between satellite and VRS

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

The change in the geometric range $\Delta\rho^s = \rho_v^s(t) - \rho_r^s(t)$ can be applied to all observations to displace the carrier phase and pseudorange observations from master reference station to VRS position. After geometric corrections are applied to master reference station raw data, the corrections of the network are used to displace VRS data. A standard troposphere model, such as Saastamoinen model (Saastamoinen, 1973), can be used to correct for tropospheric delay effects. Then the VRS data is generated as RTCM or CMR (Compact Measurement Record) format (Talbot, 1996) and delivered to the user.

As described above, the VRS data generation strategy consists of three steps. The first step is to resolve the

double-differenced carrier phase ambiguities between stations of the network in real-time. The second step is to generate the corrections on a satellite-by-satellite, epoch-by-epoch basis for user according to user's approximate position. The third step is to form VRS data as RTCM or CMR messages by applying the corrections to the data of the master reference station and displaced to the location of the VRS for users. The VRS data is then transmitted to the user where it is fed into the receiver as single reference station RTK corrections. The receiver can then use these corrections just as it would in the single reference station RTK approach. VRS data communication link issues are discussed in the following section.

3 VRS Data Communication Issues

An efficient communication link is critical for VRS RTK positioning since timely transfer of the VRS data is required for such a system. The communication link must provide reliability for data transfer and should not cause any significant transmission time delay. It is also desired that the links are available without much restriction in order to cover wide range of users. To date, there are several practical modes of distribution of the VRS data to users in real-time, such as GSM and Internet (Hada et al., 1999; Vollath et al., 2000; Liu and Gao, 2001; Ko et al., 2001).

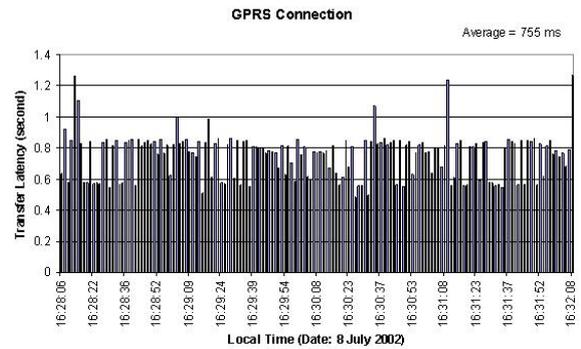


Fig. 1 GPRS data transfer latency on 8 July 2002

Given a developed mobile phone network, the most straightforward delivery mechanism is GSM, the low risk approach. A cellular phone allows bi-directional communication between a user and the VRS data control center. Therefore the user can transmit its approximate position to the control center. Further advantages are that there is no need to apply for radio frequencies, and reduced installation cost. One of the disadvantages of GSM is the limited number of parallel users imposed on the control center because each GSM line can only support one user. Another major drawback of GSM is cost as the user needs to be logged on constantly while using the VRS RTK service. In Singapore, this costs about 6-7 US\$ per hour. This cost will be significantly

reduced with GPRS (down to 2-3 US\$ per hour). More importantly, GPRS provides an “always-on” service. GPRS provides a stable and reliable connection with latencies less than 1 second. Fig. 1 shows a sample series of the data transfer delay via GPRS tested on 8 July 2002 in Singapore. For details of the test method see, for example, Liu et al. (2001). Latencies observed are usually in the order of a few hundred milliseconds in the test. Occasional latency of up to one or two seconds is not critical for GPS RTK positioning.

There is also a possibility to use the Internet as a data link between the control center and the user (Hada et al., 1999; Liu and Gao, 2001; Ko et al., 2001). Internet is the worldwide computer network system and becomes more important and common communication method mainly because of its fast data rate and availability to unlimited users. The Internet uses a bi-directional communication. Therefore, the user can also send its approximate position to the control center and request their demand to the control center, and the control center can provide VRS data for each user's demand according to the approximate position of user.

With the increased capacity of the Internet, and the recent developments in communication technology, especially of GPRS, the open Internet is a reliable choice to return GPS VRS data for RTK positioning via a GPRS. GPRS

can send and receive information directly from the Internet, support the transfer of the VRS data through the Internet in a favorable way. Therefore, an Internet-based GPS VRS RTK system was developed in Nanyang Technological University. This system uses the GPRS as the communication link between the control center and user stations.

Software at control center server has been written to generate and broadcast VRS data via Internet, which is assigned with a global IP address. The software opens the ports and waits for user connection. There is a login procedure required to gain access to the data. The software handles incoming login and generates the VRS data for the user according to user's approximate position.

For user side, a client software was written in the PocketPC environment. The user is equipped with either a single or dual frequency receiver capable of performing RTK positioning and is connected to a GPRS-enabled PDA (Pocket PC only). The PDA establishes the communications with the receiver through its serial port. The user can connect to the server of the control center through the Internet via GPRS at his location without any extra equipment. Figure 2 shows the architecture for linking the control center with the user receiver using GPRS.

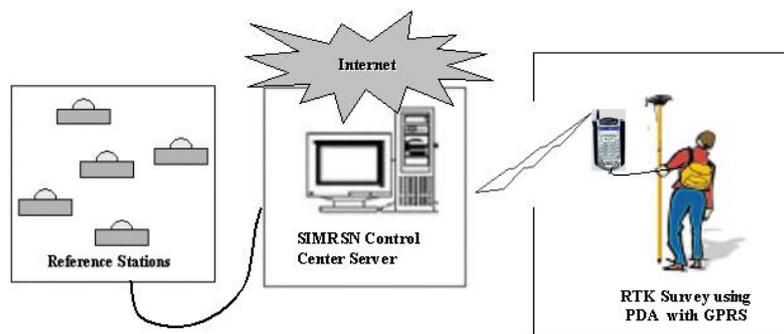


Fig. 2 Setup of Internet-based VRS RTK positioning via GPRS

4 Analysis of Internet-based VRS Performance for RTK Positioning

In order to validate the viability and performance of Internet-based VRS RTK positioning using above method, the first field test was carried out at different locations in Singapore in July and August 2002, based on a prototype reference station infrastructure (Singapore Integrated Multiple Reference Station Network (SIMRSN)). SIMRSN consists of five reference stations located at four corners and in the middle of Singapore with dual-frequency GPS receivers, as shown in Fig.3. Some of the features of the SIMRSN are described in Chen et al. 2000, or Hu et al. 2002.

Raw observations at each reference station are relayed to a control center using leased lines. The user is equipped with a RTK receiver and a Pocket PC with GPRS, as shown in Fig. 2. He uses the client software to log in the server of the control center through Internet via GPRS, and sends his approximate position to the SIMRSN control center. The control center software automatically receives the user's approximate position and selects the nearest reference station to the user as the master reference station. The raw data from that reference station is then geometrically displaced and improved by applying the corrections of the network according to the approximate position of the user. This is formed as VRS data, then transmitted as RTCM or CMR messages to the user receiver through the serial port of Pocket PC via GPRS at a data rate of 9,600 bps. The receiver can then

use these messages just as it would be in the single reference station RTK approach.

Five test points with different distances to the master reference station (NYPC) were used for testing the new communication method, as shown in Fig. 3.

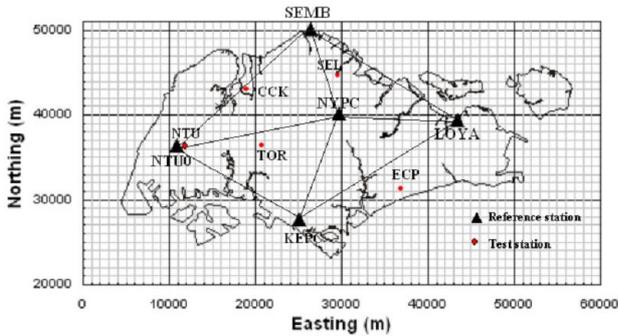


Fig. 3 Singapore Integrated Multiple Reference Station Network (SIMRSN) and Internet-based VRS RTK test stations

4.1 Results at NTU Test Site

The test station identified as NTU is taken as the first example, 19.1 kilometers away from the master reference station NYPC. A Leica SR530 dual-frequency receiver was used together with an AT502 antenna. This test was conducted during the time span 00:49-07:29 UTC (08:49-15:29 local time) on 31 July 2002 (DOY 212, GPS week 1177) at the rooftop of the N1 building located at Nanyang Technological University. The real-time positions during the test were continuously recorded by logging NMEA data output by one port of receiver. The surveying mode used was RTK and log data. Hence, the ground truth position could be computed from the logged long time raw data. Fig. 4 shows a representative sample of the differences (“true errors”) in the northing, easting and height components in the local datum SVY95 to the ground truth position. The standard deviations (inner accuracy) of easting, northing and height components are 0.012m, 0.010m and 0.048m respectively. As expected, the standard deviation in horizontal position is a factor of 2 to 3 better than in height. The reason for significant offset in the height component is caused by the residual tropospheric delay.

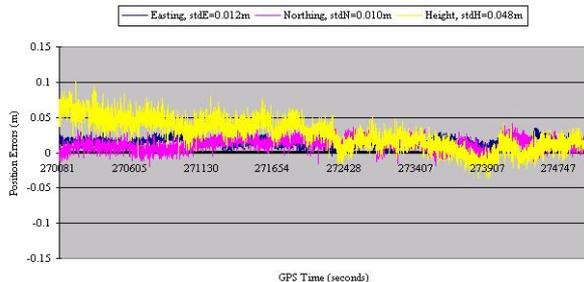


Fig. 4 “true errors” in the northing, easting and height for NTU station

To graphically ascertain the distribution of the computed errors, histograms of the horizontal and vertical position accuracy are plotted in Fig. 5 and Fig. 6. These figures present the absolute as well as the cumulative frequency for the horizontal and vertical position accuracy (external accuracy). It can be seen that 99% horizontal (2D) position accuracy is below 3 centimeters, and 99% vertical position accuracy is below 6 centimeters.

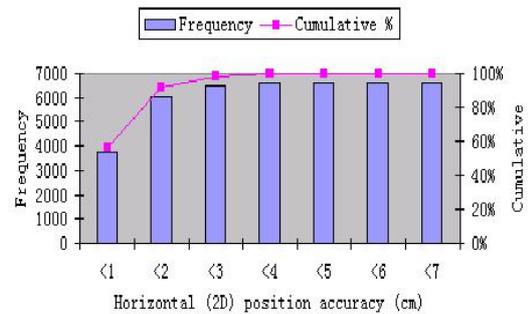


Fig. 5 Analysis of Horizontal (2D) position accuracy for NTU station

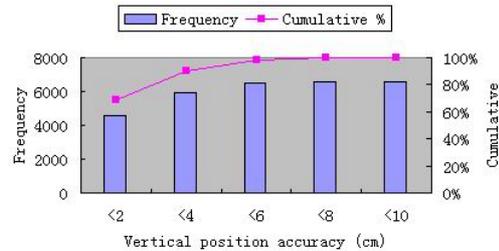


Fig. 6 Analysis of Vertical position accuracy for NTU station

Besides the accuracy, a crucial factor in the operational use of RTK GPS is the speed with which it can initialize (i.e. solve for integer ambiguities). This is expressed as TTF (Time to Fix) or TTFA (Time To Fix Ambiguities) value (Edwards et al., 1999; Wübbena et al. 2001). The TTF of RTK refers to the observation time it requires to resolve integer ambiguities in real-time after re-initialization. A program was written to monitor the status of the receiver’s positioning mode. Five seconds after each successful fixing – or 3 minutes at the latest, if no fixing occurred – the receiver’s RTK engine was completely reset. Hence, an analysis of TTF was possible. For the NTU station, sample time series of the TTF for RTK vs. number of satellites and HDOP value is given in Fig. 7. As can be seen, excluding those requiring more than 3 minutes to initialize, the TTF for VRS RTK was within one minute at most of time during the test, with the average of 40 seconds.

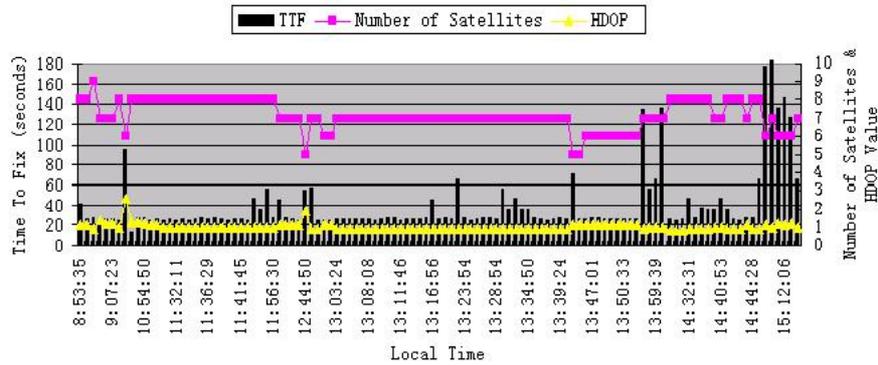


Fig. 7 Time To Fix vs Number of satellites and HDOP value for NTU station

4.2 Other Test Station Results

The accuracy and initialization time were analyzed at all the test stations. In the previous section, the results of the NTU test station were discussed. In this section, the five test stations were compared to evaluate the performance of the Internet-based VRS RTK positioning at different locations in Singapore, as summarized in Tab. 1. Note that similar accuracy and initialization time can be achieved during these tests. The worst performance was recorded at ECP station, about 3 kilometers outside the network, and 12.3 kilometers away from the master reference station. ECP test station uses Trimble 5700 dual-frequency receiver and Zephyr geodetic antenna, was conducted on 8 August 2002 (DOY 220, GPS week 1178), approximately between 02:48 and 07:13 UTC (10:48-15:13 local time). The position of the test station has been determined approximately 4636 times, providing a large test sample with independent ambiguity resolutions during the test period.

Tab. 1 Summary of results for five test stations

Test Station	Distance from Master Reference Station (km)	Standard Deviation (m)		
		Northing	Easting	Height
NTU	19.1	0.010	0.012	0.048
CCK	11.1	0.016	0.024	0.042
TOR	9.7	0.014	0.017	0.038
SEL	6.3	0.022	0.015	0.039
ECP	12.3	0.012	0.016	0.051

The horizontal position scatter and the true position of the ECP station is displayed in Fig. 8. The standard deviation for the northing, easting and height components are 12 millimeters, 16 millimeters and 51 millimeters, respectively. Fig. 9 and Fig. 10 show the histograms of the horizontal and vertical position accuracy for ECP station. These figures present that 91% horizontal (2D) position accuracy is below 3 centimeters, and 92% vertical position accuracy is below 6 centimeters.

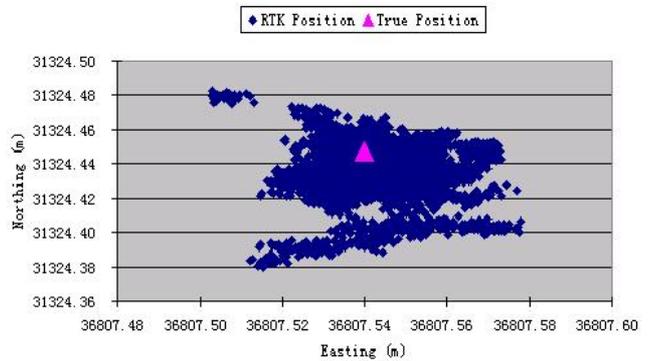


Fig. 8 Horizontal position scatter and true position for ECP station

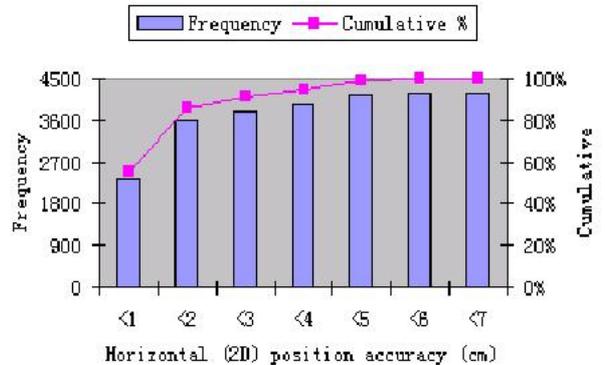


Fig. 9 Analysis of horizontal position accuracy for ECP station

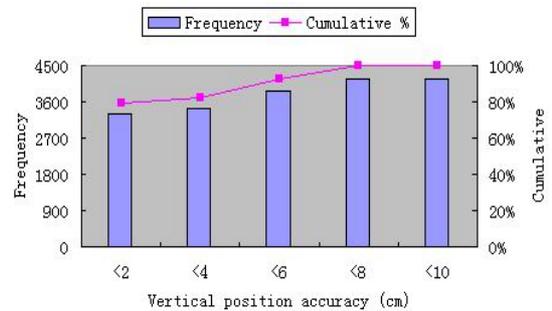


Fig. 10 Analysis of vertical position accuracy for ECP station

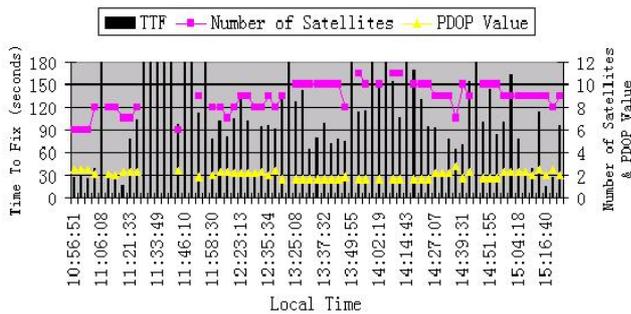


Fig. 11 Time To Fix vs number of satellites and PDOP value for ECP station

Fig.11 shows the TTF for RTK vs number of satellites and PDOP value. It can be seen that the TTF for VRS RTK was within 3 minutes at most of time. The average initialization time is 107 seconds. Initialization is more difficult when there is a larger PDOP value and fewer satellites. The reason for the larger dispersion during some times is the weaker satellite geometry, which results in larger PDOP value. This is responsible for the longer times needed to fix ambiguities. At some epochs this can exceed three minutes.

5 Concluding Remarks

Precise RTK positioning over longer distances requires a network of GPS reference stations. An Internet-based VRS RTK positioning infrastructure via GPRS has been developed and introduced in Singapore by Nanyang Technological University, Singapore in collaboration with the University of New South Wales, Australia. Using the active multiple reference station network in Singapore, field tests at different locations in Singapore confirmed that better than 4 centimeters horizontal accuracy and 1-6 centimeters vertical accuracy can be achieved, with initialization time less than 3 minutes. It is worthy to be noted that it is difficult to do standard RTK positioning in the tropics where turbulent atmospheric conditions result in rapid changes in ionospheric and tropospheric errors even over short distances.

Internet-based VRS RTK positioning system is a real-time, centimeter level service for construction, rapid surveying, and GIS. Some navigation applications like automatic parking and ship docking also require centimeter level accuracy. It can also easily be used in various related application areas including Intelligent Transportation System (ITS), emergency system, Automatic Vehicle Location (AVL), and personal navigation system. With better wireless communications being introduced, VRS RTK positioning will see more usage soon.

Acknowledgements

The authors would like to thank Dr. Chen Xiaoming and Mr. Teo Swee Tiong who help to develop the software used in SIMRSN. Also thanks to Prof. Chris Rizos and his research group SNAP of University of New South Wales for their technical support.

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