Monitoring of Slope Stability by Using Global Positioning System (GPS)

Eric Ma[1], Yongqi Chen[2], Xiaoli Ding[3]

Department of Land Surveying and Geo-Informatics

Hong Kong Polytechnic University, Hung Hom, Hong Kong.

Email: 98902035r@polyu.edu.hk Phone: 27665967 Fax:23302994

Biography :

1. Mr. Ma received a Bachelor degree in Surveying and Geo-informatics from the Hong Kong Polytechnic University in 1997. His research focuses are on GPS theory and application and he is currently studying a part-time MPhil degree specialized in GPS. He now works in the Lands Department of the Government of the Hong Kong Special Administrative Region as an Assistant Land Surveyor and will be elected as a corporate member of the Hong Kong Institute of Surveyors in June 2001.
2. Chen Yong-qi, chair professor and head of Department of Land Surveying and Geo-informatics at the HK polytechnic university. He received his degree education from the Wuhan Technical University of Surveying and Mapping, China and his PhD from the University of New Brunswick, Canada. He was chairman of commission 6, FIG. He published over 200 technical papers and 6 books.
3. Dr. Xiaoli Ding received education in China and Australia. He has lectured in China, Australia and Hong Kong and is currently an Associate Professor at the Hong Kong Polytechnic University.

Abstract :

Recently, the use of Global Positioning System (GPS) in slope deformation monitoring has received great attention in various countries. However, in Hong Kong, this application is still in a planning stage. The reasons may be the high expenses of purchasing numerous receivers for various monitored points and the reduction of GPS accuracy due to biases such as multipath effect. This study developed a GPS multi-antenna system for landslide detection in Hong Kong. In this system, a special electronic device called GPS Multi-Antenna Selector (GMAS) was employed to connect various antennas to one receiver and GPS data was taken sequentially from each of these antennas to the receiver. By adopting this design, the expenses spent on purchasing receivers were dramatically reduced. Furthermore, the adaptability of using long cables (longer than 60m) for data communication was evaluated. The development and implementation of the system were discussed in detail. Additionally, we estimated the multipath effect on slope environment by making use of its day-to-day repeatability characteristic. This system can be applied widely in Hong Kong and many parts of the World to identify potential slope failures and also can be used to study the stability of many other objects such as dams, high-rise buildings and structures.

1. Introduction

Since Hong Kong is a small and hilly city with a dense population, many people live in the areas which have high risk of landslides. Today, many of the over 50,000 existing slopes in Hong Kong are unstable. More than 20,000 of them were built decades ago and might collapse under certain conditions. In order to avoid disasters, it is necessary to accurately monitor the movement of slopes.

In Hong Kong, two types of techniques have been used to monitor the deformation of slopes. They are the conventional survey techniques and the geotechnical techniques. The main drawbacks of conventional survey techniques are the low efficiency, sensitivity to atmospheric conditions and their requiring direct line-of-sight between instrument stations and the measured points. In addition, geotechnical techniques can only measure relative deformations within a limited area. As a result, an automatic system is needed to continuous monitor the progressive deformation of slopes with time.

GPS (Global positioning System) is a potential tool used to measure ground displacements over an extensive area in various engineering projects involving high cut slopes, large open pit mines, subsidence and landslide. Several researchers have already studied the applications of GPS in ground displacements (Chrzanowski, 1988; Murria and Saab, 1988; Strange, 1989; Blodgett, 1990; Ding, 1996;Stewart et al., 1996b and Tsakiri, 1996). Several factors make GPS an attractive tool for ground displacements: less labour intensive, the decrease in the price of GPS hardware, it measure three dimensional vector of displacements of the ground, real time monitoring and its ability to measure ground displacements over an extensive area.

Many scientists from different fields have spent much of their time in developing GPS slope monitoring system. For example, Kondo (1995) developed a system to continuously determine positions in real-time of up to ten locations using GPS. Result shown that the order of 2 cm of displacements could be detected by statistical tests. Shimizu et al. (1996) also designed a system to measure displacements of many points simultaneously in real-time. They tested the system in a limestone open quarry in Yamaguchi, Japan and the result revealed that the system could measure displacements almost as accurately as total station surveying. Furthermore, Shimizu (1994) proposed a method for improving the accuracy of GPS displacement measurements by using adaptive filtering. Other applications to slope monitoring were also conducted by Ananga (1996, 1997) and Sakurai and Hamada (1996).

However, existing researches have used the standard methods of attaching one GPS antenna to a GPS receiver. To monitor a slope, a large number of points usually need to be monitored. As a result, numerous receivers must be required to monitor a group of points. This approach is so expensive that it can only been used on a very limited scale. In addition, there have been few studies in consideration of the special conditions of slopes. GPS satellite signals are often obstructed by tall vegetation and high-rise buildings nearby. The slope surface can also cause GPS signal multipath errors. More importantly, there is little information available on the application of GPS in slope monitoring in

Hong Kong. Therefore, this paper sets out to develop a new GPS slope monitoring system, which employs a single GPS receiver and multiple antennas for monitoring slope deformations in Hong Kong. This research project includes tests of different hardware configuration and software development. The project also aims to study the methods to reduce GPS signal multipath effect. Experimental results from some preliminary tests of the system will also be given. The accuracy, advantages and limitations of GPS in deformation monitoring of slope will also be evaluated.

2. System Overview

The GPS Multi-Antenna System is developed to reduce the expenses of hardware in slope monitoring survey (see figure 1). Some early work on the system can be found from Chen et al. (2000) and Ding et al. (2000). A GPS Multi-Antenna Selector (GMAS) is used to connect a number of antennas to one receiver so the expenses spend on purchasing receivers are dramatically reduced (see figure 2). The GMAS does not change the structure of the GPS signal and it scans the antennas sequentially so that each antenna is connecting to the receiver for a fixed time interval. User can set the interval in advance according to their applications.

Figure 1 The basic element of the GPS

Figure 2 GMAS - Antenna Connector

The GPS multi-antenna system has the following elements (Fig. 3):

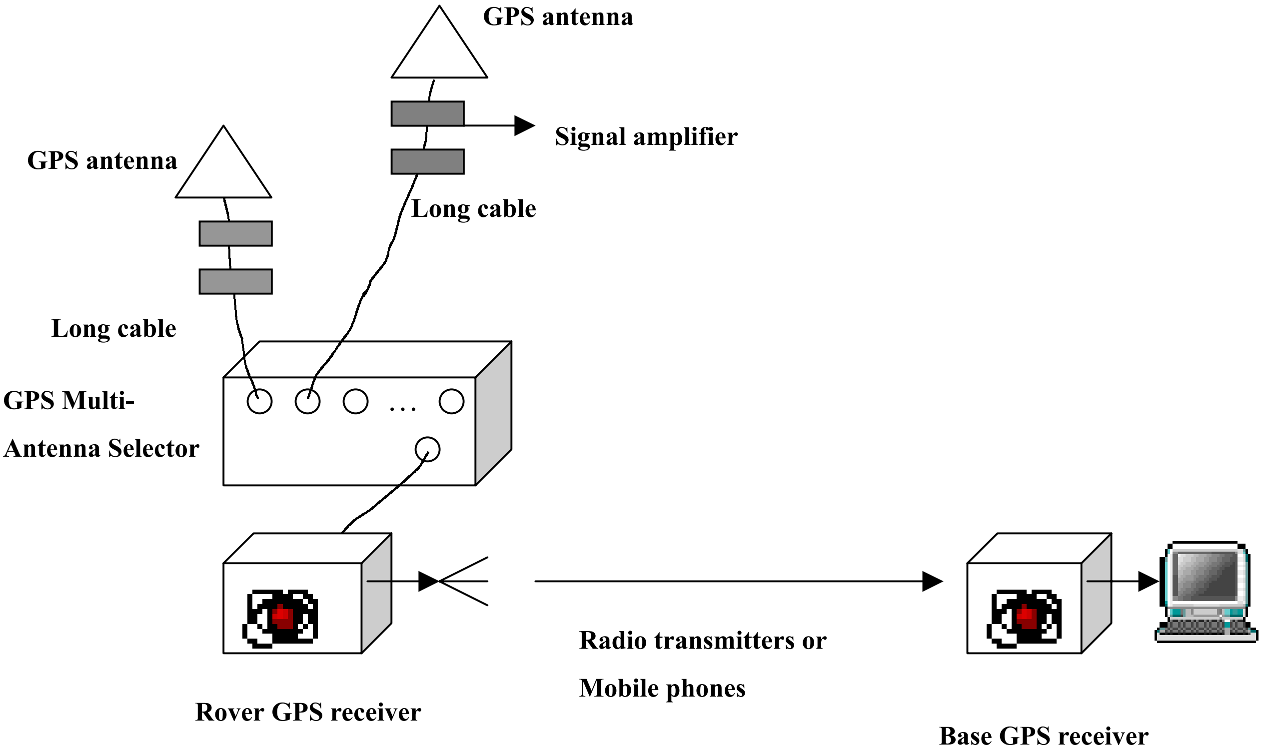

Fig. 3

2.1 GPS Multi-Antenna Selector (GMAS)

It is a special electronic device containing two hardware. One is the antenna connector and the other is the timing controller. The antenna connector contains multi-input and one-output terminals. Different antennas are connected to these multi-input terminals and a receiver is connected to the one-output terminal. GPS signals received from different antennas, which passing through these multi-input terminals, are measured in the same receiver. On the other hand, the timing controller is used to control measuring period of each antenna. With the help of the GMAS, only one receiver is used to monitor a number of points.

2.1.2 GPS antenna and receiver

To achieve high accuracy result, using dual frequency receivers are recommended in slope deformation monitoring. In view of which model of receiver should be chosen, this depends on the purposes of the survey and location of the site.

2.1.3 Data transmission

Data communication is a vital part in this research. We need to deal with two critical issues. The first one is how the data is transferred from the antennas to the rover receiver. The second one is how the data is transferred from the rover receiver to the base receiver. For the first question, the problem is that in a slope site, monitoring points are usually dispersed. Therefore, long cables (longer than 60m) are usually used to connect the antennas to the rover receiver.

Generally, there are three types of cable can be choose from. They are Twisted Pair cable, Coaxial Cable and Fiber Optic Cable. Twisted Pair cable is often considered a low-frequency transmission medium Its main benefits are relatively inexpensive and easy to install. Coaxial Cable consists of a single wire in the center surrounded by a core of insulating material, with an outer conductive wrapping which is usually a copper cylinder. This copper cylinder is capable of absorbing any noise or interference from the surroundings and then sending them to the ground. This type of cable transmits high frequencies like several hundred Mbps. Compared with the above two types of cable, Fiber Optical cable offers the widest bandwidth, the lowest attenuation and is also the most expensive one. It is especially suitable for long distance data transmission up to 10 km.

In this project, Coaxial cable is selected. It is because for twisted cable it is relatively too sensitive to noise and providing the lowest bandwidth. In addition, for transmitting GPS signal through Fiber Optical cable, it is necessary to convert the GPS signal, which is an analog signal to optical signal using a GPS fiber optic network. However, the cost of such a network is about ten times higher than the cost of using a coaxial cable linked with a signal amplifier. This is not practical for most small scale slope monitoring surveys. As a result, Coaxial Cable is considered the most appropriate one to be employed in this study.

After having selected the appropriate cable, another problem is how to minimize the GPS signal loss during data transmission. As GPS signal is an analog signal, which is susceptible to noise and the noise is an unwanted signal that has sufficient amplitude to interfere with the communication process. There are two alternatives to solve this problem. The first one is to convert the GPS signal from analog signal to digital signal first for data transmission and then convert the signal back to analog signal when it arrives at the base receiver. This conversion process can be done by using the Pulse Code Modulation (PCM) method which is a standardized method used in the telephone network to change an analog signal to digital one for data transmission. As digital signal is less susceptible to noise, it can replaces analog signal for long distance data transmission. However, GPS signal may be destroyed after the PCM conversion process and therefore is not recommended in this project.

The second method, which has been adopted in this research, is to use a signal amplifier to compensate the GPS signal loss during data transmission. GPS signal strength decreases with increasing distance from a GPS antenna. This attenuation is usually expressed in decibels (dB). An attenuation of n dB means that the original GPS signal is reduced by a factor of $10^{-0.1n}$. For a 60m RG58A/U coaxial cable, the attenuation is about 60 dB and this means the GPS signal strength is reduced by about $1^{-0.6}$ of its original strength. In this project, a GPS antenna with 25dB gain were linked with two 20dB signal amplifiers to transmit signal over a 60m RG58A/U coaxial cable. The function of the signal amplifiers was to compensate the loss in signal strength during long cable transmission.

The second critical issue in data transmission is to send the GPS signal from the rover receiver to the base receiver for data processing and analysis. Various options can be adopted such as mobile phones and radio transmitters. The mobile phones are suitable for long distance data transmission while the costs are higher compared to radio transmitters. The radio transmitters require direct ling-of-sight between a pair of transmitters, thus they are only proper for flat area and short distance application. Generally speaking, the right choice to be used is depended on the site environment and survey requirement.

2.1.4 Solar panels and battery

To ensure the system can be capable of continuous operating, a continuous power supply should be provided. Therefore, it is suggested that solar panels and the rechargeable battery have to be used to power all the electronic devices on site.

2.2 Reduction of the Multipath Effect

With the recent development in advance GPS receiver technology and differential GPS positioning methods, many of the errors sources in GPS carrier-phase measurements have been drastically reduced. For instance, most of the errors in the carrier-phase measurements, such as atmospheric delays, orbital and clock errors are spatially correlated and generally cancel through the differencing process. Consequently, GPS multipath effect has become a dominant error source for high precision applications and extensive researches have been conducted to reduce the effect. More importantly, high multipath interference from slope surface has limited the application of GPS in slope monitoring.

Formation of Multipath effect on slope surface-

According to Hofmann-Wellenhof, B. et al.

(1997), the effect of multipath on carrier phases can be estimated for a known surface. The situation where the direct signal from satellite interfere with the indirect signal from the receiver surface can express as follows:

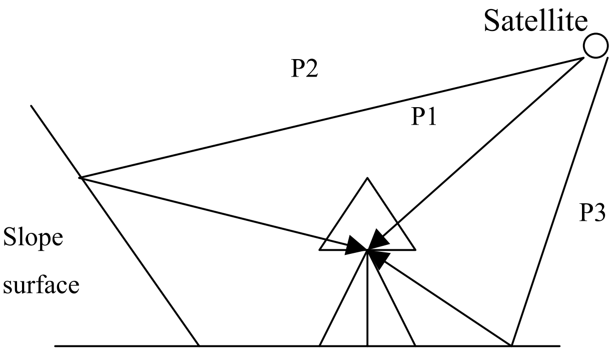

Fig. 4 Formation of Multipath effect on slope surface

P1 = $a\cos\varphi$ …………………(1)

P2 = $\beta\cos(\varphi + d\varphi)$ …………………(2)

Where P1 denotes the direct signal from satellite, P2 denotes the indirect signal from the slope surface, a and φ are the amplitude and the phase of direct signal respectively. β is the reduction factor and dφ is the phase shift caused by multipath. The combined signals is represented by

$$P = P1 + P2 = a^d\cos(\varphi+\gamma) \quad \text{……(3)}$$

Where the combined signal amplitude a^d is

$$a^d = a(1+2\beta\cos\varphi + \beta^2)^{1/2} \text{……….(4)}$$

and the carrier phase multipath delay γ is

$$\gamma = \tan^{-1}\left[\frac{\beta\sin\varphi}{1+\beta\cos\varphi}\right] \quad .(5)$$

$$\varphi = \frac{2h}{\lambda}\sin E \quad ..(6)$$

Where E is the elevation angle of the satellite, λ is the wavelength of the signal and h is perpendicular distance between the antenna and the slope surface. For a slope surface, the multipath effect can be found by

$$Ps_{multi} = \frac{\gamma}{2\pi}\lambda = \frac{\lambda}{2\pi}\tan^{-1}\left[\frac{\beta\sin\varphi}{1+\beta\cos\varphi}\right] \quad ..(7)$$

The maximum effect of multipath on phase measurements occurs when $\gamma = 90^0 = 1/4$ cycle. Thus, the maximum error in L1 signal (λ=19.05 cm) is about 5 cm. However, in practical circumstance, mulitpath signals may be reflected from different surfaces simultaneously. In this circumstance, the combined signal can be written as

$$P_c = P_1 + P_2 + P_3 + \cdots + P_n \quad ..(8)$$

$$= P + P^d = a_c\cos(\varphi+\gamma+\gamma^d) \quad ..(9)$$

$$P = P_1 + P_2 = a^d\cos(\varphi+\gamma) \quad ..(10)$$

$$P^d = P_3 + \cdots + P_n = \beta^d a^d\cos(\varphi+\gamma+\gamma^d) \quad ..(11)$$

Where applying the same principle of equations (4) and (5), the combined signal amplitude is

$$a_c = a^d(1+2\beta^d\cos\varphi + \beta^{d2})^{1/2} \quad ..(12)$$

and the carrier phase multipath delay γ^d caused by P_3 + … P_n is

$$\gamma^d = \tan^{-1}\left[\frac{\beta^d\sin\varphi^d}{1+\beta^d\cos\varphi^d}\right] \quad ..(13)$$

the resulting multipath effect P_{multi} can be found b by

$$P_{multi} = \frac{\gamma+\gamma^d}{2\pi}\lambda \quad ..(14)$$

where P_3 + … P_n represent the multipath signals from other reflected surfaces and P^d represent their combined signal. The meanings of the other terms are same as before.

For short baseline observation, most of the GPS errors such as ionoshperic delays, orbital errors and clock errors are very small compared to multipath effect. In view of this, we can assume that multipath effects are the major sources of error contained in the observations. If we compared a set of data with multipath effect reflected from a slope surface with that do not has the effect, we can determine the magnitude of multipath effect reflected from a slope surface.

According to equation (14), the resulting multipath reflected from a slope surface and other reflected surfaces is give as

$$P_{multi} = \frac{\gamma + \gamma^d}{2\pi} \lambda$$

On the contract, the multipath effect caused by the other reflected surface is equal to

$$P^d{}_{multi} = \frac{\gamma^d}{2\pi} \lambda \qquad ..(15)$$

Therefore, minus equation (14) by equation (15), the multipath effect caused by the slope surface can be found out

$$Ps_{multi} = \frac{\gamma}{2\pi} \lambda \qquad ..(16)$$

As multipath reflected from the slope surface is the most significance error source affecting precise GPS slope monitoring, it is vital to find out how large it is and how does it affect the coordinate computation of the monitored points.

In the next section, experiments will be conducted to examine the effect of multipath on coordinate computations, deformation measurements and observation residuals. We will study the Day-to-Day repeatability characteristics of multipath effect and make use of these characteristics to reduce the effect on GPS survey.

3. Experimental Results

3.1 Multi-Antenna GPS System

To demonstrate the utilization of the GPS multi-antenna system, an experiment was performed at the roof top of the Hong Kong Polytechnic University. Location of the site was shown on the figure 4.

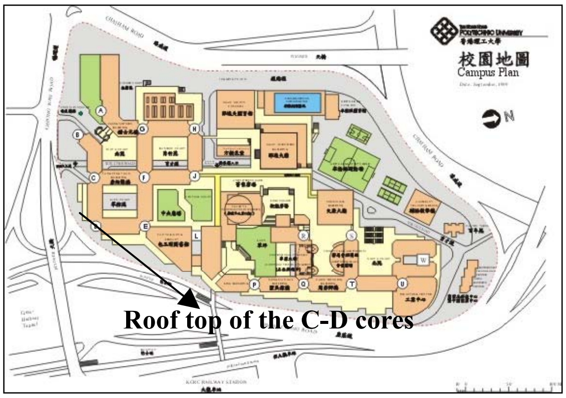

Figure 4 Location of the experiment site

After detail investigation, one reference station and two monitored points were selected. Two baselines were formed from the reference station to each monitored points individually. Both of these baselines were approximate 45 m in length. The GMAS has six input terminals and one output terminal, only terminals 3 and 5 were used for illustration. Two antennas were connected to these input terminals and one receiver was linked to the output terminal. A 60 m long cable linked with two 20 dB signal amplifiers was used to connect the antenna to the GMAS so as to stimulate the slope environment. The observation time of each terminal can be set by user in advance. In this experiment, the time interval was set as about 16 minutes which was long enough for fast static positioning.

Two sessions of fast static positioning were launched and the observation period for each antenna was selected as 16 minutes. When the maximum time interval was reached, the GMAS would switch to the other terminal to collect GPS signal. The receiver did not recognize the switch of the GMAS, thus the data logging kept continue when GMS switch form one antenna to the other. At the end, all the data from different antennas were recorded as a file and we needed to divide it into two parts in data processing.

Terminal 3			Terminal 5		
Coordinate Value in Conventional Terrestrial (CT) System			Coordinate Value in Conventional Terrestrial (CT) System		
X	Y	Z	X	Y	Z
*78.0216	*36.0814	*68.8746	*76.8583	*36.4678	*69.1484
*78.0147	*36.0710	*68.8733	*76.8612	*36.4688	*69.1515

Remark - Where * are the first five digits of the coordinates and are the same for the two monitored points.

3.2 Reduction of Multiapth effect

Experiments were conducted to analyze the multipath effect in monitoring survey. The aims of the experiments were to investigate the following factors :

a. The magnitude of the multipath on coordinates;
b. The effect of multipath on measurements of displacements;
c. The magnitude of the multipath effect on L1 residuals and L2 residuals.

In this experiment, two points of 9.682 m apart were selected to form a baseline. One was the base station and the other was the rover station. The locations of the points were carefully selected so that they were free of obstructions and located in a low multipath environment. The tripods were fixed and the antennas were taken down after each observation and were mounted on before next observation. More than three hours observations were taken for each experiment. The experiments last 9 days, however only 6 days were recorded due to poor weather condition. The results of the experiments were listed in table 1:

Exp. No.	Date	Location	Observation Period (pm)	Type
1	12/1/2000	C-D cores roof	2:22 - 6:00	No special reflector was placed (static mode- 30 min)
2	13/1/2000	C-D cores roof	2:19 – 6:00	Special reflector was placed (static mode – 30 min)
3	14/1/2000	C-D cores roof	2:18 – 8:00	Special reflector was placed (static mode –1 hr 30 min)
4	15/1/2000	C-D cores roof	2:15 – 8:00	No special reflector was placed (static mode- 1 hr 30 min)
5	17/1/2000	C-D cores roof	4:00 - 6:00	No Special reflector was placed (a pole was located in a tripod)
6	19/1/2000	C-D cores roof	4:00 – 6:00	Special reflector was placed (a pole was located in a tripod)

Table 1 Time schedule of the multipath experiments from 11/1/99 to 19/1/2000

In order to examine the effect of multipath caused by a slope surface, two observation conditions were employed. The first one was the normal observation condition, that mean, no special reflected surface was placed. Another was the condition that a special reflected surface was established. We selected a large digitizer as the reflected surface (see figure 5) and placed it near the receiver antenna. In an aim to ensure the signal from satellite could reflect form the reflected surface to the receiver antenna, the digitizer was placed very close to the receiver antenna. The direction of the surface was established approximately so that at least one satellite can form a multipath signal during the whole observing period.

Fig. 5 Experiment set up at the roof top of the HKPU

In this paper, we focused on the magnitude of the multipath effect on L1 and L2 residuals. In order to compare the change caused by multipath, we must use the same satellite geometry of the two successive days. For instance, if we want to determine the multipath change between 12 January (exp. 1) and 13 January (exp. 2), we must use the time period in which the satellite geometry in 12 January is as same as that in 13 January. The generally assumed sidereal day time difference is 3 min 56s (236s). However, Gunter Seeber et al. (1997) reported that there were slightly different values for different satellites. Base on a four days experiment, they computed the periods for different satellites. In our experiment, the only two satellites (PRN3 and PRN 22) were concerned since their azimuth was around 30 to 70 degree during the observation period. This was the period when multipath signal would be reflected from the special reflector. Therefore, we could investigate the observation residuals of these two satellites in this period to determine the mulitpath effect caused by the special reflector. These two satellites are listed as follows:

Satellite (PRN)	3	22
Sidereal Day Time Difference (s)	-246	-247.5

Due to the fact that, the baseline used in this experiment is relatively short, the most of the GPS errors such as ionospheric delays, orbital errors and clock errors are very small compared to multipath effect. In view of this we can assume that multipath effects are the mainly sources of error contained in the observation residuals. Therefore, these residuals can be utilized as the estimation of the multipath effect. We can compute the multipath effect cause by the special reflector by computing the differences of observation residuals of the two observation conditions in experiments 3 and 4 respectively.

$$Ps_{multi} = \frac{\gamma}{2\pi}\lambda = DL(t) = V_{15} - V_{14}(t + n\alpha) \qquad ..(17)$$

Where *DL(t)* is the differences of observation residuals, V_{15} denote the observation residuals of 15 January in experiment 4, V_{14} denote the observation residuals of 14 January in experiment 3, n is the differences of experiment days (n=1 in this case) and α is the sidereal day time difference.

The L1 residuals of PRN 22 in these two days are used to demonstrate the result and it is shown on the following figures:

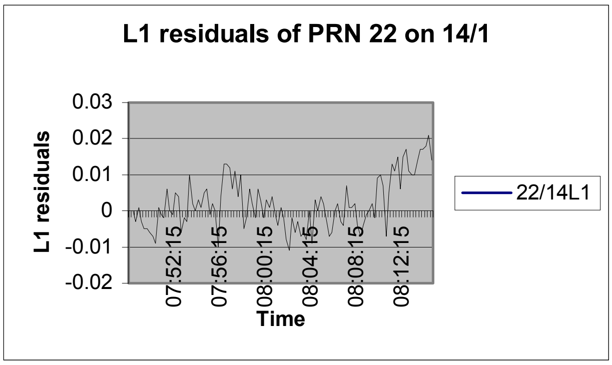

Figure 6 The L1 residuals of PRN 22 on 14/1 (special reflector)

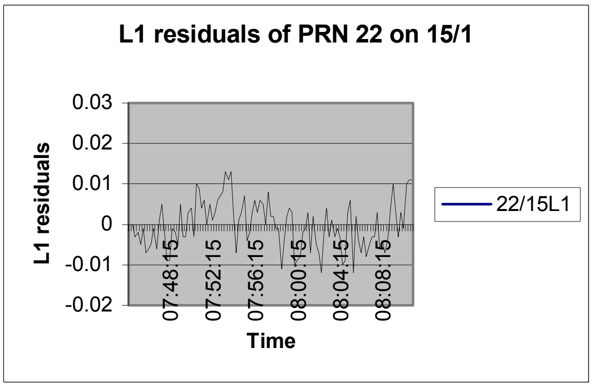

Figure 7 The L1 residuals of PRN 22 on 15/1 (no special reflector)

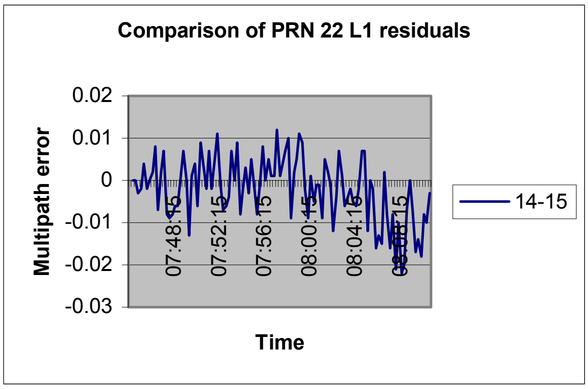

Figure 8 Comparison of L1 residuals of PRN 22 between 14/1/2000 and 15/1/2000

These figures illustrated the effect of multipath on observation residuals and the magnitude of the effect can be estimated in the differences of residuals. We here take figures 6, 7 and 8 as examples to demonstrate the results. As mentioned before, in this tests, the major source of error contain in observation residuals is multipath effect. Consequently, the fluctuation of the observation residuals will reflect the changing of the multipath effect. By comparing figure 6 with figure 7, we can see that as a result of multipath effect caused by the special reflector, L1 residuals of PRN 22 on 14/1 has larger fluctuation than that on 15/1. Furthermore, the peak value of the residuals on 14/1 is 0.022 m while that on 15/1 is only 0.015 m. This is resulted from the larger influence of multipath effect on 14/1 than 15/1. According to equation 17, we can also estimate the magnitude of multipath effect by comparing the differences of the L1 residuals between the two days. Figure 8 illustrates the changing of the effect with time and we can use it as estimation of the effect.

4. Conclusion and recommendation

A multi-antenna GPS system has been introduced in detail. The development of the system and some experiments were outlined. The system can significantly reduce the cost of applying GPS in slope monitoring and offer vital advantages over existing techniques. Additionally, the multipath effect in slope environment was studied. Some tests were conducted and the results were presented in depth. This method can be combined with the multi-antenna GPS system to provide high accuracy result for slope deformation detection in Hong Kong.

In future, the availability of this system in a real field will be evaluated by conducting some field tests. A longer cable (longer than 90m) linked with 60 dB signal amplifier will be employed to stimulate the slope environment. In addition, the system will be further developed for real-time landslide detection.

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