Critical Issues on GPS RTK Operation using Hong Kong GPS Active Network

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Abstract

The Lands Department of Hong Kong is establishing a permanent GPS array of reference stations for various applications. It collects GPS data continuously from multiple reference stations and delivers quality-checked data to users. This well-positioned and dense array of reference stations is designed to allow users to achieve cm-level accuracy within a short period of time, even using one low-cost single frequency GPS receiver. It will also support meter-level navigation and transportation management applications using DGPS correction. The array of permanent GPS stations can also be used for scientific research, such as deformation monitoring and weather forecasting. The station spacing for the active network is about 10 to 15 km, and there will be 13 to 14 stations covering the whole territory.

The main challenge today is how to implement the network solution using carrier phase measurement in real-time operation. In order to achieve this, there are still some problems to be overcome. For example, the ionosphere in Hong Kong is highly active during the daytime. This causes a serious problem for carrier phase ambiguity resolution. This paper investigates a number of important issues associated with the real-time operation of the network, including atmospheric corrections and system integrity. Possible solutions to these problems will also be proposed in this paper.

1 Introduction

Permanent GPS networks have been established in many parts of the world to serve high-precision navigation, engineering surveying and scientific research (Martin and Jahn, 1998, Chen et al., 2000, der Marel, 1998, Li and Gao, 1998). The first Hong Kong GPS network was established in 1991. It consisted of 15 stations. Thirteen of these were the existing main triangulation stations. Four were also fixed by satellite Doppler positioning. This network utilised the absolute position of Doppler stations as the origin. As a result, the reference frame of Hong Kong's 1991 GPS network had a bias of about 0.05m to the North, 0.3m to the East, and 1.5m vertically when compared with the ITRF system. In 2000, a densified GPS network consisting of 46 points covering the whole territory (Figure 1) was established. The average station spacing is about 10 km. The average relative accuracy of the 2000 GPS network is 0.2 ppm. In order to improve the global positional accuracy of the Hong Kong network, the 2000 GPS network was connected to the ITRF96 reference frame. The connection of the Hong Kong GPS network to ITRF96 was established using two months' continuous GPS observation (April and May 1998) carried out at the Kai Yi Chau and Fanling permanent GPS reference stations in Hong Kong and six other IGS GPS global stations in south east Asia. The baseline length of the connection survey ranged from 1200 km to 5500 km. The accuracy of the ITRF96 coordinates determined in this survey is estimated to be better than 2 cm (Chen, 1999).

Currently, the Hong Kong Lands Department is implementing a project to extend the scope of the existing permanent GPS reference stations to an active control system. The objective of the active network is to provide a fundamental geodetic infrastructure for engineering surveying (RTK and rapid static surveying), DGPS, and scientific research (deformation monitoring and atmosphere monitoring).

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Figure 1 The 2000 GPS Network of Hong Kong

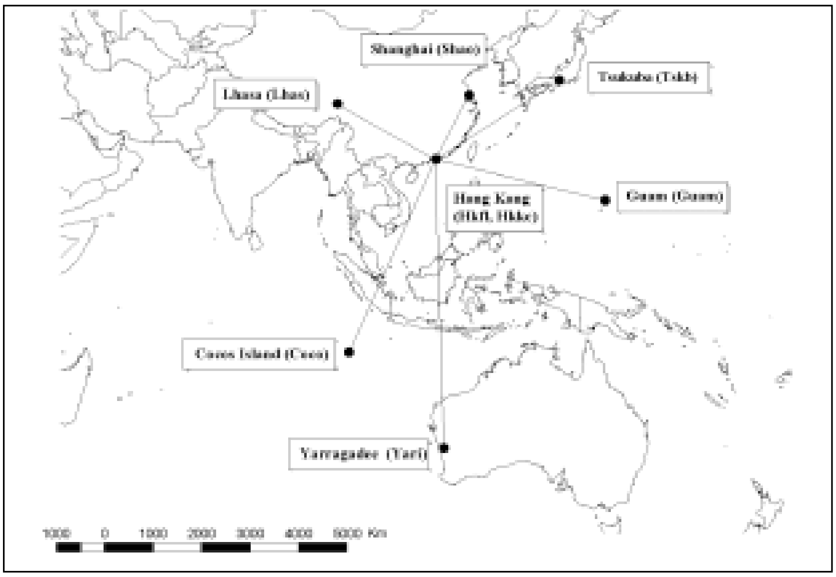

Figure 2 Connection of Hong Kong to 6 IGS Global Stations

The Hong Kong GPS active network aims to enable any GPS user in most of the area of Hong Kong to measure baselines to at least two reference stations within 10 km. This enables users to cancel out most GPS errors. Therefore, high precision positioning can be achieved even with a low cost single frequency GPS receiver, with minimum operation time. The Active Control System consists of an array of 13 to 14 continuously operating GPS reference stations with about 10 to 15 km station spacing that will cover the whole territory. The preliminary layout of the Hong Kong Reference Station Array is shown in figure 3. The project is divided into two phases. Phase I of the project has been completed and consists of six stations covering the northwest areas of the territory. In Phase II, 7 to 8 more Active Control Stations will be set up to cover the remaining area of the territory, together with a more advanced communication link. The Phase II of the project will be implemented in 2002**.**

The techniques using GPS to establish control networks have been well developed. A number of commercial and research software packages are available on the market. Users can use just one GPS receiver to collect GPS data in the field. After going back to the office, the GPS measurements from the reference network can be downloaded and conventional static GPS positioning methods applied to determine the position of the receiver. On the other hand, for some applications, such as setting out and high precision positioning for remote sensing, users need to know their positions in real time or near real time in the field. For this type of application, the Real-Time Kinematic (RTK) technique has to be used. A RTK system consists of three main components: reference receiver(s), a user receiver and a communication link between the reference station and the user. The GPS carrier phase measurements from the reference stations are transmitted to a user in real time. The position of the user can then be immediately determined to centimetre-level accuracy. The key to the RTK techniques is the fast ambiguity resolution algorithms, which require the measurement noise level to be sufficiently small. In Hong Kong, due to the high humidity of the troposphere and disturbance of the ionosphere, GPS measurement errors can be significantly different from one location to another. Therefore, to resolve the ambiguity becomes more difficult. This paper examines the effects of the atmosphere in GPS measurements and positioning accuracy. Possible solutions to reduce such errors are also suggested in this paper. Moreover, for real time applications, the integrity of the system becomes more important. We propose a two-step approach to the integrity monitoring of RTK performance.

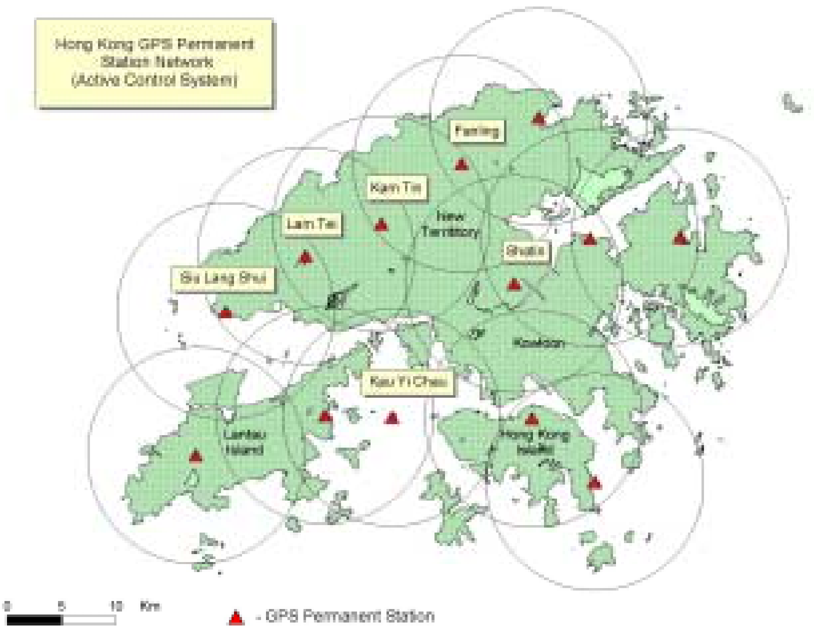

Figure 3 Preliminary Layout of the Active Control System

2 Atmospheric Effects on the GPS Active Network in Hong Kong

Over the last ten years, we have witnessed rapid developments in GPS data processing, especially in RTK techniques, which enable users to determine their positions in real time with centimetre-level accuracy using GPS carrier phase measurements. Currently, RTK techniques are widely applied in routine surveying works, and a number of software packages are available from different GPS receiver manufacturers, such as SKI (Leica), PRISM (Ashtech), and PINNACLE (Topcon). The assumption based on these algorithms is that GPS errors are highly correlated within short baselines (i.e. < 20 km). Thus, during the differencing procedures with two GPS receivers, the GPS measurement errors are largely cancelled out. This is also one of the main reasons for designing Hong Kong's GPS active network to space the reference stations 10-15 km apart.

However, the conventional GPS RTK techniques do not work in Hong Kong. We processed a baseline of 9.2 km in Hong Kong using every 15 minutes of GPS observation for a whole day on 4 March 2000. Figure 4 shows the success rate of ambiguity resolution using a commercial GPS processing software package. It can be seen that during half of the day (from 10 am to 11 pm local time) GPS carrier phase ambiguities could not be fixed and therefore the positioning accuracy was poor during that period. The main reason is that the differencing method cannot cancel out the ionopsheric effects on GPS measurements. As Hong Kong is located at low latitude (~22 degrees), there exist strong disturbances and scintillation of the ionosphere due to the complicated interactions among solar radiation, the geomagnetic field and the atmosphere. Consequently, the ionospheric delays are significantly different, even with baselines less than 10 km. Figure 5 gives the single difference ionospheric delay with the same baseline. It can be seen that the differences can reach up to 40 cm, which is equivalent to almost two cycles of the GPS carrier phase.

Chen et al. (2001) implement a method to model ionospheric residuals based on the double difference observable using the reference network. The algorithm consists of three steps. Firstly, the ambiguities among reference stations are determined by constraining the known positions of reference stations. The double difference residuals among the reference stations are then estimated using dual frequency GPS measurements. Finally, the corrections of ionospheric residuals between reference stations and user location is interpolated using the residuals between the reference stations. Figure 6 shows the success rate of ambiguity resolution after the network ionospheric corrections are applied. The data used are exactly the same as those used in figure 4. Compared with figure 4, significant improvement has been made with network corrections. The ambiguities are correctly resolved 100% of the time, while conventional RTK software can only fix the ambiguity about 45% of the time. Figure 7 shows positional errors after the network ionospheric corrections are applied. It can be seen that the positioning accuracies are about 5 mm horizontally and 3 cm vertically.

The troposphere also affects GPS positioning accuracy. The effects of the Hong Kong reference network mainly come from two aspects. Firstly, the tropospheric delay in GPS measurements is height-related. Thus the height differences among reference stations and user receivers will cause different tropospheric delays that cannot be cancelled out by differencing. Normally, a 10 m height difference causes a vertical delay error of 2-3 mm. A number of Hong Kong GPS reference stations are located on the tops of hills in order to have a better view of the sky, and the height difference can cause significant positional errors, especially with vertical components. Moreover, Hong Kong is surrounded by the sea and there is high humidity in the air (which can reach more than 95% in summer). The delays caused by the water vapour are more difficult to model. The best method of reducing the water vapour effect is to directly estimate the tropospheric delays, together with the position of user receivers. The method of estimating the tropospheric delay in the static mode has been proved to be well established. However, how to estimate the tropospheric delays precisely on the RTK mode is still a topic for research (Dodson et al., 2001). Without tropospheric corrections, a few centimetre position errors can be introduced, mainly on height. More research needs to be carried out to study RTK positioning errors due to the troposphere in Hong Kong.

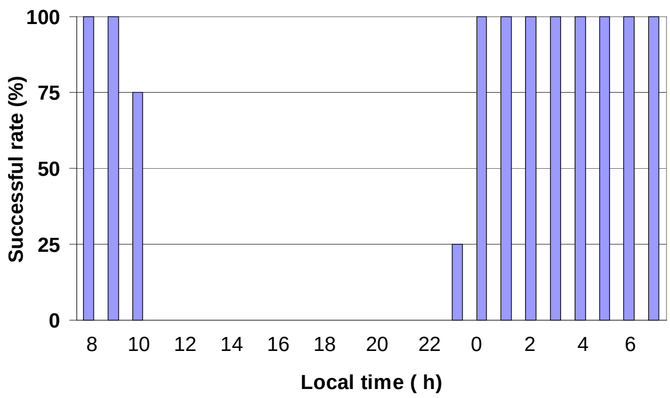

Figure 4 Success Rate for Ambiguity Resolution Using Commercial GPS Software

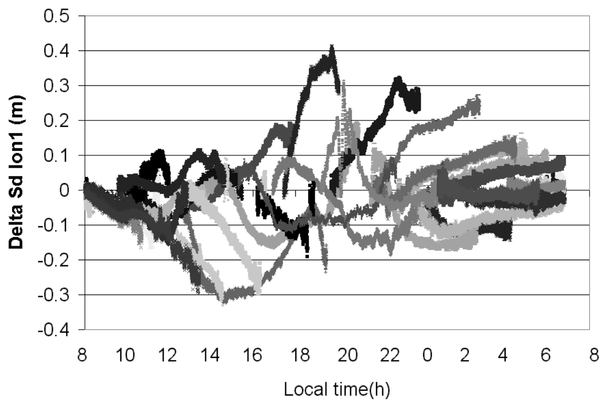

Figure 5 GPS Carrier Phase Single Difference Ionospheric Variation

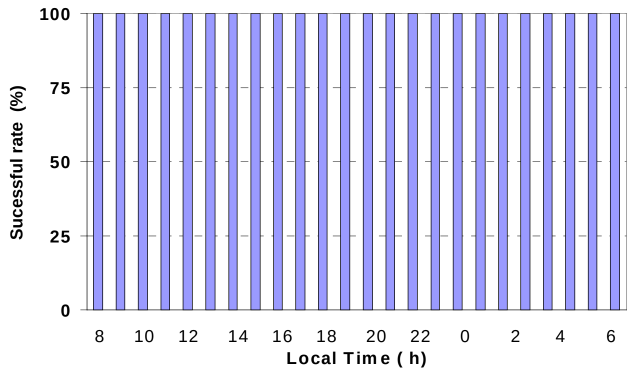

Figure 6 The Success Rate of Ambiguity Resolution with Network Corrections

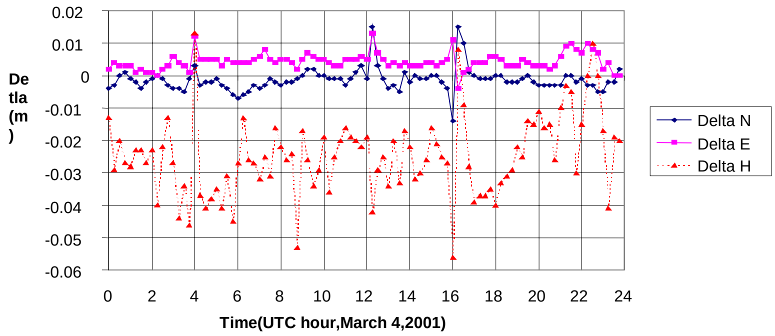

Figure 7 Positioning Error with Network Corrections

3 Integrity of GPS Active Network

Integrity is the ability of a positioning system to give a timely warning to users when large positional errors occur. In recent years, integrity has become a major issue for satellite navigation. However, most research in this area has concentrated on navigation applications using pseudorange measurements. For conventional GPS static surveying, integrity is not important as, if we discover problems during data processing, we can always come back to re-survey the point. For RTK applications, however, the quality of the position estimation has to be determined in the field. In this paper, an integrity checking procedure is proposed for GPS RTK users, based on an active GPS network. The integrity monitoring procedure can be divided into two levels: system integrity and user integrity.

3.1 The system integrity

The heart of the Active Control System is the Central Control Station. Figure 8 shows the linkage between the Central Control Station (CCS) and the GPS Observation Stations. The Communication Unit at the CCS can remotely control the equipment at the GPS observation station. This provides great savings in system maintenance costs, as the need for sending service engineers to the remote site is greatly reduced.

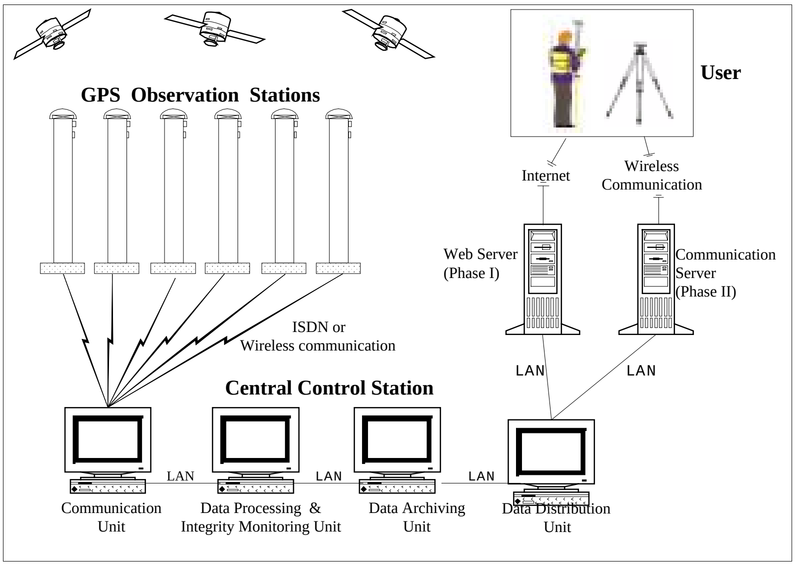

Figure 8 Overview of Hong Kong GPS Active Control System Integrity Monitoring

The Integrity Monitor checks the operation of the GPS Observation Stations and the quality of the data collected. After quality checking, the data are stored in the Data Archiving Unit. The system regularly checks three critical performance and reliability indicators. First, are the data being collected and transmitted to the Central Control Station? Second, is the data quality acceptable? Third, has the position of the permanent station been moved due to vandalism or gradual ground deformation? The Central Control Station will not send bad data to users if the system fails to pass the integrity check. Figure 9 gives the general procedure for the integrity check.

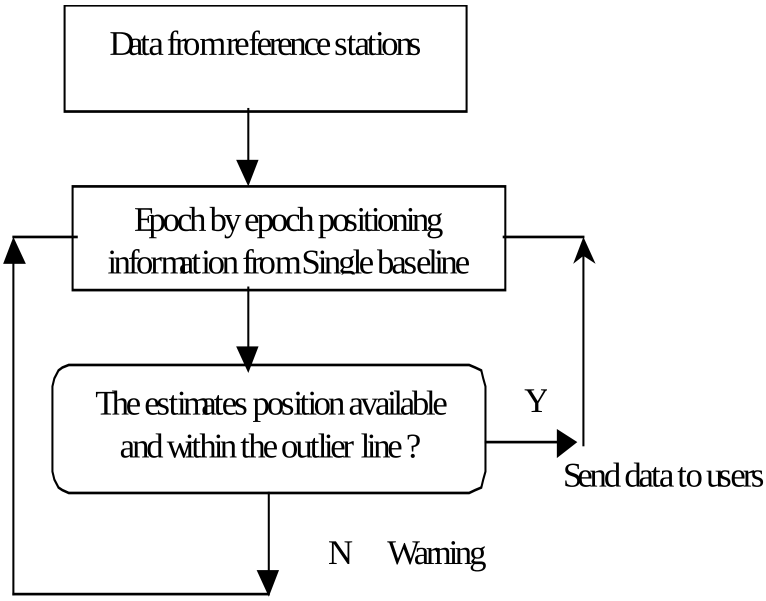

Figure 9 Procedure for system integrity monitoring

The system integrity for Hong Kong GPS network is currently examined by the CRNet software package. This is basically an RTK positioning software to estimate the coordinates of reference stations epoch-by-epoch. CRNet makes use of the dual frequency and code data to calculate the station position relative to one reference station. Because the calculated position is based on a single epoch, it reflects the geometry of the satellites and the data quality. The main information is the single epoch positional errors displayed on the computer screen (as shown in Figure 10). Two robust statistical estimators are used to analyse the positional error data, namely the median and the interquartile range (IQR). The median is taken as a central value and the IQR is used to characterise the dispersion of the data about their central value. The IQR is defined as the range of the middle 50% of the data. Figure 10 shows the positional errors of one reference station for 24 hours (March 4, 2001). It displays positional errors in all three components, together with the IQR band and the maximum allowed positional errors.

If the positional errors are larger than the predefined thresholds, the data of that station will not be sent to the user and further investigation will follow. Figure 10 shows that the positioning errors are within a few centimetres most of time that they are within the predefined thresholds. However, there are a few peaks where the positioning errors are larger.

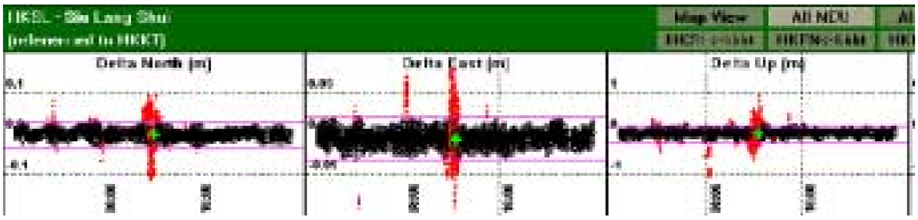

Figure 10 The Integrity Monitoring with Positioning Information

Further, it is possible to check the quality of individual measurements with known coordinates of the reference stations. As the distances between stations are within 10-15 km, double differences may cancel out most GPS errors. Therefore, the estimated ambiguity will be close to integers if the measurement errors are small. Figure 11 shows the L1 ambiguities of one reference station in the middle of the night (0:30). All the ambiguity residuals (after removing the integers) are within 0.1 of a cycle, which indicates the high quality of the carrier phase measurements. If the ambiguity residuals are larger (not close to integers), the data should not be transmitted to users. Figure 12 shows L1 ambiguity residuals at 18:00 for a period of 15 min. It can be seen that there are systematic trends up to 0.7 cycles (~14 cm). This is mainly due to the ionospheric delay, as the residuals of the ionospheric free observation are bounded within a few centimetres (figure 13). Thus, in Hong Kong, ionospheric effects cannot be ignored even with very short baselines.

3.2 User Integrity

The functions of user integrity monitoring include checking the data quality received from the reference stations, and monitoring the position results of user data processing. The general procedure is given in figure 14. The first part is similar to the system integrity check, which analyses the ambiguity residuals of reference stations. If the residuals are not close to integers, the data quality from the reference stations is poor. The second part involves a statistic RAIM algorithm (Michaelson, 1995) by examining the residuals after the user position is determined. The size of user residuals should also be compatible with the ambiguity residuals of the reference stations:

$$R = \frac{V^T PV_{user} / m_{user}}{VTPV_{ref} / m_{ref}} \sim 1 \qquad (1)$$

where $VTPV_{user}$ and $VTPV_{ref}$ are the sums of the residuals for user and reference stations respectively, and m_{user} and m_{ref} are number of observations.

If R is significantly larger than 1, either the data quality of the user receivers is significantly worse than that of the reference stations, or it is fixed to the wrong ambiguities.

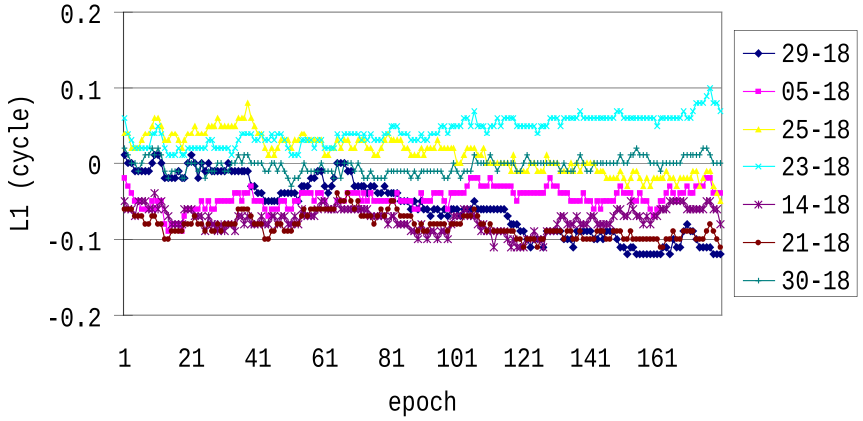

Figure 11 L1 Ambiguity Residuals at 0:30

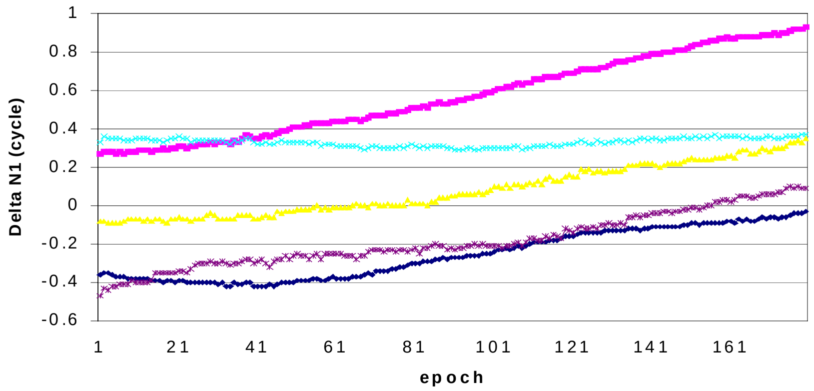

Figure 12 L1 Ambiguity Residuals at 18:00

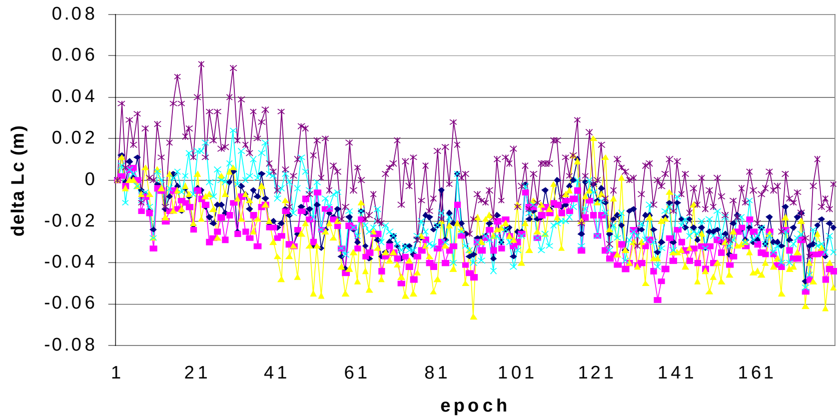

Figure L3 Ionosphere-Free (Lc) Residuals at 18:00

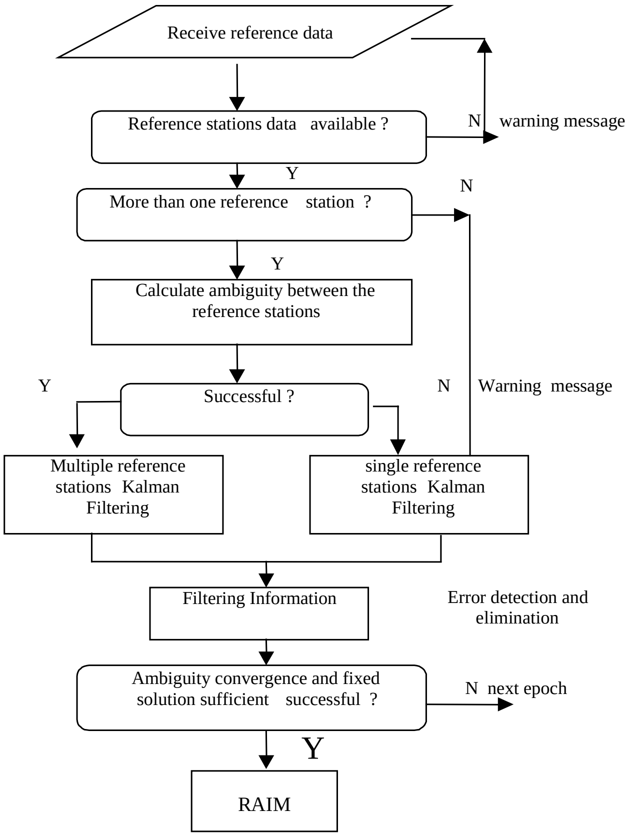

Figure 14 User Integrity Monitoring Procedure

4 Conclusions and Suggestions

The Hong Kong Lands Department is establishing an active GPS array as a fundamental geodetic infrastructure in Hong Kong. The active network is designed to satisfy the requirements of engineering surveying, land navigation and scientific research. The first phase of the project has been completed, with six reference stations and a control centre. The second phase of the project will be completed in 2002, with more reference stations to cover the whole area and more advanced communication links.

However, how to implement RTK operation with the Hong Kong GPS network is not an easy task. Without proper modelling of the ionospheric delays, the carrier phase ambiguities are difficult to fix when ionosphere disturbances are strong. An interpolation method can be used to reduce the effects of the ionosphere using the reference network. More research needs to be carried out to study the disturbance behaviour of the ionosphere in Hong Kong, and better models need to be developed. In order to improve RTK positioning accuracy, the effects of tropospheric delays also require further study.

Procedures for integrity monitoring for both control centre and user have been proposed in this paper. Both integrity monitoring procedures include two levels: measurement level and position level. For the control centre, the carrier phase measurement quality is examined by the ambiguity residuals, while the estimated epoch by epoch position is checked against the known coordinates of the reference stations. The user will verify the quality of the reference station data and examine the position quality using a RAIM algorithm.

Apart from the atmosphere and integrity problems mentioned in this paper, other issues related to RTK operation for the Hong Kong GPS reference network also need to be studied, such as communication between the control centre and users, and the network processing software. For RTK operation, GPS measurements from reference stations need to be transmitted to users in real time. Currently, the Hong Kong reference network only collects data from reference stations every

5 minutes, and does not support the RTK functions. How to economically transmit the data from the control centre to the users is a further problem. Currently, there are not many software packages on the market for network RTK processing. On the other hand, the existing software may not work in Hong Kong, as the Hong Kong environment is quite unique (high ionosphere disturbance and high humidity). More studies are needed to evaluate the performance of existing network processing software with Hong Kong GPS data, and new processing algorithms and software may need to be developed.

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