The Hong Kong Polytechnic University

Department of Land Surveying and Geo-Informatics

# INVESTIGATION OF A GPS MULTI-ANTENNA SYSTEM FOR SLOPE STABILITY MONITORING

by

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# CERTIFICATE OF ORIGINALITY

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_______________________________(Signed)

MA KA CHUN, ERIC_______________(Name of student)

# 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 planning and testing stage. The reasons may be the high expenses of purchasing several receivers for various monitored points and the reduction of GPS accuracy due to biases such as multipath effect. A GPS multi-antenna system was developed by Ding et al. (2000) for the monitoring of slopes. This system links several antennas to one receiver so that the cost of a monitoring system will be diminished dramatically. The aim of this study is to review the state of art of this system and suggest improvements in views of software and hardware.

Three aspects of the system are studied. They are the GPS algorithms and software, system configuration design, and the GPS multipath effect in slope monitoring surveys. Two programs are developed for the improvements of software for the system. One is the automatic alarm system which is capable of checking the real time GPS data against a pre-defined threshold value and sending warning message by email and SMS message to mobile phones to prevent problems. The other is the automatic data extraction program that can automatically divide the single GPS data

file collected from the GPS multi-antenna system into different sections to ease the data computation. A low cost GPS long distance data communication method is introduced in which it links a 200 m long cable with only a 40 dB signal amplifier to provide accurate and low cost GPS solutions. To demonstrate the effectiveness of this method, experiments are conducted in the Ho Hai University in Nanjing. Finally, the multipath effect on GPS measurements is studied by making use of its day-to-day repeatability characteristic.

From the successful experimental results in this study, it is contemplated that this enhanced system may 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 engineering projects such as dams, high-rise buildings and structures.

At the end of the research, the limitations of the enhanced GPS multi-antenna system are pointed out. It is the hardware constraint and restriction in static application. Improvements in these two aspects are suggested to further enhance the system.

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# CHAPTER 1

# INTRODUCTION

## 1.1 Slope Monitoring in Hong Kong

Landslides have been great concern to the public and the Government of Hong Kong over years. They usually cause heavy casualties and huge economic losses. Among the 50,000 existing slopes in Hong Kong, more than 20,000 of them had been formed decades ago and are now considered unstable under certain conditions.

Due to the rapid economic growth in Hong Kong after the World War II, there were increasing uses of steeply sloping sites with extensive cut and fill for building development. As there were inadequate safety measure and lack of proper maintenance at that time, numbers of serious landslides killed many people in the past. The most disastrous landslide in Hong Kong occurred in June 1972 in which about 185 slopes failed and 138 persons were killed (See figures 1.1 and 1.2). Another disastrous landslide occurred in August 1976, in which 18 persons were killed in a fill slope failure in north-east Kowloon (See figure 1.3). Landslides could generally be classified into 5 different types as illustrated in figure 1.5.

Those landslides have alerted the Government to seriously consider the safety of slopes in the territories. In 1977, the Geotechnical Engineering Office (GEO) was established to prevent landslides by way of maintenance and setting up of safety standards/guidelines for geotechnical works. The office also gives advice to other government departments on potential dangers arising from landslides and to suggest emergency measures, where appropriate.

Nowadays, the Government is taking many actions to minimize the damages caused by the landslides to the public. Land Preventive Measures programmes were launched to investigate the stability of slopes in the territories. GEO had carried out the remedial works to more than 1000 unstable slopes or retaining structures up to March 1996. Besides, a Computerized Slope Information System was set up in 1994 to identify and register all the 50,000 slopes in Hong Kong. The aim of the System is to determine the responsibility for the maintenance of each slope.

**Figure 1.1 Landside at Mid-levels, Hong Kong Island In June 1972, where 67 persons were killed. (from Spalton et al., 1998)**

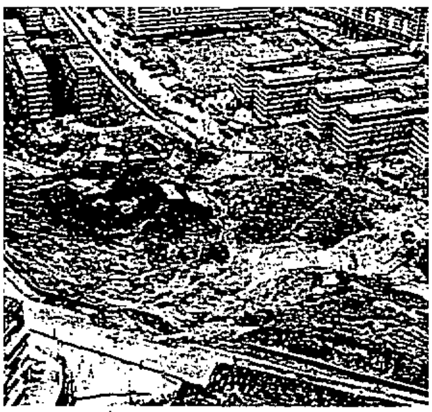


**Figure 1.2 Fill Slope failure in north-east Kowloon in June 1972, where 71 persons were killed. (from Spalton et al., 1998)**

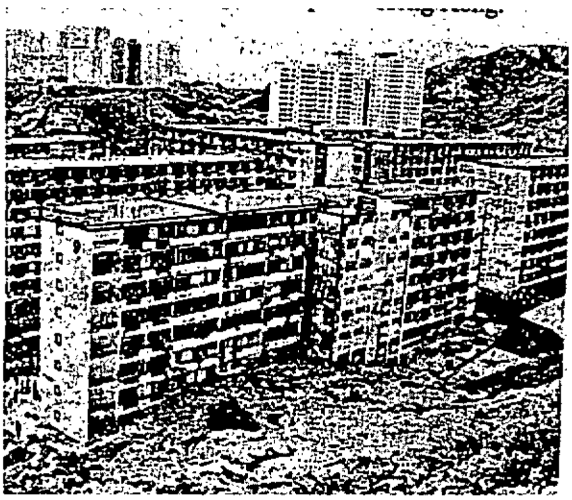


**Figure 1.3 Fill slope failure in north-east Kowloon in August 1976, where 18 persons were killed. (from Spalton et al., 1998)**

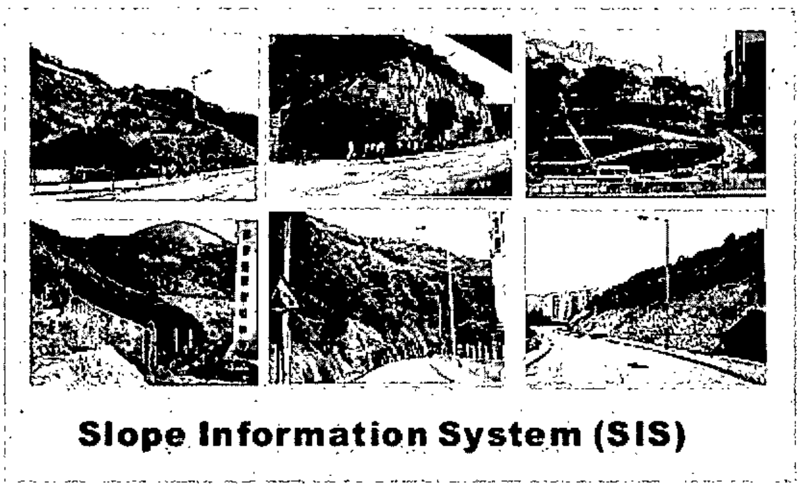



**Figure 1.4 Slope Information System (SIS) (from Hong Kong Slope Safety Web Site, 2000)**

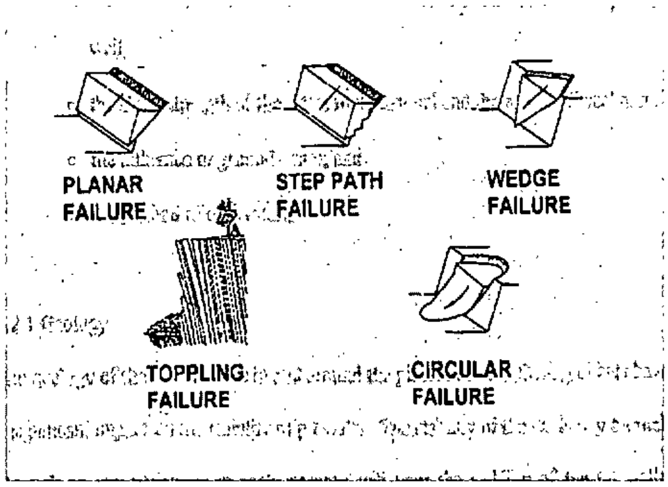



**Figure 1.5 Basic Types of Slope Failure (from Lye, 1996)**

According to the geology, the slopes in Hong Kong can generally be classified into rock or soil basis slopes.

Rock slopes usually are composed of two major types of rock - granitic and volcanic rocks. The granitic rocks have been intruded into volcanic rocks in the form of a batholith, or stock, with irregular outlines. The granites generally extensively jointed with typical joint spacing between 0.5 m and 2 m. While the volcanic rocks contain a mixture of lithologies including fine tuffs, coarse tuffs, welded tuffs, etc. These rocks are generally jointed with typical joint spacing between 5 cm to 20 cm. The behaviour of rock slopes are usually controlled by the presence of discontinuities in the rock mass and the water pressure in these discontinuities. Spalton et al. (1998) explained that groundwater pressure and deformation are the primary parameters although the loads in rock bolts are also important particularly in excavated rock slopes.

Soil slopes are made up of soils, which are derived as products of the processes of both chemical and physical weathering. The soils derived from granitic rocks are usually sandy, while those derived from volcanic rocks tend to be silty. The stability of soil slopes is controlled by the ratio of available shear resistance along a potential failure surface and the actual shear stress on that surface. Due to the fact that the shear resistance is inversely proportional to the pore pressure along the surface, any increase in pore pressure indicates an increased potential of the slope failure. As the groundwater pressure and surface deformation are the primary parameters, they are required to be determined for the analysis of soil slope stability.

## 1.2 Conventional Monitoring Techniques

In slope monitoring, a number of instruments and methodologies is used to determine the major parameters such as loading, stresses, surface deformations, groundwater levels and pore pressures.

### 1.2.1. Geotechnical methods

Geotechnical methods are adopted to detect relative movement of monitoring points with small separation and some physical properties of a monitored body. The following geotechnical measuring devices are used for slope monitoring:

- Standpipes are installed in boreholes to measure groundwater levels. They comprise a length of perforated PVC tubing wrapped in mesh surrounded by a sand filter.
- Piezometers are used to measure pore pressure. They are placed in sand pockets in the boreholes, in a specific zone in which knowledge of pore pressure is required. There are various types of piezometers such as twin tube hydraulic piezometers, pneumatic piezometers and vibrating wire piezometers. To choose the piezometers most suitable for the project, their cost and characteristics and the location of site are considered.
- Anchor load can either be determined by measuring the force required to jack anchor head away from its seating, or it may be monitored continuously with a compression load cell.
- Demec gauge and calliper are used to measure the distance between designed points at high accuracy level.

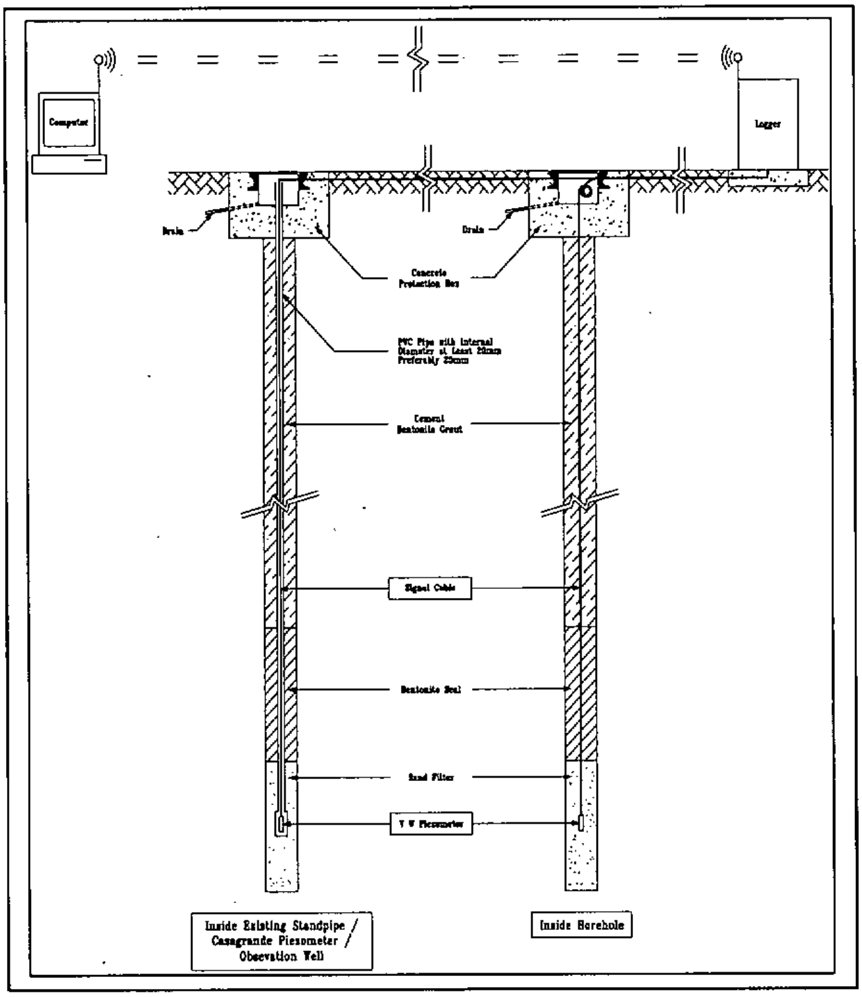
- Inclinometers are widely used in Hong Kong to detect subsurface lateral movements of soil and rocks. They comprise an access tube, usually grouted into a borehole, which should extend to a depth well below any potential failure planes.
- Extensometers are used to detect movement of rock slopes when these slopes are near to failure. They are also most suited to measure deformation of, and behind, retaining structures and in soils and rock stressed by anchoring or affected by excavation.

Geotechnical methods trend to be automatic. Two automatic systems, namely Automatic Piezometric Data Acquisition System (APDAS) and Automatic Inclination Monitoring System (AIMS), which are developed by Fugro Geotechnical Services (FGS) Ltd. in 2002, are discussed below.

#### *1.2.1.1. Automatic Piezometric Data Acquisition System (APDAS)*

The Automatic Piezometric Data Acquisition System (APDAS) which was developed by FGS in May 2001, was used in the Landslip Preventive Measures (LPM) project. In that project, 3 sets of the APDAS were installed for the automatic acquisition of continuous records of groundwater levels before, during and after rainfall. The System took the advantage of recent developments in data logger and communications technology, allowed real-time monitoring of groundwater behaviour from a remote location. The hardware set up and the schematic layout of the Systems are illustrated in figures 1.6 and 1.7 respectively.

**1.6 The Automatic Piezometric Data Acquisition System (APDAS)**




**1.7 A schematic layout of the Automatic Piezometric Data Acquisition System (APDAS)**

The System comprised a data logger and modem to transfer the data from the instruments installed in the slope features to a remote monitoring station through a GSM telecommunication link that was on a reliable wireless environment and was easy to install. The data from the instruments were then processed and presented in a Data Plot format. In figure 1.8, the correlation between piezometric pressure and hourly rainfall over four days of heavy rainfall is illustrated.

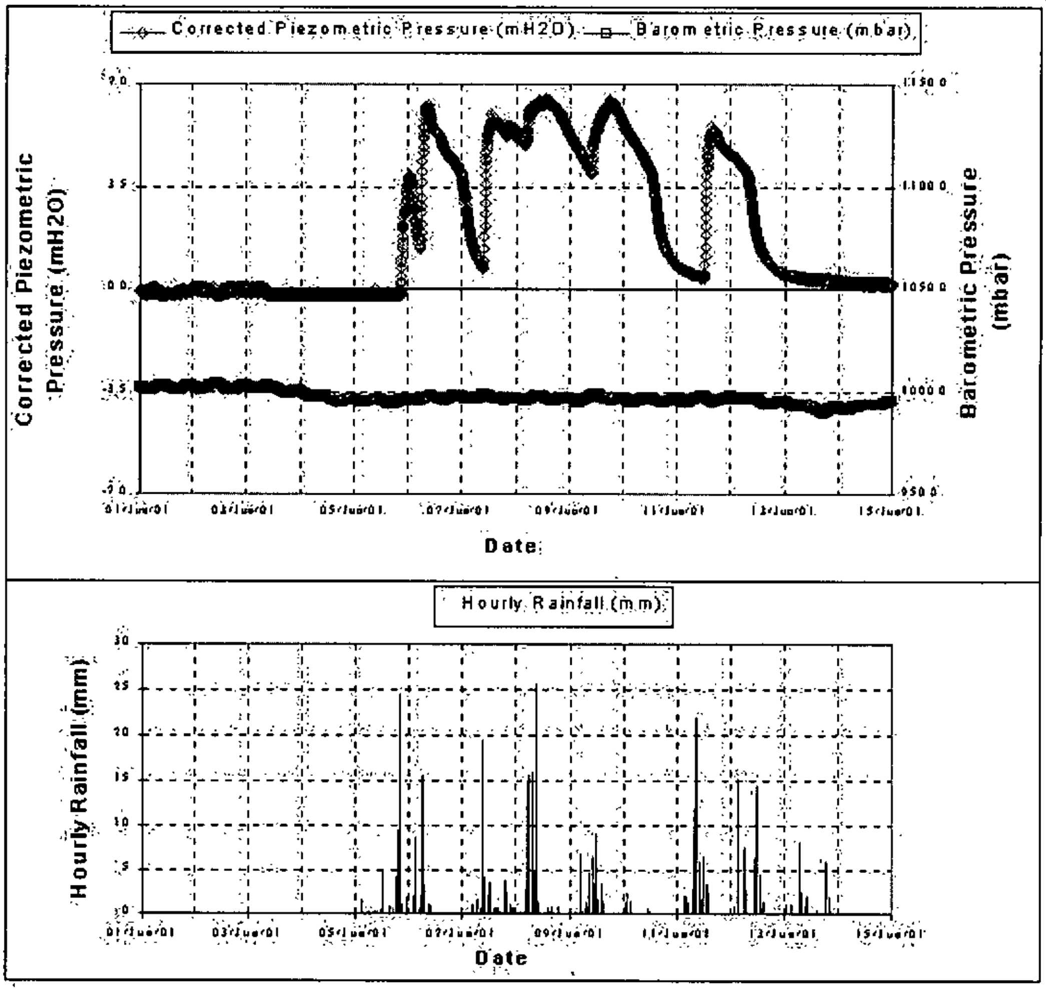



**Figure 1.8 An example data plot of the APDAS**

Compared with the conventional manual monitoring technology, APDAS offers numerous advantages. It allows remote access and enhances the efficiency in data acquisition. Besides, the System is possibly connected with in-place electronic inclinometers so as to correlate the slope movement with the groundwater levels for further analysis.

#### *1.2.1.2 Automatic Inclination Monitoring System (AIMS)*

The System was developed by FGS in 2002 for the MTRC Contract 521 – Kowloon Tong Station Interchange. The scope of the project was to extend the existing concourse and it involved extensive excavation works immediately adjacent to the existing station box. In order to detect any possible disruption to the railway operation caused by the construction activities, FGS had developed the System to closely monitor the behaviour of the existing structural diaphragm walls of the station box during the excavation. The System comprised 15 electrolytic (EL) tiltmeters which were made up of an electrolytic tilt sensor housed in a weatherproof enclosure. The tilt sensor is a precise bubble level that was sensed electrically as a resistance bridge. The bridge circuit outputs a voltage proportional to the tilt of the sensor.

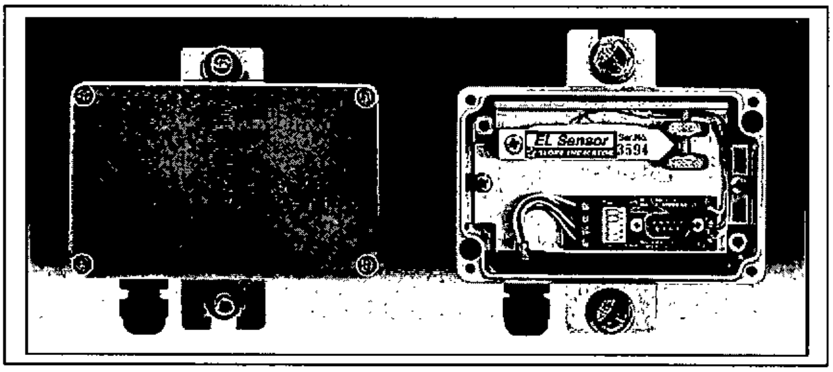



**Figure 1.9 Electrolytic (EL) Tiltmeters**

To provide continuous monitoring record without physical access to the site, the System was designed to install an automated data acquisition system based on a data logger and a modem. That allowed readings from the sensors installed on the diaphragm walls to be transferred to a remote monitoring station through a GSM communications link that was on a reliable wireless environment. The readings were downloaded and configured the data acquisition parameters (such as frequency of readings).

The System was installed at the concourse and platform levels of the existing MTRC Kowloon Tong station, to monitor a total of 15 sensors over a period of 7 months. The main merits of that system was that it significantly reduced the numbers of site visit by field staff and provided continuous monitoring records around the clock.

### 1.2.2 Photogrammety

Saggers et al., (1994) considered terrestrial photogrammetry as a very good technique for close-range monitoring of a pit wall. He further commented that 'photogrammetry is a time saving tool and does not require access to the stations in a site'. Wei (1996) developed a new method using close-range photogrammetry to monitor deformation of a large abrupt slope. Lam (1996) reported that both aerial and terrestrial photogrammetry was commonly employed in monitoring projects in the Geotechnical Engineering Office (GEO). The applications of these methods in monitoring deformation is widely investigated by researches.

### 1.2.3 Survey robots

Chan (2003) reported that a fully remote and automated deformation monitoring system (ADMS) was developed for the MTR Tsim Sha Tsui (TST) Modification Work's Project. The ADMS comprising four automatic tracking total stations and over 280 prisms were installed to monitor the deformation of the existing underground railways tunnel during the excavation of new pedestrian subways. That system could be widely applied in various applications including the monitoring of the lateral movement of structures and slopes.

### 1.2.4 Conventional survey method

Conventional survey methods using levels and total stations have been used in the monitoring of slope deformation for a long time. Vertical movements can be detected with precise levelling. While horizontal movements can be detected by using triangulation, trilateration and triangulateration.

### 1.2.5 Laser scanning

Recently, the application of laser scanner has received a great attention. It is an emerging technology offering great potential for rapid collection of dense, three-dimensional (3D) spatial datasets of entire surfaces. The fine angular sample interval, which ranges from a few microradians to a few milliradians, allows collection of several millions of points over an entire surface. Data collection rate can exceed several thousand points per second, which allows entire surfaces or structures to be measured instantly. This technique can be applied in slope monitoring which could provide on-contact measurement, rapid acquisition rate and dense data coverage.

### 1.2.6 Global positioning system (GPS)

Conventionally, GPS was only used in monitoring surveys to establish control network (Bock and Shimada, 1990, Chen, 1998). Nowadays, it is widely employed in actual monitoring of points. For instance, Murria (1996) and Chrzanowski et al. (1988) applied GPS in land subsidence monitoring. Dale (1996) developed a system by using GPS to monitor a hydro-electirc station. GPS is also extensively applied in Open Pit Slope Deformation Monitoring (Ding et al., 1996; Stewart et al., 1996a and Tsakiri, 1996). Recently, numerous researches have been conducted to investigate the use of GPS in slope monitoring.

### 1.2.7 Application of GPS in slope monitoring

As mentioned above, there are two types of techniques traditionally being used to monitor the deformation of slopes. They are conventional survey techniques and geotechnical techniques. The main drawbacks of conventional survey techniques are the low efficiency, sensitivity to atmospheric conditions and the requirement of direct line-of-sight between instrument stations and the measured points. In addition, geotechnical techniques can only measure relative deformations within limited ranges. As a result, an automatic system is needed to continuously 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, like high cut slopes, large open pit mines, subsidence and landslide. Several researchers have already studied the applications of GPS to 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: it is less labour intensive, the decrease in the price of GPS hardware, it can measure three dimensional vector of displacements of the ground, it does 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, GPS was used to measure displacements of a cut slope, which was made up of rock. The rock medium was composed of highly weathered sandstone and slate and the slope height and width were about 120 m and 200 m respectively. Experimental result shown that the differences of measured displacements obtained from GPS and total station surveying within 10 mm in horizontal direction and 20 mm in the vertical direction (Sakurai and Shimizu, 1992a; Sakurai and Shimizu, 1992b). Sakurai and Shimizu (1994) proposed to use the back analysis method to assess the slope stability. They first measured the slope displacements by using GPS and then interpreted the results by using the back analysis method. The method was proved to be effective in determining the factor of safety, as well as strength parameters such as the cohesion and the internal friction angle.

Kondo (1995) developed a system to continuously determine positions in real-time of up to ten locations using GPS. Result showed 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 accurate 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 has only been used on a very limited scale. In addition, there have been few studies on the problems of GPS in slope monitoring. GPS satellite signals are often obstructed by nearby tall vegetation and high-rise buildings. The slope surface can also causes GPS signal multipath errors. Most importantly, there is little information available on the application of GPS in slope monitoring in Hong Kong. Hence, it was considered necessary to implement a new GPS slope monitoring system in Hong Kong.

### 1.2.8 Integrated approach of deformation monitoring

In order to make use of the respective benefits of each instrument technique, recently there is an increasing trend of the integrated approach of deformation monitoring. In slope monitoring, it is worth nothing that GPS also has its limitations. The primary one is that it can only measure surface deformations. Moreover, its utilization depends much on the sky window that is the availability of satellites.

Therefore, it is considered that GPS should be integrated with conventional geotechnical monitoring techniques in practical applications. For example, the Automatic Piezometric Data Acquisition System (APDAS) and Automatic Inclination Monitoring System (AIMS) introduced in section 1.2.1 can be used to integrate with GPS in slope monitoring. The APDAS and AIMS mainly monitor the ground water behaviour and the sub-surface slope movement respectively while the GPS mainly monitor the surface movements of a slope. Research is currently being performed to demonstrate the merits of integrating the technologies (Ding et al. 2004).

## 1.3 Research Objectives and Organization of Thesis

The GPS multi-antenna was developed by Ding, et al. (2000) for the monitoring of slopes. This new GPS measurement technology is using a single GPS receiver and multiple antennas for the monitoring the deformation of the structures or slopes worldwide. This research is intended to study the feasibility of using the GPS multi-antenna system for monitoring the slope stability in Hong Kong, with an aim to identify the problems in association with the system and to suggest solutions to these problems. Three main aspects are evaluated. They are the GPS algorithms and software, GPS hardware design, and the GPS multipath effect in slope monitoring. This research includes tests of different hardware configuration and software development in order to build up an enhanced GPS multi-antenna system and aims to develop software to check the GPS data in real time and to study the methods to estimate the multipath effect of GPS signal. The accuracy, advantages and limitations of the enhanced GPS multi-antenna system in deformation monitoring of structures or slopes are also evaluated. This research also intended to study the possibility of savings on operation cost so as to broaden the application of GPS multi-antenna system in other types of engineering surveying, i.e. structural health monitoring system for the proposed Stonecutter Bridge and ShenZhen Western Corridor.

This research is focused on the following three aspects:

***(1.) GPS algorithms and software:***

Two main problems in this area are identified -

a. No checking of threshold values and sending of warning messages - the design of the GPS multi-antenna system does not cater for the above issue. For a real time automatic system applies in structure or slope monitoring, it is required to check the movements of the monitoring points against a predefined threshold value. Once the movements exceed this value, it is considered that the structure or slope is in an unstable situation. An action plan will then be implemented to alert and to rectify the situation. A program is designed to automatically check the movements of the monitoring points and to notify the relevant control centre by email and SMS message if the movements exceed a predefined threshold value.

b. Grouping of GPS data - the GPS multi-antenna system connects one receiver to several antennas through a hub with multi-input channels. The system receives and stores the GPS data from the antennas sequentially and to form a single GPS data file. As the system can not automatically identify the sources of signal from different antennas, it is necessary to split them into different groups. A program is designed to split the GPS data file automatically according to the pre-defined time intervals and occurrences of the cycle split effect.

*(2.) System configuration:*

In a monitoring site, monitoring points are usually dispersed. Therefore, long cables (longer than 200m) are commonly used to connect the GPS antennas to the rover receiver. However, GPS signal will be weakened or even lost during this long distance data transmission. Therefore, GPS signal amplifier will be used to compensate the signal lost during data transmission. In Hong Kong, a test will be conducted to connect a GPS multi-antenna by using a 60 m long cable connected with two 20dB signal amplifiers. However, in practices, the cost of using this long cable and signal amplifiers are too high. For instance, the cost of the high quality cable (60m) is about $5000 and the cost of two signal amplifiers is $10000 (about $5000 per unit). As the major benefit of the GPS multi-antenna system is to connect only one receiver to several antennas in order to reduce the costs of the receivers. If the price of the data transmission is high, it will make the system very difficult to be implemented into practical use. For the implementation of the system, a method to dramatically reduce the cost of the data transmission is considered necessary.

Therefore, experiments will be performed in the Ho Hai University in Nanjing by using GPS long cable and signal amplifier with lower costs. A 200m cable links with only one 40 dB signal amplifier will be used to connect antenna to the receiver. The positioning result and the signal to noise ratio (S/N) will be analyzed in order to investigate the effect of external noise in this long distance GPS data transmission.

(3.) ***Study of GPS multipath effect in slope monitoring surveys:***

The major error source of applying GPS system in structure or slope monitoring is the muiltpath effect. In this project, the Day-to-Day repeatability of multipath effect will be evaluated. In view of the occurrence of receiver multipath effect depends mainly on the reflectivity of antenna environment. If the position of the antenna is fixed, this effect recurs after one sidereal day due to repeated satellite-reflector-antenna geometry. In view of the recurrent characteristics of the muiltpath effect, it is then possible to determine the magnitude of the effect under the slope environment.

The system describes in this research can be widely applied in Hong Kong and many other parts of the world to monitor dangerous slopes and to prevent tragedy. The system helps us extend the understanding of using GPS in high precision monitoring survey for the study of slope deformation and stability to determine strength parameters as well as factor of safety. Additionally, the research results can also be implied in the study of the stability of many other objects including dams, high-rise buildings and structures.

Chapter 2 will discuss the development of the GPS Multi-Antenna System. Chapter 3 will present the development of software including the Automatic Alarm System (AAS) and Automatic Data Extraction System (ADES). Functions of the developed software will also be highlighted in this chapter. Chapter 4 will show the system configuration improvement and will demonstrate experimental results performed in Nanjing. Chapter 5 will discuss the multipath effect in GPS measurement in detail. Survey data will be analyzed and the result will be showed in this chapter. Finally, Chapter 6 will conclude the significance of the enhanced GPS multi-antenna system and will describe the limitations of this research and will make recommendations for further studies.

# CHAPTER 2

# AN OVERVIEW OF THE

# GPS MULTI-ANTENNA SYSTEM

## 2.1 Development of the GPS Multi-Antenna System

GPS Multi-Antenna System is developed to reduce the cost of hardware in monitoring survey. A GPS Multi-Antenna Selector (GMAS) is used to connect several antennas to one receiver so the expenses spent on receivers are dramatically reduced. The GMAS does not change the structure of the GPS signal and it receives and stores the GPS data from the antennas sequentially at a fixed time interval. Users can preset the time interval according to their applications. Figure 2.1 shows the GPS Multi-Antenna System:

### 2.1.1 GPS Multi-Antenna Selector (GMAS):

It is a special electronic device containing two pieces of hardware. One is the antenna connector and the other is the timing controller. The antenna connector provides multi-input and one-output terminals. Different antennas are connected to those multi-input terminals and a receiver is connected to the one-output terminal. GPS signals received by the antennas through those multi-input terminals, are recorded in the same receiver. On the other hand, the timing controller is used to control measuring period of each antenna. With the GMAS, only one receiver is required to monitor a number of points.

### 2.1.2 GPS antenna and receiver

To achieve high accurate results, dual frequency receivers are recommended in slope deformation monitoring. To choose the types of GPS receiver, it depends on the purposes of the survey and the site location.

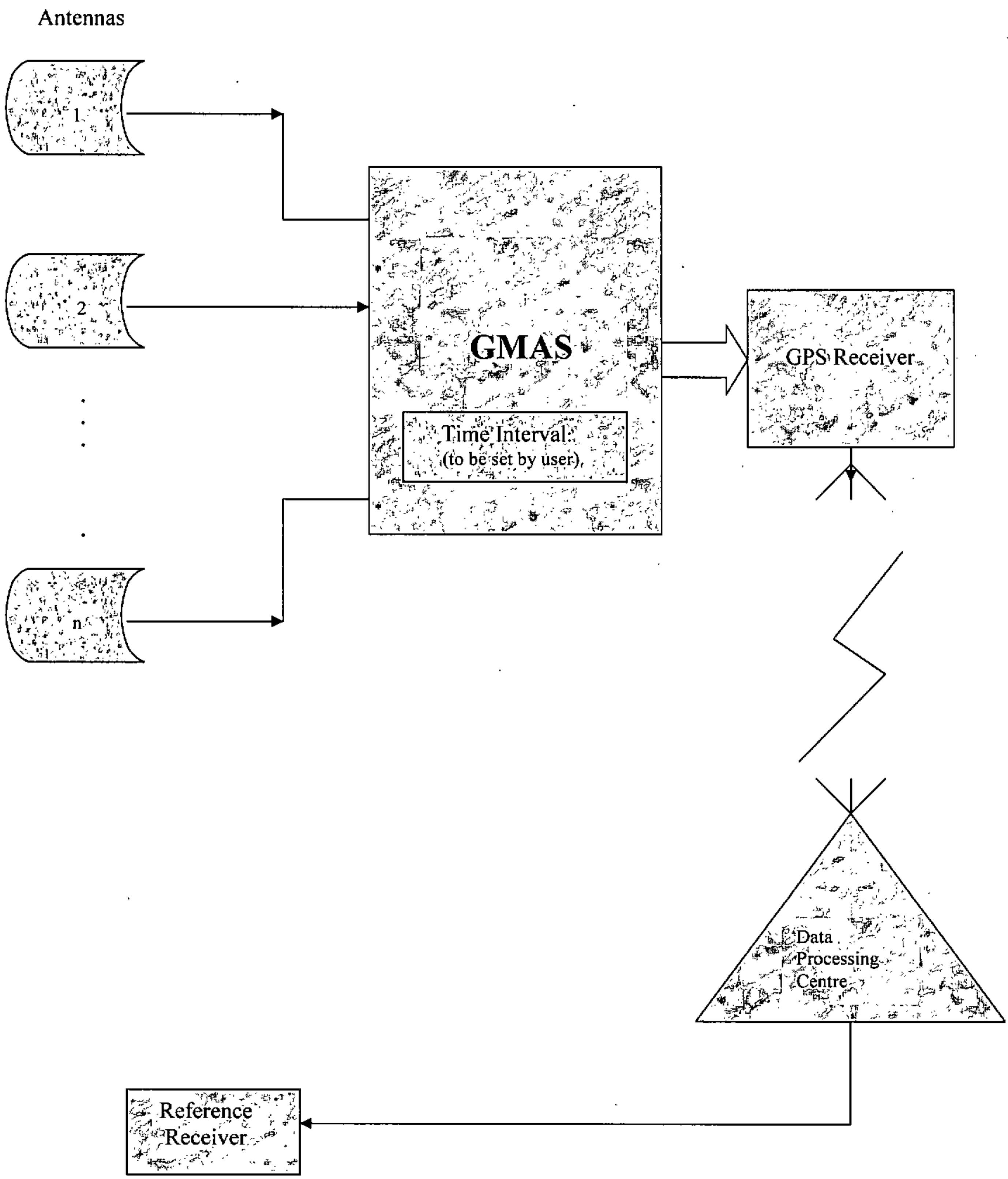
### 2.1.3 Data transmission

An effective tool is necessary to transmit data from the monitoring points to the control centre. Various options can be adopted such as mobile phones and radio transmitters. The mobile phones are suitable for long distances data transmission while the cost is higher compared to radio transmitters. The radio transmitters require direct line-of-sight between a pair of transmitters, thus they are only recommended for flat area and short distance application. Ding et al. (1996) suggested that fiber optic cables could be considered for large survey areas to reduce noise in data transmission.

### 2.1.4 Data processing and analysis software

The main objective of this software is to compute the coordinates of the monitoring points with respect to the reference station and to give warning if the displacements of those monitoring points exceed the allowable tolerances.

**Figure 2.1 Design of the GPS multi-antenna system**



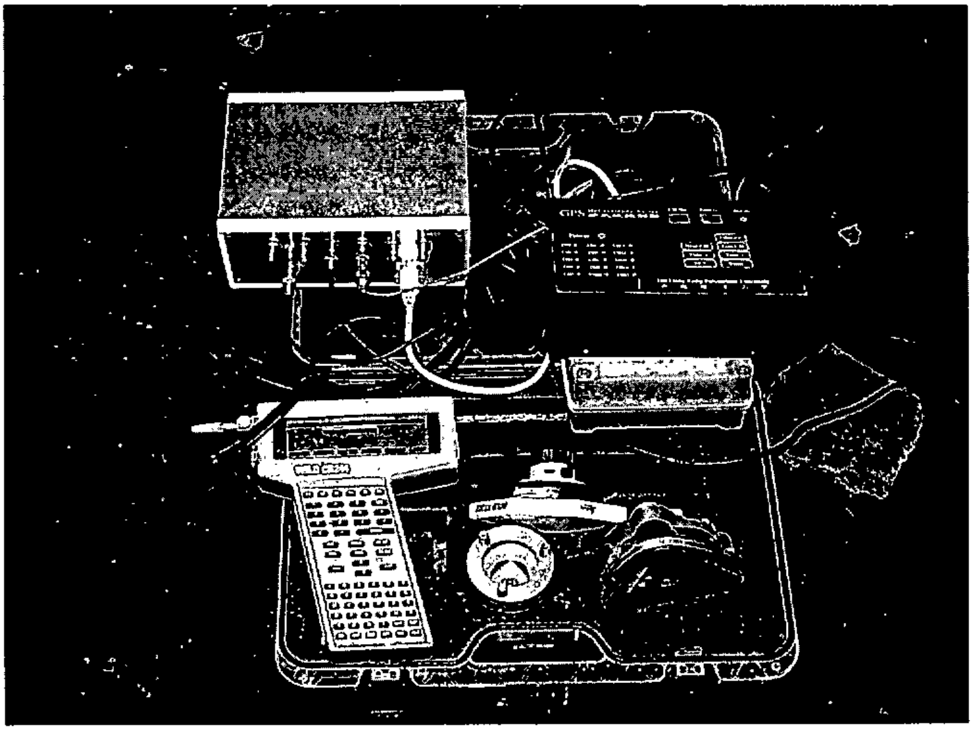


Figure 2.2 The basic element of the GPS multi-antenna system

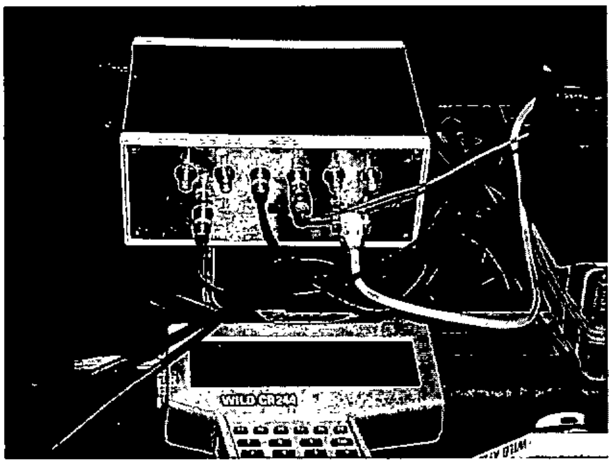



Figure 2.3 Antenna connector

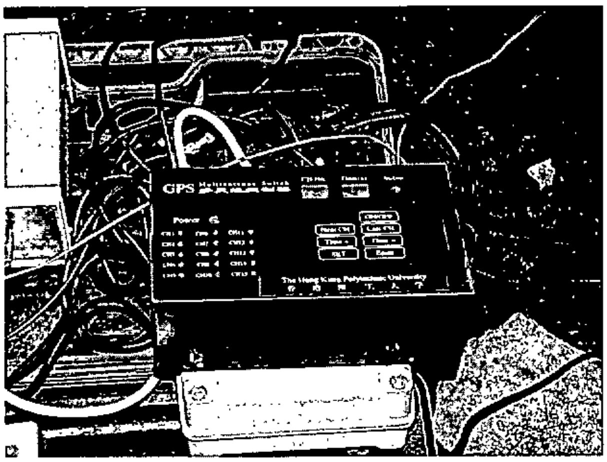



Figure 2.4 Timing controller

## 2.2 GPS Multi-Antenna Experiment in Hong Kong

### 2.2.1 GPS multi-antenna experiment without connecting signal amplifier

To demonstrate the utilization of the multi-antenna system, an experiment was performed at the rooftop of the C-D Cores of the Hong Kong Polytechnic University, Hung Hom. Location of the site was shown in Figure 2.5.

After detail investigation, one reference station and two monitoring points were selected. Two baselines were formed from the reference station to each monitoring points. Both of those baselines were approximately 45m in length. Only terminals 3 and 4 out of 6 input terminals were used for illustration. Two antennas were connected to those input terminals and one receiver was linked to the output terminal. In that experiment, the observation time interval for each terminal was preset to 16 minutes which was the maximum designed time interval of the GMAS and was considered long enough for fast static positioning.

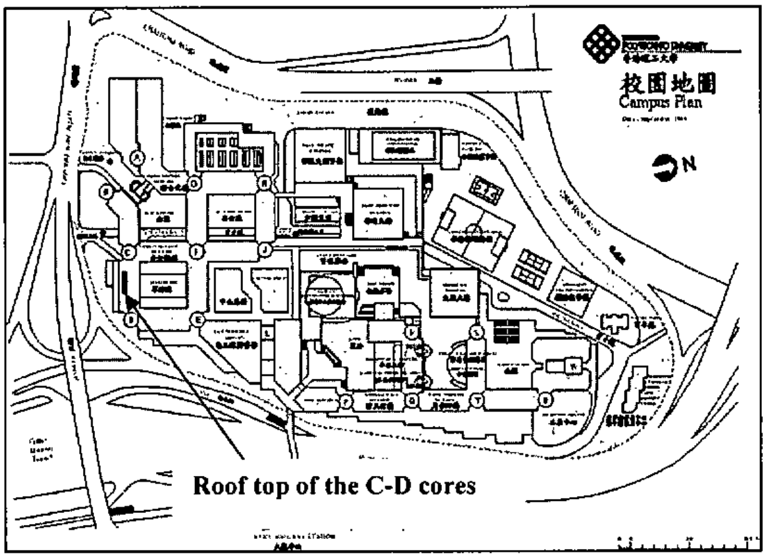



**Figure 2.5 Location of the experiment site**

When the maximum time interval was reached, the GMAS would automatically switch to the other terminals in sequence to collect GPS signal. The receiver would not recognize the switch of the terminals of the GMAS, thus the data logging would continuously collect GPS signal when GMAS switched from one antenna to the other. Consequently, all the data from the antennas would be recorded as a file and it would be necessary to pre-process the GPS data and to split them into different groups. The following table shows the processing results.

| **Terminal** | **Terminal 3** | | | **Terminal 4** | | |
|---|---|---|---|---|---|---|
| **Session** | **Coordinates in Conventional Terrestrial (CT) System** | | | **Coordinates in Conventional Terrestrial (CT) System** | | |
| Coordinates | X | Y | Z | X | Y | Z |
| 1 st Session | 65.9712 | 08.1510 | 65.8071 | 67.2088 | 07.8016 | 65.3114 |
| 2 nd Session | 65.9741 | 08.1501 | 65.8042 | 67.2050 | 07.8004 | 65.3141 |
| Differences (mm) | 3 | -1 | -3 | -3 | -1 | 3 |

In the above table, only the ten-metres with four decimal places of the coordinates are compared.

### 2.2.2 GPS multi-antenna experiment with the use of signal amplifier

In the following experiment, it aimed to illustrate the problems encountered in manipulating the system in practice and to suggest solutions to overcome them.

In a monitoring site, the monitoring points are usually dispersed. Therefore, long cables are commonly used to connect the GPS antennas to the rover receiver. However, GPS signal would be weakened or even lost during this long distance data transmission. As an alternative, GPS signal amplifier would be used during the data transmission. In order to evaluate the use of the GPS signal amplifier, an experiment was conducted to use a 60m long cable linked with two 20dB signal amplifiers to connect the antenna to the GMAS so as to simulate the slope environment. The 60m long cable and 20dB signal amplifiers were connected to the Terminal 3 of the GMAS. While the Terminal 4 only linked with a short cable to the antenna. The observation time of each terminal was preset to 16 minutes which was the maximum designed time intervals and was considered long enough for fast static positioning.

Two sessions of fast static positioning were launched. When the maximum time interval was reached, the GMAS would switch to the other terminals in sequence to collect GPS signal. The result was listed as follows:

| **Terminal** | **Terminal 3** | | | **Terminal 4** | | |
|---|---|---|---|---|---|---|
| **Session** | **Coordinates in Conventional Terrestrial (CT) System** | | | **Coordinates in Conventional Terrestrial (CT) System** | | |
| Coordinates | X | Y | Z | X | Y | Z |
| 1 st Session | 78.0216 | 36.0814 | 68.8746 | 76.8583 | 36.4678 | 69.1484 |
| 2 nd Session | 78.0147 | 36.0710 | 68.8733 | 76.8612 | 36.4688 | 69.1515 |
| Differences (mm) | -7 | -10 | -1 | -3 | 1 | 3 |

In the above table, only the ten-metres with four decimal places of the coordinates are compared.

As seen from the above results, the quality of the GPS's solutions was slightly affected by the use of the long cable and signal amplifier. The range of differences in coordinates between session 1 and session 2 of the Terminal 3 (the long cable's set up) was 10mm while that of the Terminal 4 was 6mm. It reflected the use of long cable would induce external noise in GPS data transmission and in return deteriorated GPS's signal quality.

# CHAPTER 3

# SOFTWARE DEVELOPMENT

## 3.1 Development of the Software for Automatic Alarm System

### 3.1.1 Overview of Automatic Alarm System

An automatic alarm system is designed to automatically check the movements of the monitoring points and to notify the relevant control centre by email and SMS message if the movements exceed a pre-defined threshold value. The operation of the system is listed as follows. An administrative page is designed for inputting the baseline values and the warning levels. The baseline values are the initial positions of the monitoring points. While three levels of warning messages have to be entered by the users into the system. These levels are designated as alert, alarm and action levels that are commonly used in most geotechnical monitoring systems. For the implementation of the alarm system and the GPS multi-antenna system, the alarm system is designed to support up to 16 monitoring channels by scanning 16 output files sequentially.

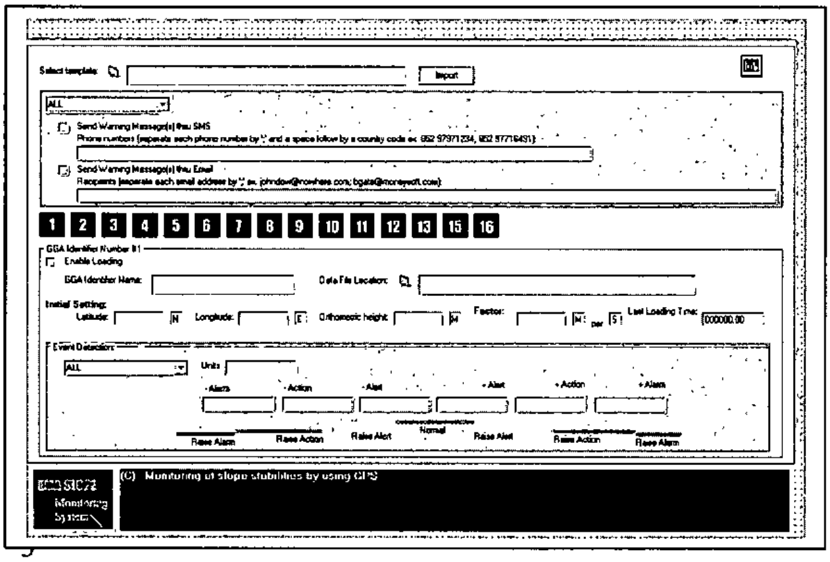


**Figure 3.1 The administrative page of the automatic alarm system**

### *3.1.1.1 Collection of real time GPS data*

Real time GPS data are collected from the Hyper terminal of Windows. The interval of the data acquisition depends on the individual project requirement and can be preset by the Users.

```
real time data by hyper terminal.TXT - Notepad
File Edit Format View Help
$GPGGA,082843.00,2223.36349794,N,11412.46626051,E,1,7,1.1,95.570,M,-1.054,M,,*7E
$GPGGA,082844.00,2223.36349681,N,11412.46625768,E,1,7,1.1,95.574,M,-1.054,M,,*76
$GPGGA,082845.00,2223.36349614,N,11412.46625728,E,1,7,1.1,95.598,M,-1.054,M,,*7D
$GPGGA,082846.00,2223.36349765,N,11412.46625409,E,1,7,1.1,95.616,M,-1.054,M,,*7C
$GPGGA,082847.00,2223.36349640,N,11412.46624983,E,1,7,1.1,95.628,M,-1.054,M,,*78
$GPGGA,082848.00,2223.36349520,N,11412.46624343,E,1,7,1.1,95.614,M,-1.054,M,,*7B
$GPGGA,082849.00,2223.36349868,N,11412.46623672,E,1,7,1.1,95.616,M,-1.054,M,,*79
$GPGGA,082850.00,2223.36350027,N,11412.46623374,E,1,7,1.1,95.613,M,-1.054,M,,*7C
$GPGGA,082851.00,2223.36350374,N,11412.46622534,E,1,7,1.1,95.598,M,-1.054,M,,*7B
$GPGGA,082852.00,2223.36350744,N,11412.46621972,E,1,7,1.1,95.561,M,-1.054,M,,*74
$GPGGA,082853.00,2223.36351325,N,11412.46621434,E,1,7,1.1,95.568,M,-1.054,M,,*71
$GPGGA,082854.00,2223.36351638,N,11412.46621102,E,1,7,1.1,95.545,M,-1.054,M,,*70
$GPGGA,082855.00,2223.36351432,N,11412.46620900,E,1,7,1.1,95.555,M,-1.054,M,,*73
$GPGGA,082856.00,2223.36351536,N,11412.46620644,E,1,7,1.1,95.548,M,-1.054,M,,*76
$GPGGA,082857.00,2223.36351619,N,11412.46620726,E,1,7,1.1,95.533,M,-1.054,M,,*70
$GPGGA,082858.00,2223.36351302,N,11412.46620641,E,1,7,1.1,95.507,M,-1.054,M,,*77
$GPGGA,082859.00,2223.36350727,N,11412.46621231,E,1,7,1.1,95.539,M,-1.054,M,,*7B
$GPGGA,082900.00,2223.36350392,N,11412.46621751,E,1,7,1.1,95.568,M,-1.054,M,,*7B
$GPGGA,082901.00,2223.36350331,N,11412.46621970,E,1,7,1.1,95.576,M,-1.054,M,,*71
$GPGGA,082902.00,2223.36350447,N,11412.46622239,E,1,7,1.1,95.563,M,-1.054,M,,*75
$GPGGA,082903.00,2223.36350775,N,11412.46622124,E,1,7,1.1,95.545,M,-1.054,M,,*7D
$GPGGA,082904.00,2223.36351214,N,11412.46622161,E,1,7,1.1,95.532,M,-1.054,M,,*78
$GPGGA,082905.00,2223.36351164,N,11412.46622483,E,1,7,1.1,95.533,M,-1.054,M,,*75
$GPGGA,082906.00,2223.36350983,N,11412.46622998,E,1,7,1.1,95.553,M,-1.054,M,,*77
$GPGGA,082907.00,2223.36351262,N,11412.46623159,E,1,7,1.1,95.534,M,-1.054,M,,*76
$GPGGA,082908.00,2223.36351037,N,11412.46623365,E,1,7,1.1,95.517,M,-1.054,M,,*77
$GPGGA,082909.00,2223.36350781,N,11412.46623999,E,1,7,1.1,95.509,M,-1.054,M,,*7B
$GPGGA,082910.00,2223.36350925,N,11412.46624023,E,1,7,1.1,95.520,M,-1.054,M,,*77
$GPGGA,082911.00,2223.36350853,N,11412.46624739,E,1,7,1.1,95.508,M,-1.054,M,,*70
$GPGGA,082912.00,2223.36350831,N,11412.46624832,E,1,7,1.1,95.515,M,-1.054,M,,*7F
$GPGGA,082913.00,2223.36350854,N,11412.46625396,E,1,7,1.1,95.520,M,-1.054,M,,*7F
$GPGGA,082914.00,2223.36350379,N,11412.46626123,E,1,7,1.1,95.548,M,-1.054,M,,*7D
$GPGGA,082915.00,2223.36350340,N,11412.46626301,E,1,7,1.1,95.543,M,-1.054,M,,*7F
$GPGGA,082916.00,2223.36350167,N,11412.46626020,E,1,7,1.1,95.546,M,-1.054,M,,*7E
$GPGGA,082917.00,2223.36350086,N,11412.46626082,E,1,7,1.1,95.560,M,-1.054,M,,*7D
```

**Figure 3.2 Typical GPS data collected from the Hyper Terminal of windows**

### *3.1.1.2 Sending of warning messages*

A software program will check the real time GPS data and will compare those data with the baseline values of the previous GPS observation epoch. If the movements of the monitoring points exceed the predefined threshold values, it will notify the relevant Control Centre by email & SMS message to their mobile phone. Figure 3.4 presented the schematic flow of the setting of the SMS gateway.

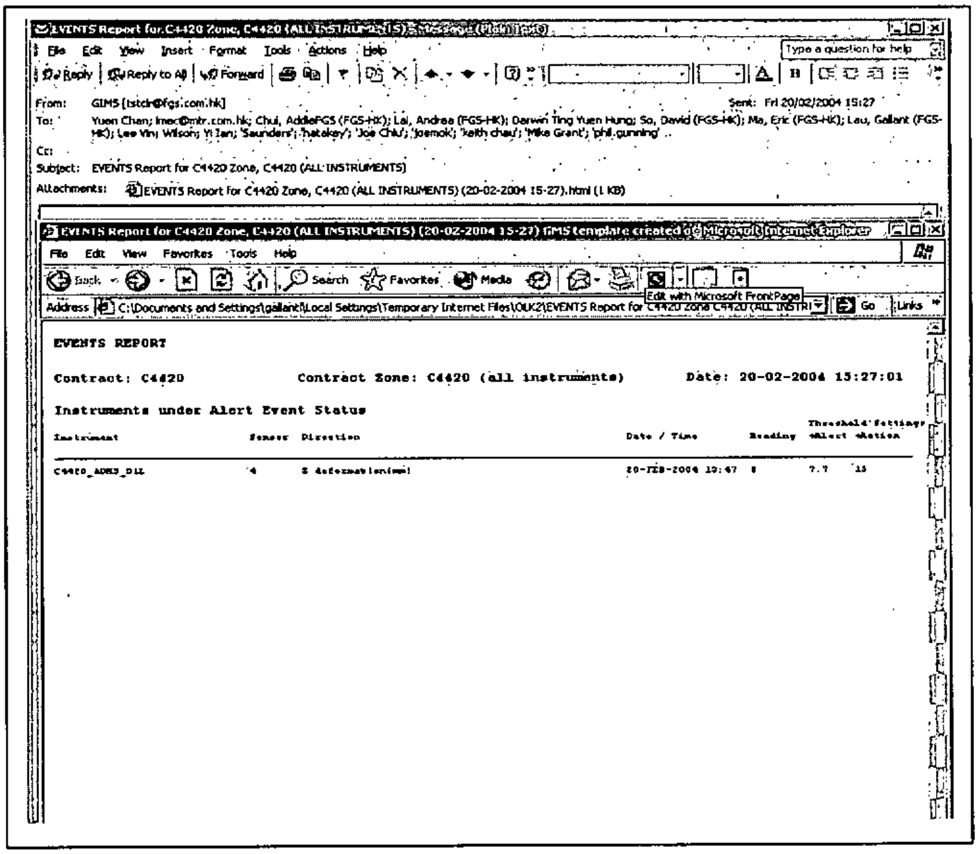



**Figure 3.3 Typical automatic event report issued to project staff by email when readings of the monitoring points exceed a predefined threshold**

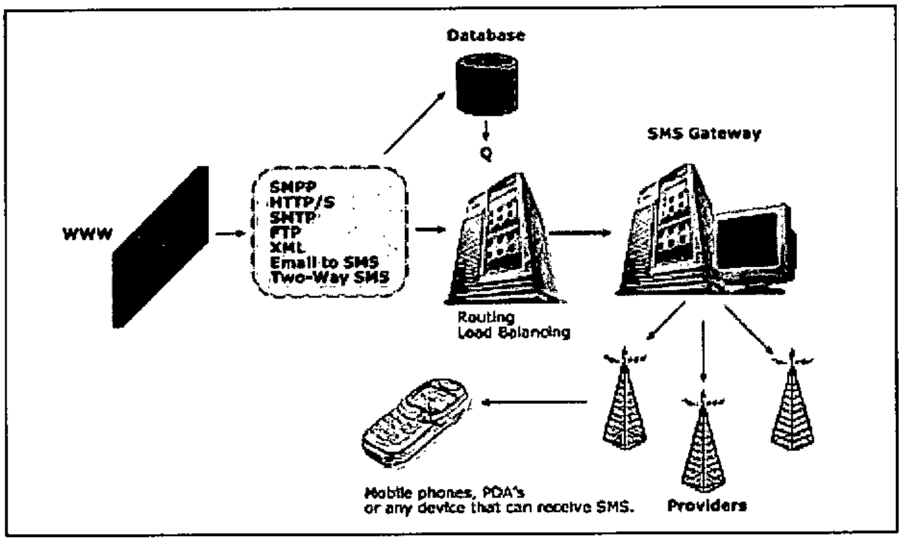



**Figure 3.4 Typical SMS gateway connections**

For sending SMS message, open-ended API (Application Programming Interface) will be dominantly used that allows one to send text messages to his bulk list, or configure his database to send messages with any trigger event. In this study, the Clickatell's API is used which is immediately multicast messaging enabled, allowing integration to any front-end or legacy system, with a direct connection into the Clickatell's global gateways. To take the hassle out of this process, the Clickatell COM-API object is adopted which exports a set of methods and definitions that will make it easy for one to integrate SMS sending into his programs or Active Server Pages. The author wrote a program with Visual Basic for sending SMS through the COM-API object. Test conducted would be demonstrated in section 3.1.2 below to show the use of the program.

For sending email message, a program called Geotechnical Instrumentation Monitoring System (GIMS) Mail Service has been designed which is a command line program GMS.EXE running on GIMS Server as well as any machine connecting to Oracle over the network. The program is installed in the C:\WINNT\SYSTEM32 directory of the GIMS server.

When the program is executed, it queries the database and generates a report for each contract zone within the GIMS database. Switches on the command line define whether the report type generated is an Alarm or an Event report. And then, the program will automatically terminate.

Summary of the command line switches for the GIMS Mail Service is referred in Fig.3.5. It may also be viewed by running GIMS.EXE with no switches or with the /? Switch.

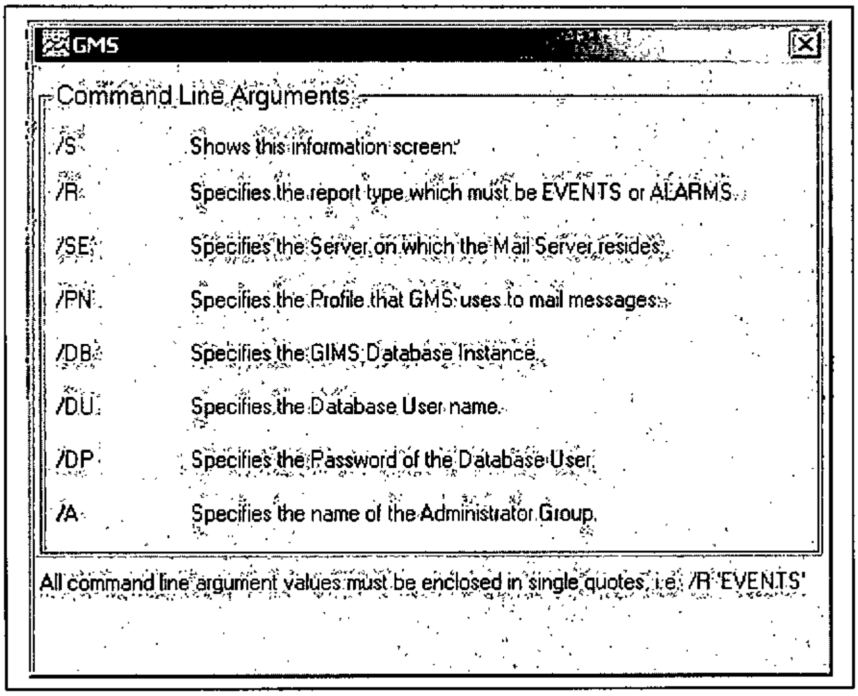



**Fig. 3.5 The command line arguments of the GIMS Mail Service**

An example command line to generate Event reports would be as shown below:

GMS.exe /R ''EVENTS' /SE 'SWR10' ?PN 'GIMS Mail Service' /DB 'nmpgims'

/DU 'mail' /DP 'secret' /A 'GMS Administrator'

This command line should be placed in a batch file (i.e. EVENTS.BAT.) Executing the batch file will generate event reports for all GIMS zones. A similar batch file, namely ALARMS.BAT, can be created to generate the alarm reports.

To generate regular reports, it requires that the GIMS Mail Service Event and Alarm batch files be run at preset time intervals by using the Task Scheduler for Windows NT installed with Microsoft Internet Explorer.

The Task Scheduler is accessed from the Windows Start menu at Start/Programs/Accessories/System Tools/Scheduled Tasks, or from the Scheduled Tasks folder in My Computer. To create a new task, open the Task Scheduler as described above and click on the Add Schedule Task icon to start the Scheduling wizard.

Starting and ending the GIMS Mail Service is a matter of controlling the scheduled execution of the GIMS Mail Service batch files using the Task Scheduler (see the above paragraphs)

Each scheduled tasks can be enabled or disabled using the Enabled check box on the Tasktab of the Properties form for the task. One can open the Properties form for the task by right-clicking on the icon representing the task in the Scheduled Tasks folder and selecting Properties from the context menu that appears.

### 3.1.2 Testing on Automatic Alarm System

For testing the automatic alarm system, a program called Stimulator is written by using VB 5 to continuously generate real time GPS data. The sample data will be enduringly input into the system that contains typical alarm data for trial purpose. The procedures for setting and testing the system are described as follows:

a. Initially, one is required to identify numbers of channel to be used for the enhanced GPS multi-antenna system. In this case, 4 channels are adopted.

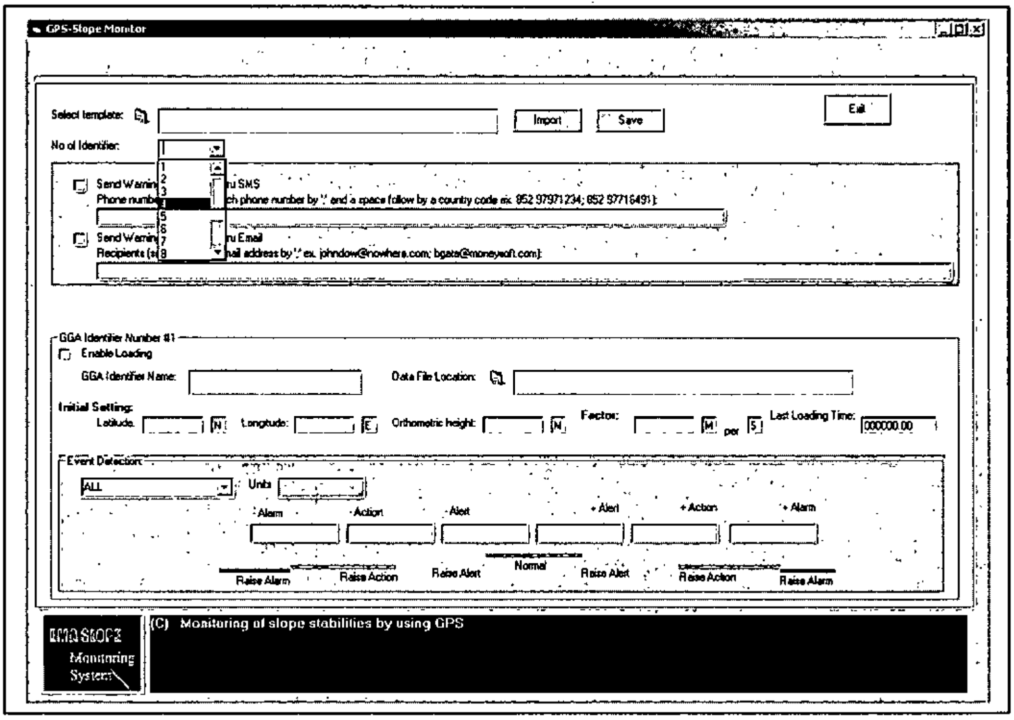



**Fig. 3.6 Selecting the numbers of channels for the enhanced GPS multi-antenna system**

b. Then, the mobile phone numbers and the email addresses of the contact persons should be entered into the system. Once the monitoring data exceeds the pre-defined baseline values, warning in the form of SMS message or email will be sent out to the contact persons. The baseline values and the trigger values are also required to be entered into the system as illustrated in Fig.3.7.

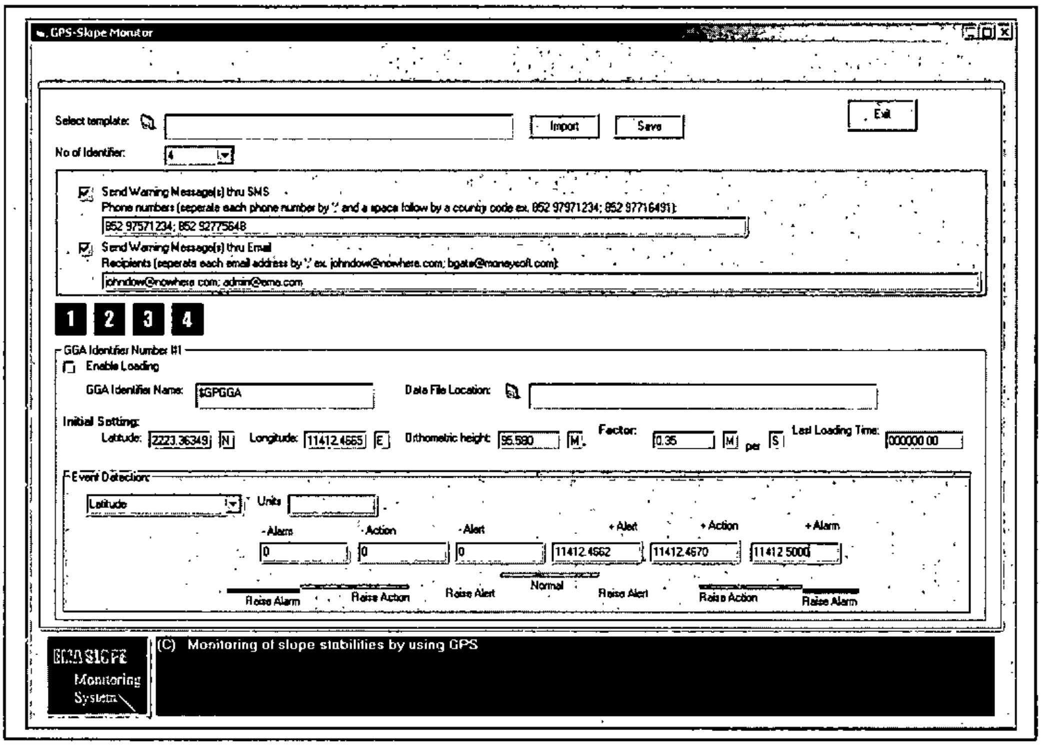



Fig. 3.7 Inputting the default parameters

c. The predefined setting can then be saved as a configure file for future use:

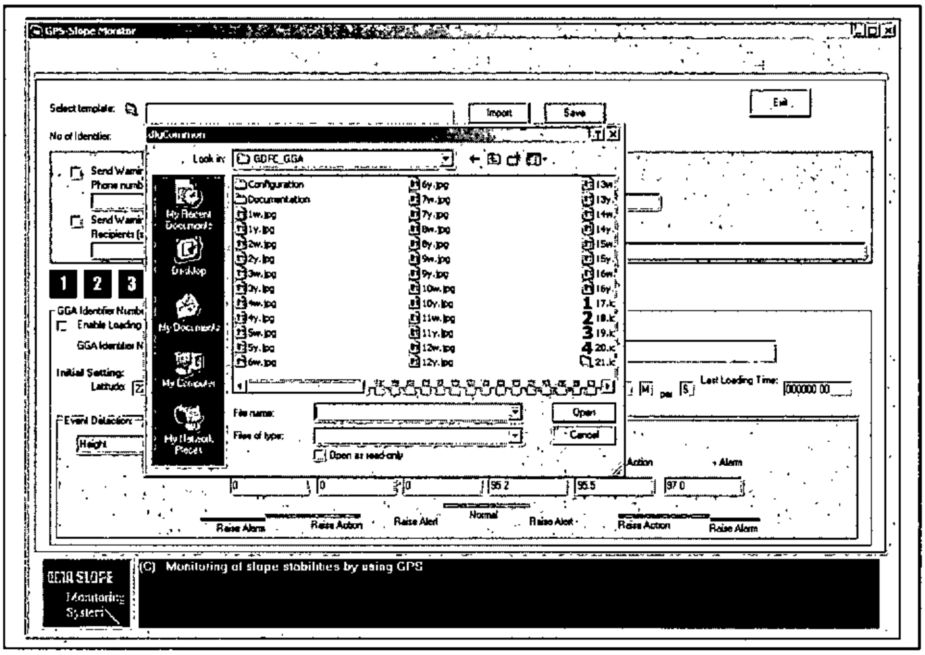



Fig. 3.8 Saving a configure file

d. After that, the system will enter into the Main Menu which displays the output status as shown in Fig.3.9:

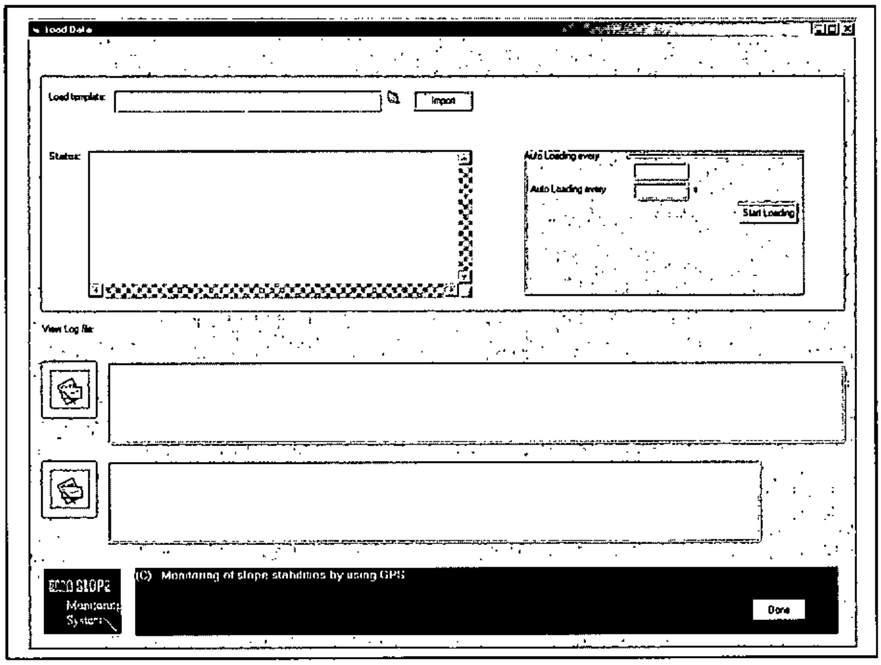


**Fig. 3.9 The main menu of the system**

e. Configure file can be loaded into the system to eliminate the setting up process:

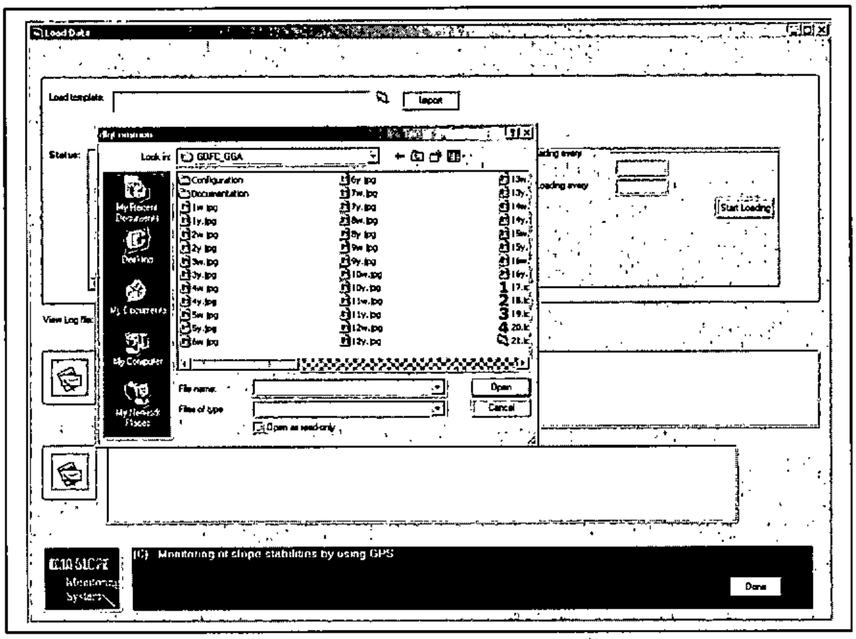


**Fig. 3.10 Loading a configure file**

f. Once the system enters in the operation mode and if any readings exceed the trigger level, warning in the form of SMS message and email will be sent out. The results will then be showed in the Main Menu:

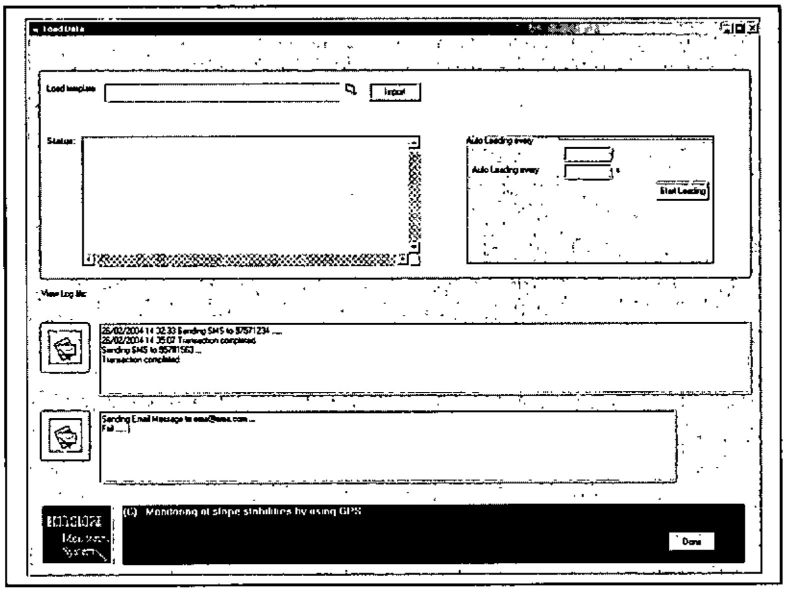



**Fig. 3.11 Sending SMS and email messages to the relevant people**

g. An output screen is design for demonstrating the movements of the monitoring points. In Fig. 3.12, the vertical movements of the monitoring point against time are shown. On the other hand, the horizontal movements of the monitoring point against time can also be shown by selecting the Latitude or Longitude function key. When the Latitude or Longitude function key is selected, the real time GPS data are then generated into the system and shown in the "Processing Data" box on display.

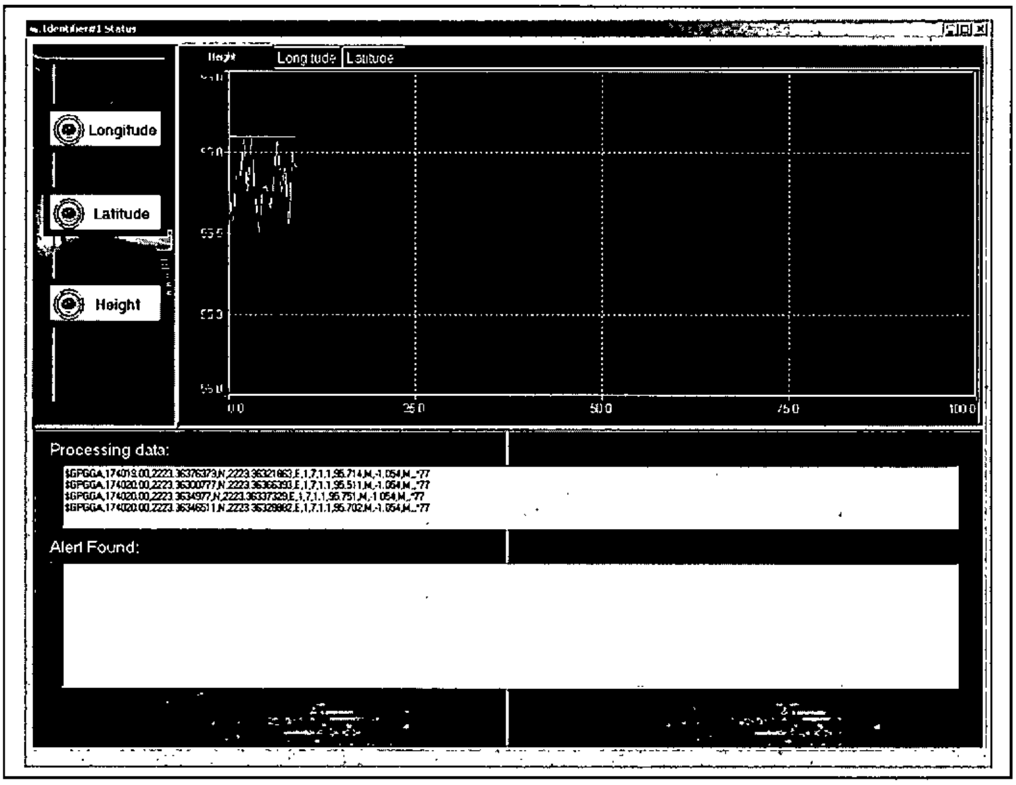



**Fig. 3.12 Typical output screen showed the vertical movement of the monitoring point against time**

h. In case any movement exceeds the pre-defined threshold value, an alert sound will be produced to notify the users and a warning message will be shown in the Alert Found box on display.

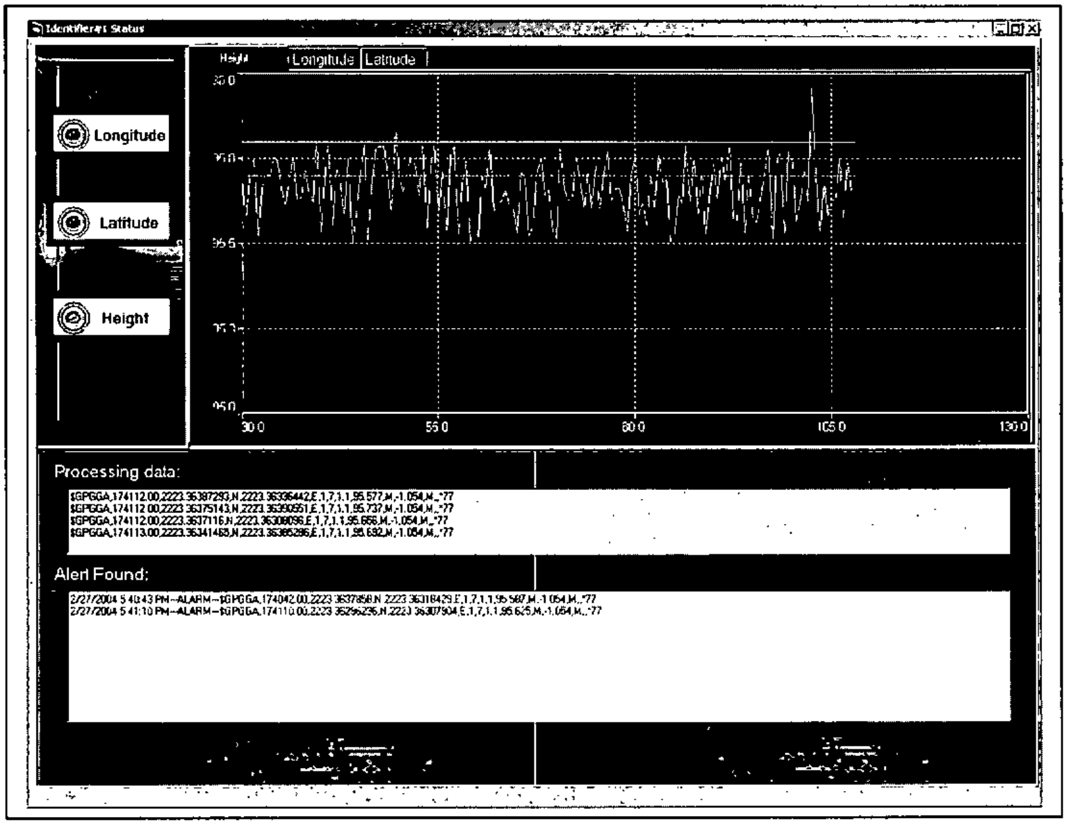



**Fig. 3.13 Typical warning messages showed in the Alert Found's box**

i. Details of the warning event will be displayed in a pop-up window to further inform the users:

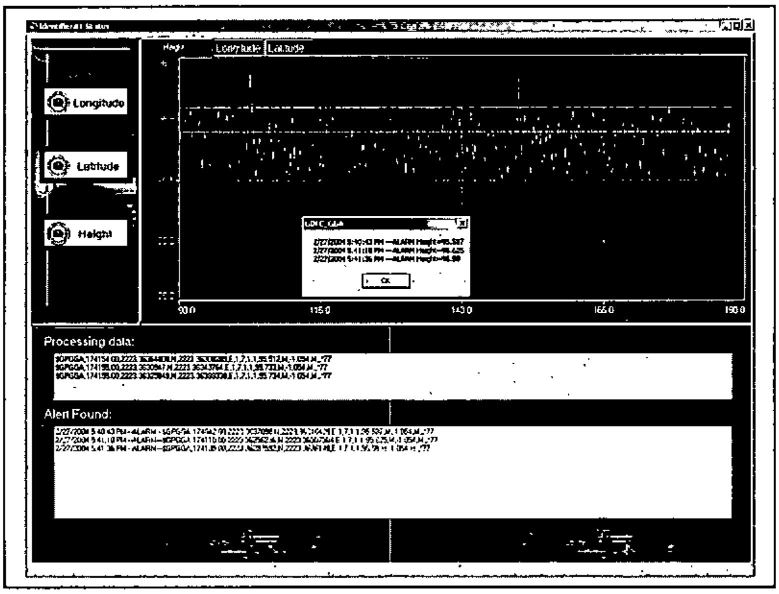



**Fig. 3.14 Example warning detail showed in a pop up window**

j. At any stage, the horizontal and vertical movements of the monitoring points can be shown by selecting the three function keys, i.e. Longitude, Latitude and Height.

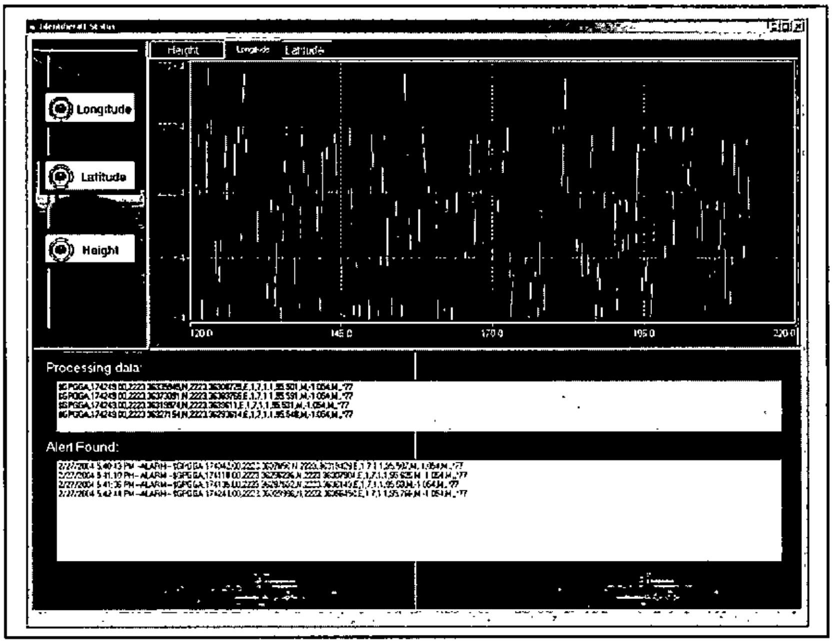



**Fig. 3.15 Switching between different screens of the movements**

## 3.2 Development of the Software for Automatic Data Extraction

### 3.2.1 Overview of Automatic Data Extraction

A program called Extractit has been designed to automatically divide the single GPS data file according to the pre-defined time intervals of each channel of the GPS multi-antenna system. Users only need to set the Starting and Ending times of each channel in the administrative page as illustrated in Fig.3.16

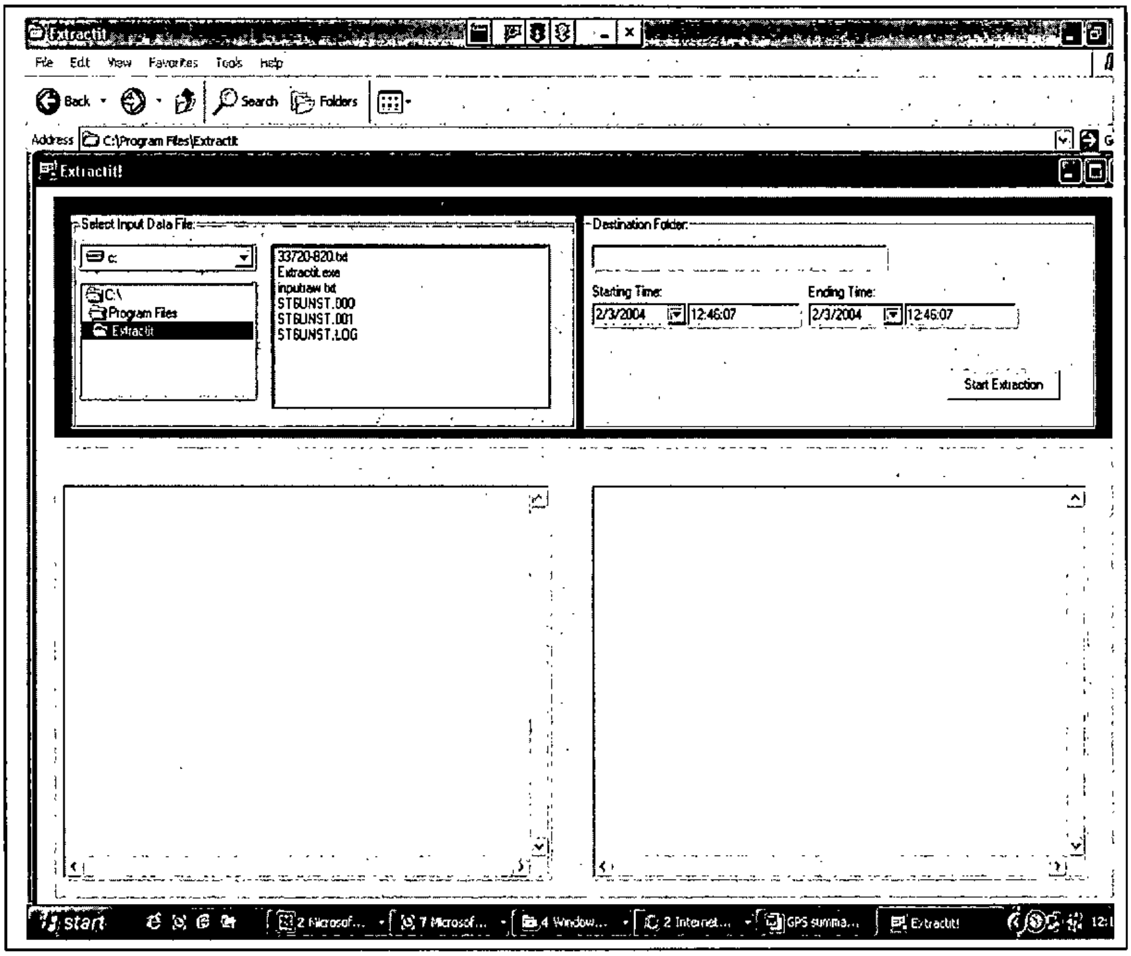
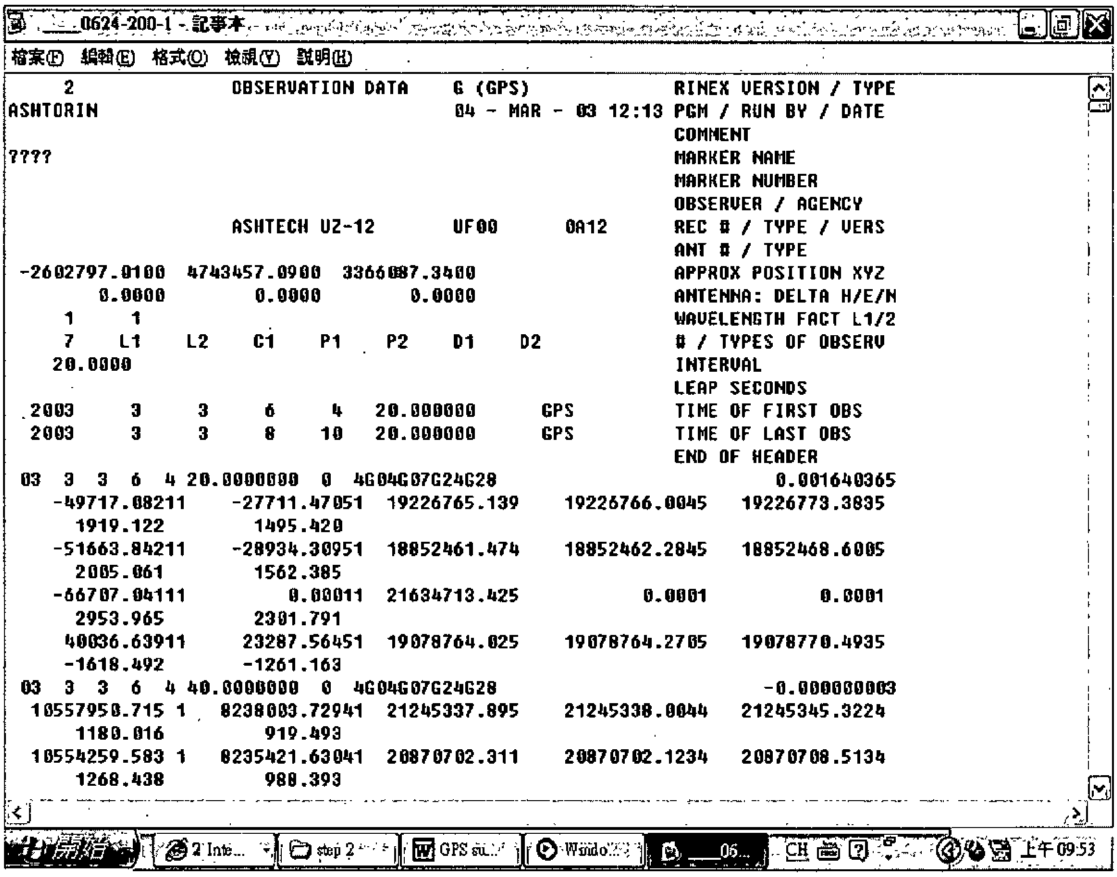



**Figure 3.16 An administrative page for inputting the occupation period of each channel**

For the Extractit, it is written in Visual Basic 5 and is installed in the directory C:\Program Files\Extractit. A typical GPS rinex file that contains data of two channels of the GPS multi-antenna system is stored in the same directory for testing purpose. The file was collected from the GPS multi-antenna experiment in Nanjing as described in section 4.4. The observation period started from 6:20:20 pm to 8:10:20pm on 3/3/2003. Seven sections of fast static positioning were launched and the observation interval for each antenna was preset to be 16 minutes. When the maximum time interval was reached, the GMAS switched to the other terminal to collect GPS signal. The receiver did not recognize the switch of the GMAS, thus the data logging kept continuous when the GMAS switched from one antenna to the other. At the end, all the data from different antennas were recorded in a file and the file was divided into different channels using the Extractit program.



```
     2              OBSERVATION DATA    G (GPS)             RINEX VERSION / TYPE
ASHTORIN                                04 - MAR - 03 12:13 PGM / RUN BY / DATE
                                                            COMMENT
????                                                        MARKER NAME
                                                            MARKER NUMBER
                                                            OBSERVER / AGENCY
                    ASHTECH UZ-12       UF00      0A12      REC # / TYPE / VERS
                                                            ANT # / TYPE
 -2602797.0100  4743457.0900  3366087.3400                  APPROX POSITION XYZ
        0.0000         0.0000         0.0000                ANTENNA: DELTA H/E/N
     1     1                                                WAVELENGTH FACT L1/2
     7    L1    L2    C1    P1    P2    D1    D2            # / TYPES OF OBSERV
    20.0000                                                 INTERVAL
                                                            LEAP SECONDS
  2003     3     3     6     4   20.000000      GPS         TIME OF FIRST OBS
  2003     3     3     8    10   20.000000      GPS         TIME OF LAST OBS
                                                            END OF HEADER
 03  3  3  6  4 20.0000000  0  4G04G07G24G28                    0.001640365
    -49717.08211    -27711.47051  19226765.139    19226766.0045   19226773.3835
      1919.122        1495.420
    -51663.84211    -28934.30951  18852461.474    18852462.2845   18852468.6005
      2005.061        1562.385
    -66707.04111         0.00011  21634713.425           0.0001          0.0001
      2953.965        2301.791
     40036.63911     23287.56451  19078764.025    19078764.2705   19078770.4935
     -1618.492       -1261.163
 03  3  3  6  4 40.0000000  0  4G04G07G24G28                   -0.000000003
  10557950.715 1   8238003.72941  21245337.895    21245338.0044   21245345.3224
      1180.016         919.493
  10554259.583 1   8235421.63041  20870702.311    20870702.1234   20870708.5134
      1268.438         988.393
```

**Figure 3.17 Typical GPS Rinex data file**

To operate the Extratit program, firstly, one is required to store the input GPS rinex file in the directory named C:\Program Files\Extractit. Then, he is required to enter the starting and the ending times of the output file. After having started the extract function, the program will generate an output file based on the predefined observation intervals.

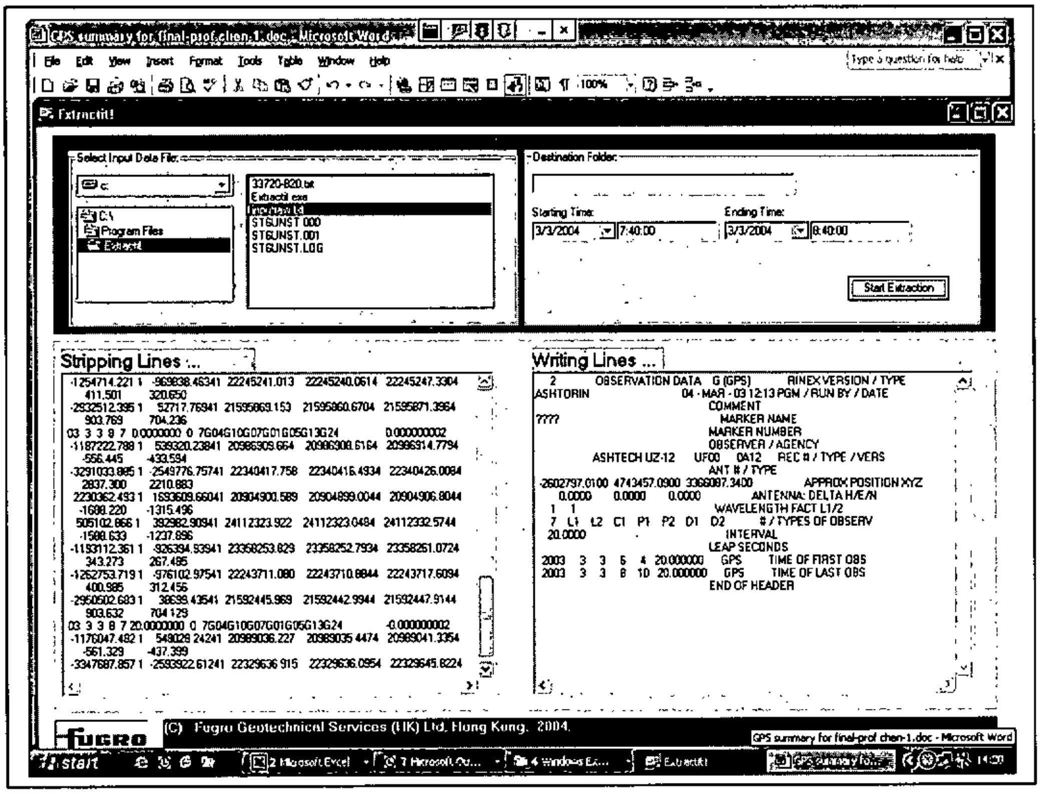



**Figure 3.18 Typical GPS rinex data extraction process**

As there will be a fraction of time delay when the GMAS switches from one channel to another, an additional program for the differentiation of the change in channel is designed. The program is capable to detect the cycle slip caused by the change of GPS observation phases in the GPS data.

### 3.2.2 Testing on Automatic Data Extraction

As discussed above, the automatic data extraction program was installed in the directory C:\Program Files\Extractit. For testing the capability of the automatic data extraction program, a typical GPS rinex data file was collected from the GPS multi-antenna experiment in Nanjing in section 4.2. This rinex file, which was named as inputraw.txt, containing two channels of data from the GPS multi-antenna system for testing purpose.

The observation period was started from 18:20:20 and was ended 20:10:20 on 3/3/2003. Seven sections of fast static positioning were launched and the observation interval for each antenna was preset to be 16 minutes.

To use the program for splitting the rinex file, it is necessary to enter the starting and the ending times of the observation period. In this case, the starting and the ending times were 19:40:00 and 20:10:00 respectively.

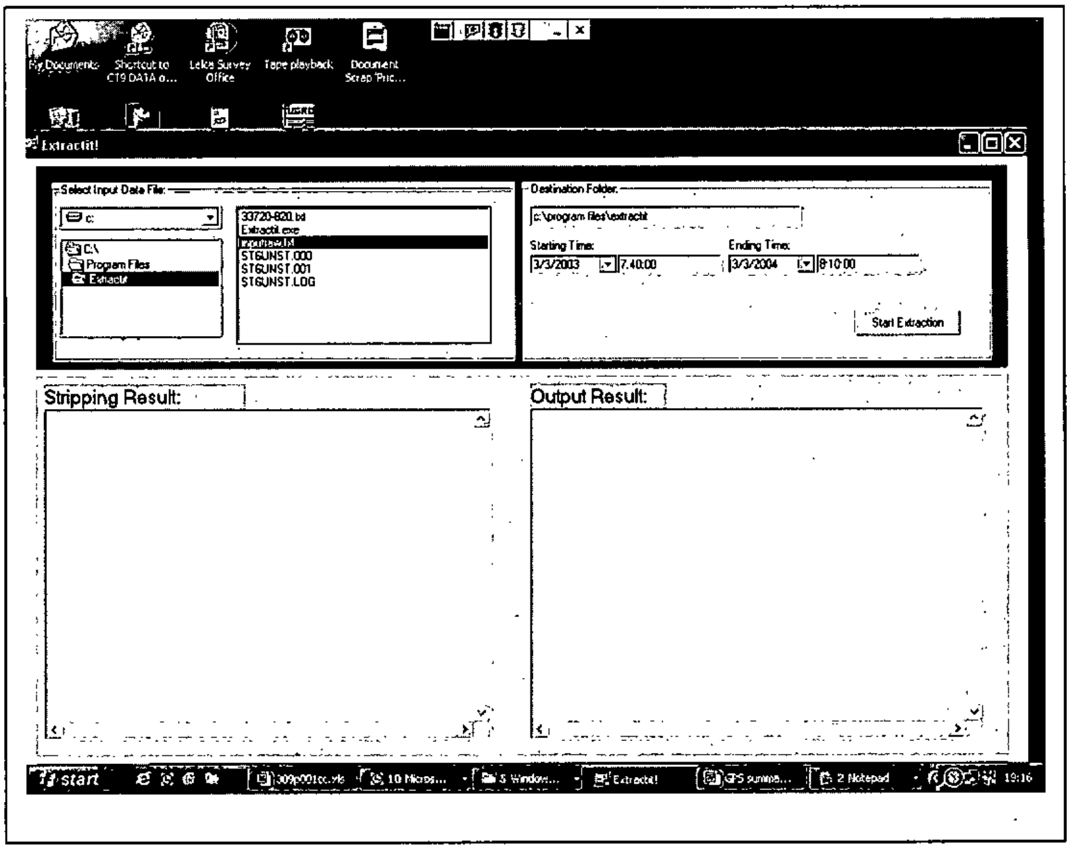



**Figure 3.19 Input the observation period into the automatic data extraction program**

After having operated the "Start Extraction" function, the program will commence to extract the data of the selected time interval from the rinex file. An output file, named 33740-810.txt will be generated and stored in the same directory.

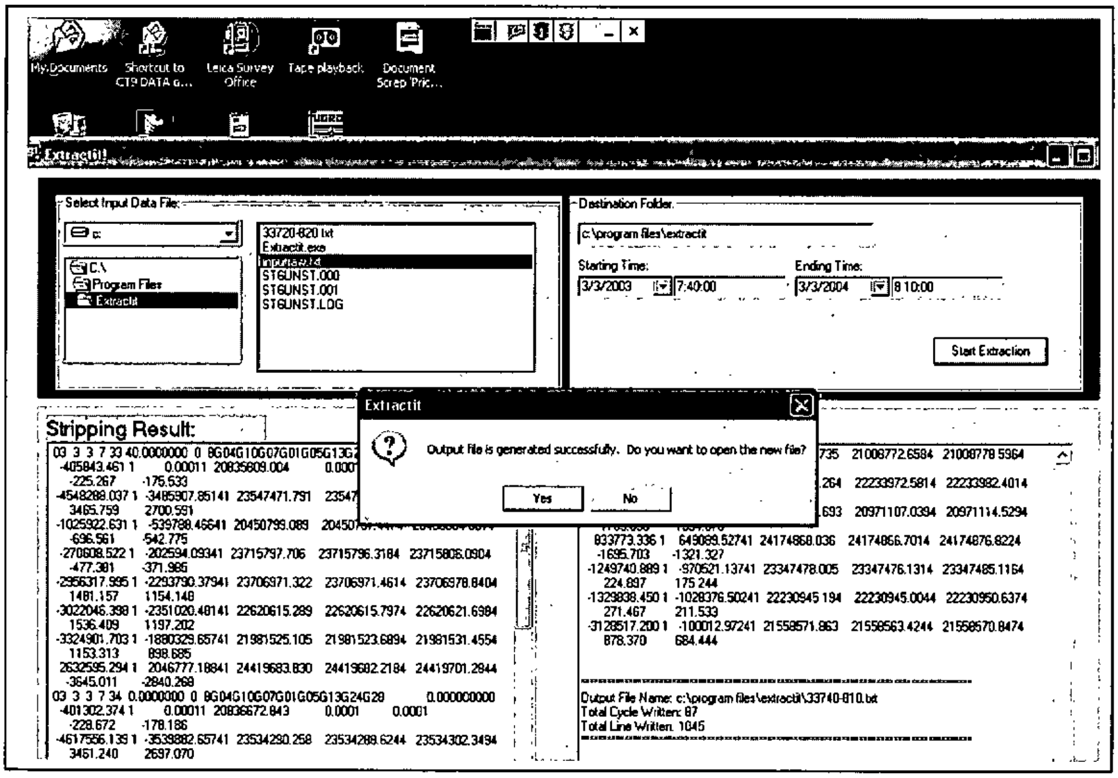



**Figure 3.20 Automatic data extraction process**

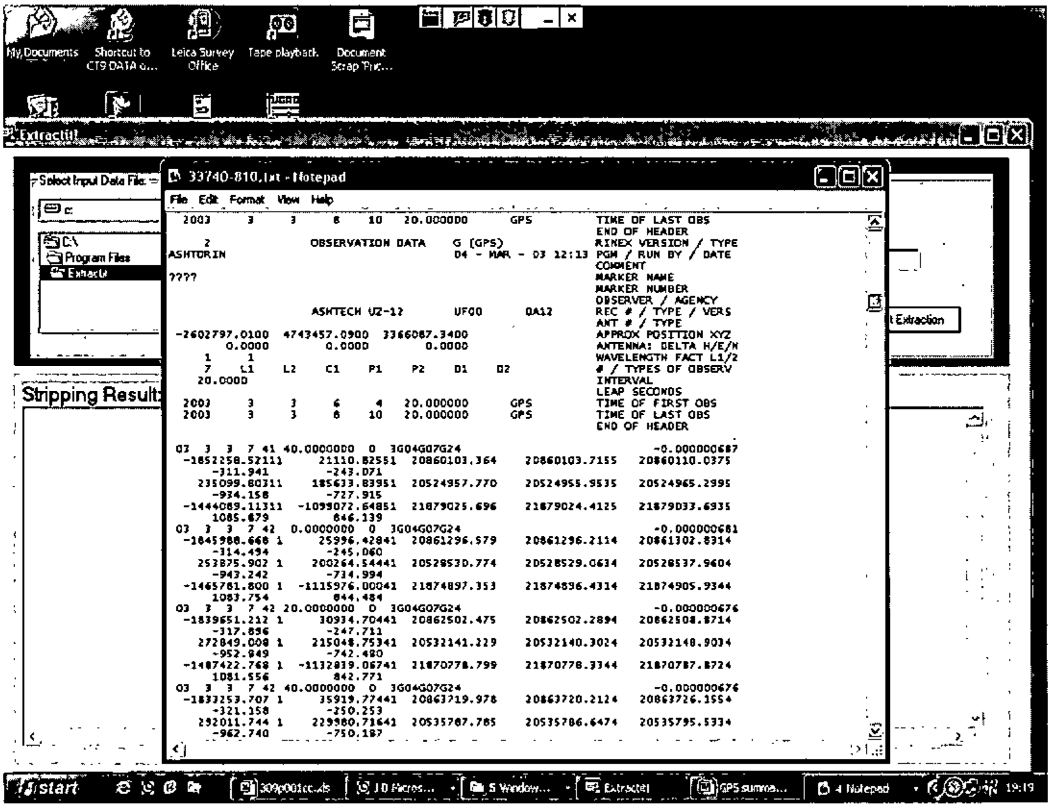
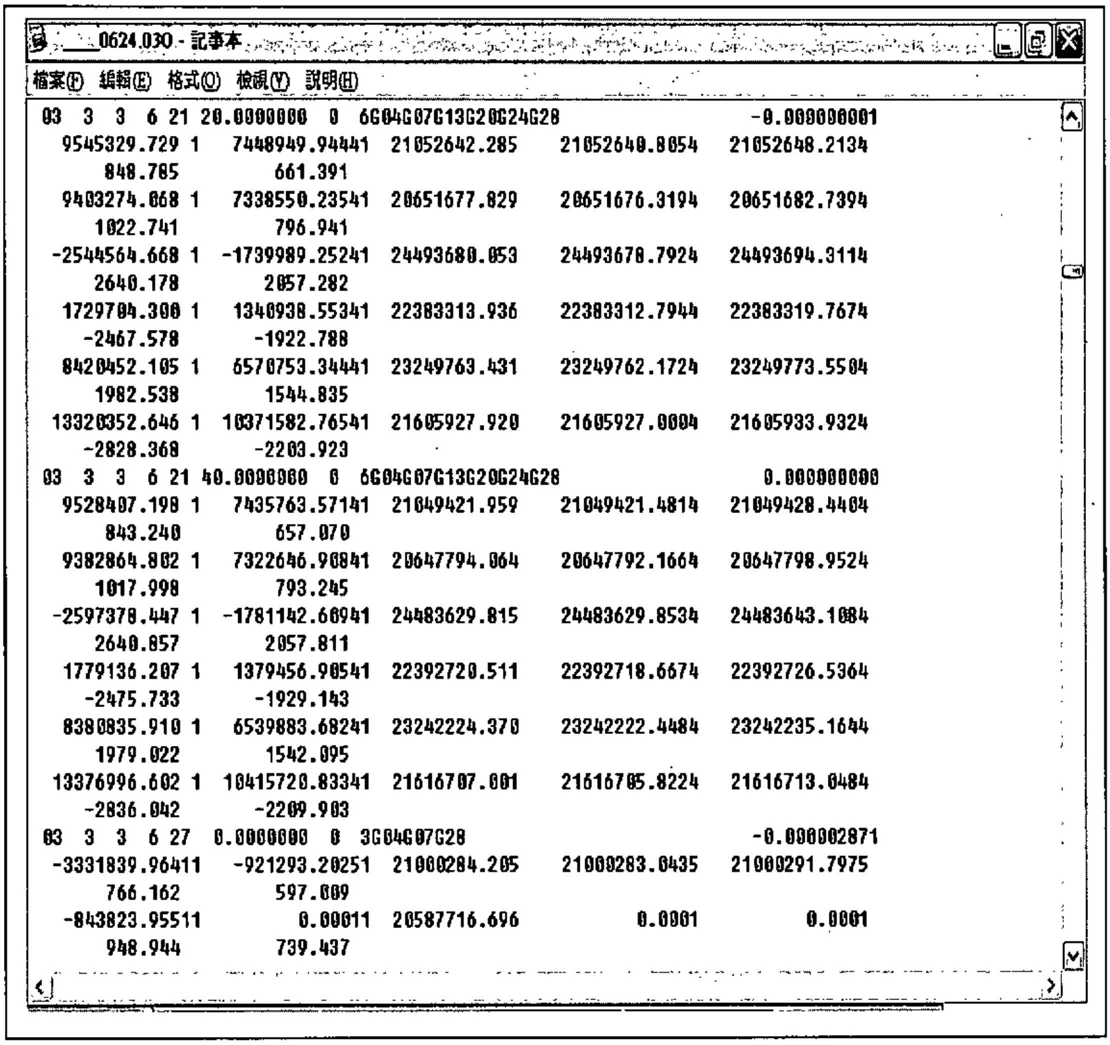



**Figure 3.21 Extracted output file generated from the program**

As mentioned above, a program was designed to detect the cycle slips, which was generated due to the change in tracking satellite. From the results of the Nanjing experiment as shown in Figure 3.22, the GMAS was switched from one channel to another at 18:27:00 i.e. line27. At that time, the first signal of the previous observation phase was sharply dropped from 9528407.198 to -331839.964. The program was capable of detecting the change in this observation phase by comparing the current phase with the previous and the latter ones. Once the program discovered a substantial change in the observation phase, it would automatically split the data file into two portions for further data computation.



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0624.030 - 記事本
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     2640.857         2057.811
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     1979.022         1542.095
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    -2836.042        -2209.903
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      766.162          597.009
  -843823.95511         0.00011  20587716.696           0.0001          0.0001
      948.944          739.437
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**Figure 3.22 Automatic cycle slip detection**

# CHAPTER 4

# SYSTEM CONFIGURATION DESIGN

## 4.1 System Configuration Design

As having mentioned in Chapter 2, data communication is a vital part in this research. The main problem is how the data is transferred from the antennas to the receiver. It is because in a slope site, monitoring points are usually dispersed. Therefore, long cables are usually used to connect the antennas to the rover receiver.

Generally, three types of cable can be chosen. They are Twisted Pair cable, Coaxial Cable and Fiber Optic Cable. Twisted Pair cable is often considered as a low –frequency transmission medium. Its main advantages are relatively inexpensive and easy to install. Coaxial Cable consists of a single wire in the center surrounded by a core of insulating material, and an outer conductive wrapping that 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.

In this project, Coaxial cable is selected. It is because twisted cable, 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 electronic 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.

Having selected the appropriate cable, another problem is how to minimize the GPS signal loss during data transmission. As GPS signal is an electronic 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 replace 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 power loss during the 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. Experiments are conducted in Hong Kong to evaluate the effect of using long cables connected to signal amplifier on the GPS signal. Comparison is also made to study different approaches for this kind of long distance data transmission.

In addition, for reducing the cost of this type of data transmission, experiments are performed in the Ho Hai University in Nanjing. The positioning results and the signal to noise ratio (S/N) are analyzed in order to investigate the effect of external noise in this long distance GPS data transmission.

## 4.2 GPS Multi-Antenna Experiment in Nanjing

### 4.2.1 Purpose of the experiment

Although the use of 60m long cable connected with two 20dB signal amplifiers can be adopted in the GPS multi-antenna system, from practical point of view, the cost of this type of set up is too high. For instance, the cost of the high qualify cable (60m) is about $5000 and the cost of the two signal amplifiers are $10000 (about $5000 per unit). As the major advantage of the GPS multi-antenna system is the reduction of the cost by connecting only one receiver to several antennas. If the price of the data transmission is relatively too high compared with the receiver, it will make the system very difficult to be implemented in practice.

In view of the above, a method to dramatically reduce the cost of the data transmission is considered necessary for the implementation of the system. Several local or overseas manufactures such as Leica, Trimble and GPS networking were contacted but their prices were still considered too high for this purpose (table 4.1). Finally, it was found that similar GPS long cable and signal amplifier with lower costs were adopted by the Ho Hai University in Nanjing (the cost of such set up in Hong Kong is about $15000 while that in Nanjing is just $6000). Therefore, experiments were conducted in the Ho Hai University to test whether this equipment could be implemented in Hong Kong.

**Table 4.1 Comparison of different methods for data transmission between GPS antenna to GPS rover receiver using long cables**

| Method | Amplifier | Long Cables | Connection Methods | Prices (HK$) |
|---|---|---|---|---|
| Method a | 20dB * 3 | 45m + 90m (normal cable) | Antenna + 20dB + 45m + 90m + 20dB + 20dB + Receiver | HK$1500 (cable Price) +HK$9900 (Price of 3 amplifiers) Total = $11400 |
| Method b | 20dB * 3 | 45m + 90m (normal cable) | Antenna + 20dB + 20dB + 45m + 90m + 20dB + Receiver | HK$1500 (cable Price) +HK$9900 (Price of 3 amplifiers) Total = $11400 |
| Method c | 20dB * 2 | 150m (high quality cable) | Antenna + 20dB + 150m + 20dB | HK$6600 (Price of 2 amplifiers) + HK$14000 (150m cable) Total = $20600 |

| | | | | |
|---|---|---|---|---|
| Method d | Fiber Optic Network | 1-9 Km | Roof Antenna<br>Transmitter Power Supply<br>Transmitter Preamp<br>FiberOptic Transmitter<br>FiberOptic Receiver<br>Receiver Attenuator<br>Receiver Power Supply | $80000 |

### 4.2.2 Preparation of the experiment

To demonstrate the utilization of the GMAS, an experiment was performed at the rooftop of the Ho Hai University in Nanjing. After detail investigation, one base station and two monitored points were selected. Two baselines were formed from the base station to each monitored points respectively. Both of these baselines were approximate 27 m in length. The GMAS had eight input terminals and one output terminal, while terminals 1 and 5 were used in this experiment for illustration. Two antennas were connected to these input terminals and one receiver was linked to the output terminal. A 200 m cable with one 40 dB signal amplifier was used to connect the antenna to the terminal 1 of the GMAS. While channel 5 was only linked with a short cable to the antenna. The observation time of each terminal could be set by user in advance. In this experiment, the time interval was set as about 16 minutes that was long enough for fast static positioning.

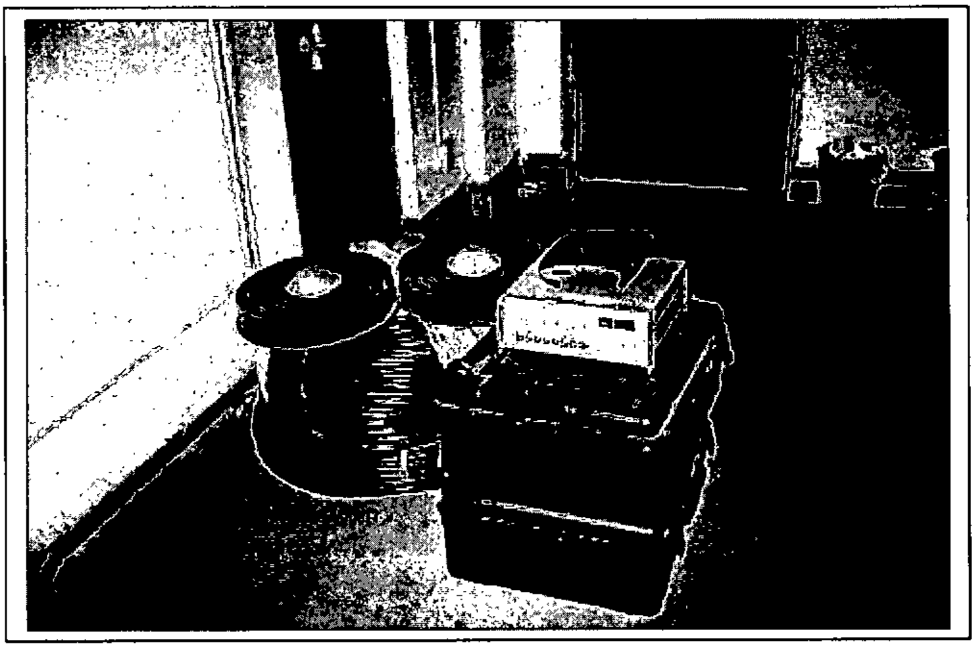


**Figure 4.1 Set up of the GPS multi-antenna system in Nanjing**

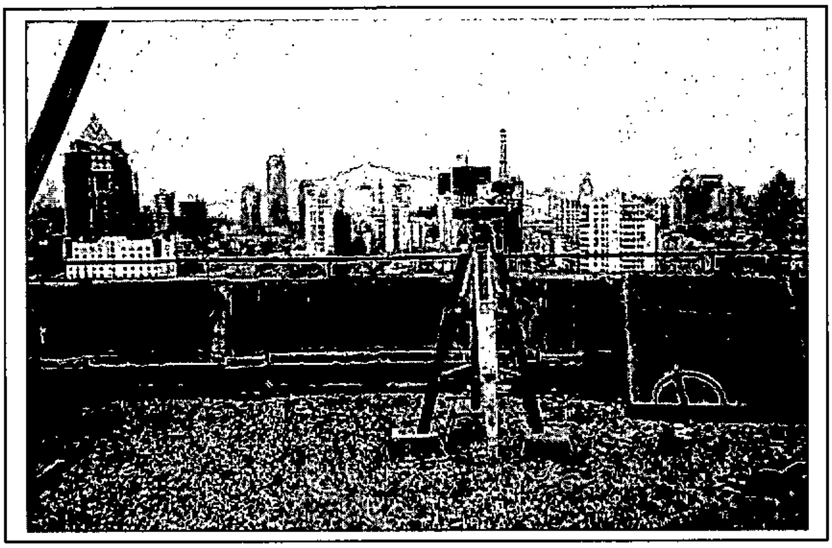


**Figure 4.2 The base station was set up at a control point at the roof top**

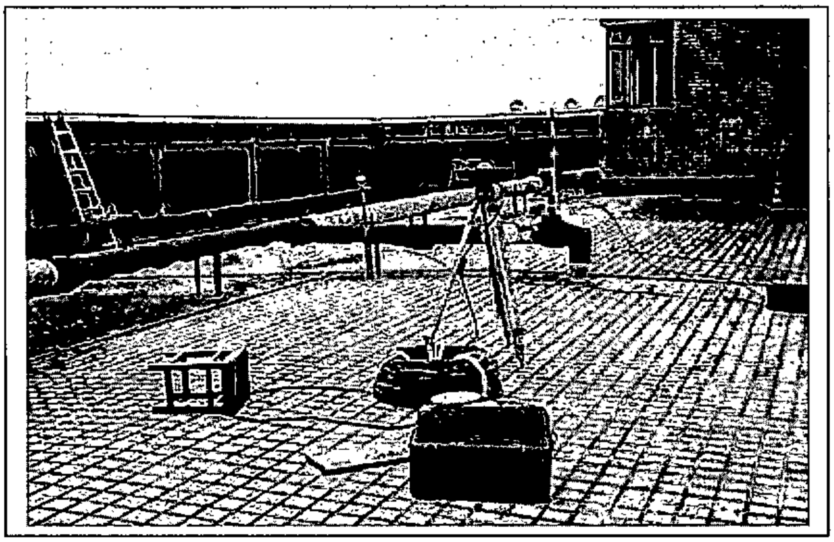


**Figure 4.3 The monitor station was set up and linked to a 200m long cable**

### 4.2.3 Survey result

Seven sections 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 continuous when the GMAS switch from 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 different parts in the data processing. The GPS data was reduced by using the Ashtech Network Adjustment Package and the GPS processing report was attached in Appendix I for reference.

| Session | Terminal 1 (with long cable)<br>Coordinate Value in Conventional Terrestrial (CT) System | | |
|---|---|---|---|
| | X | Y | Z |
| 1 | 25.674 | 7.970 | -4.120 |
| 2 | 25.667 | 7.976 | -4.118 |
| 3 | 25.669 | 7.979 | -4.117 |
| 4 | 25.668 | 7.969 | -4.122 |

**Table 4.2 The survey result of the GPS multi-antenna system connecting to a long cable**

| Session | Terminal 5 (without long cable)<br>Coordinate Value in Conventional Terrestrial (CT) System | | |
|---|---|---|---|
| | X | Y | Z |
| 1 | 24.452 | 6.841 | -4.110 |
| 2 | 24.451 | 6.844 | -4.111 |
| 3 | 24.454 | 6.845 | -4.112 |
| 4 | 24.451 | 6.842 | -4.114 |

**Table 4.3 The survey result of the GPS multi-antenna system without connecting to a long cable**

From table 4.2, one can saw the maximum differences in coordinate component among sessions were 7 mm in X, 10 mm in Y and 5 mm in Z. While in table 4.3, the maximum difference in coordinate component among sessions were 3 mm in X, 4 mm in Y and 4 mm in Z. Although the results with 200 m long cable seem not as good on those without long cable, they were similar to those with 60 m good quality cable (see section 2.2.2). Therefore the new setup was acceptable. According to He (2004), the new system setup worked well in a project with 300 m cable

To further prove that the new setup was acceptable, the signal to noise ratio (S/N) of L1 signal was plotted and attached in the following pages for reference. It was found that the magnitudes of the S/N ratio of the channel 1 were similar to that of the channel 5. For example, in section 2, the magnitudes of the S/N ratio of the satellites 20, 24, 28. 4 and 7 of channel 1 were 45 dB, 47 dB, 46 dB, 53 dB and 54 dB respectively. While the magnitudes of the S/N ratio of those satellites of channel 5 were 43 dB, 48 dB, 45 dB, 54 dB, 54 dB respectively. This reflected that the use of this type of long cable only induced low noise in the GPS data and did not affect the GPS signal quality.

### 4.2.4 Conclusion

In this experiment, a 200m cable connecting to a 40 dB signal amplifier was successfully used in the GMAS. This type of long cable was specially designed so as to provide a high bandwidth, low attenuation and was also not very expensive (this set up is cost about $6000). Therefore, only one 40 dB signal amplifier was adopted for using this long cable and this eventually significantly reduced the cost of the GMAS.

Figure 4.4 L1 signal to noise ratio (Channel 5-1 section)

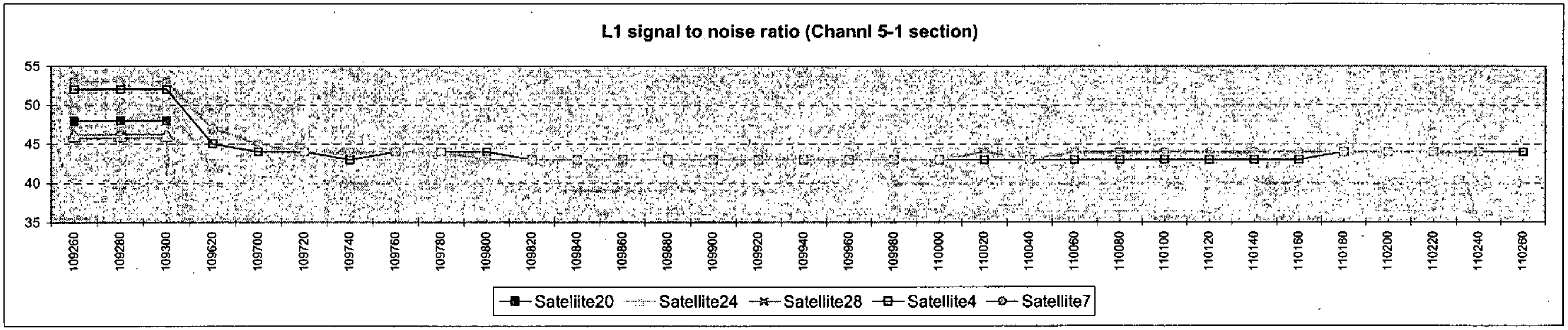


Figure 4.5 L1 signal to noise ratio (Channel 5-2 section)

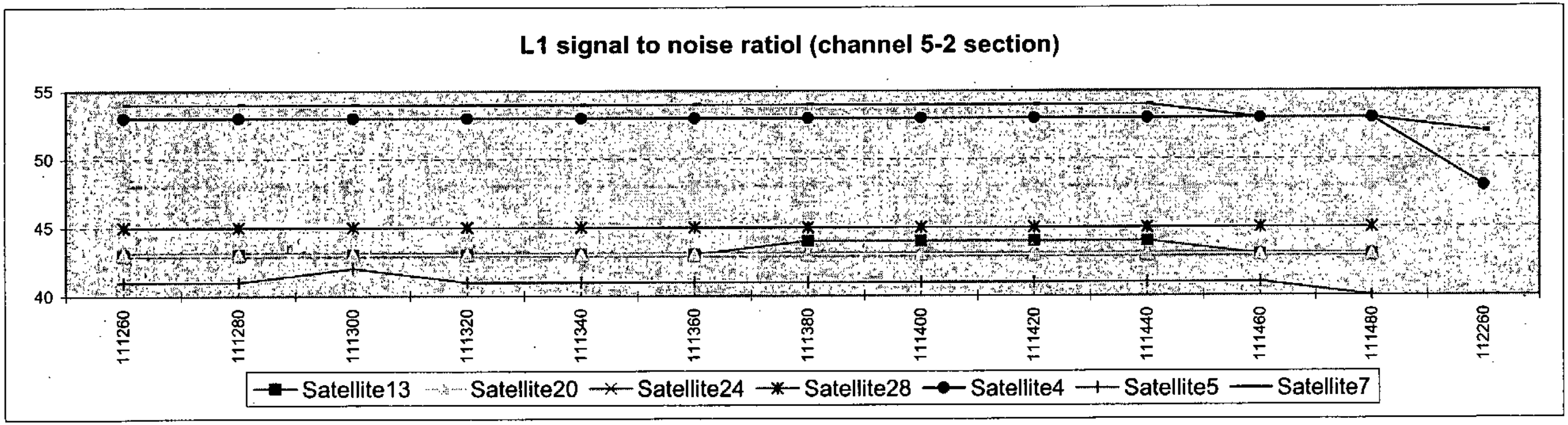


Figure 4.6 L1 signal to noise ratio (Channel 5-3 section)

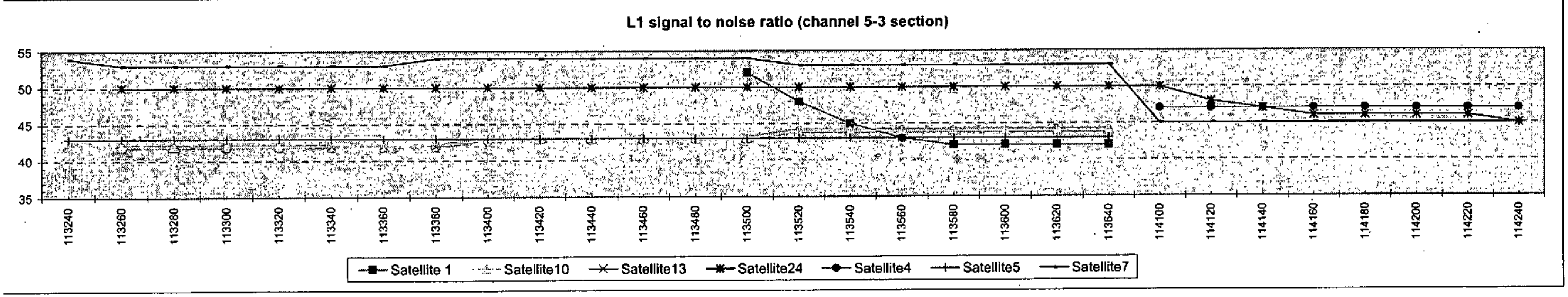


Figure 4.7 L1 signal to noise ratio (Channel 1-1 section)

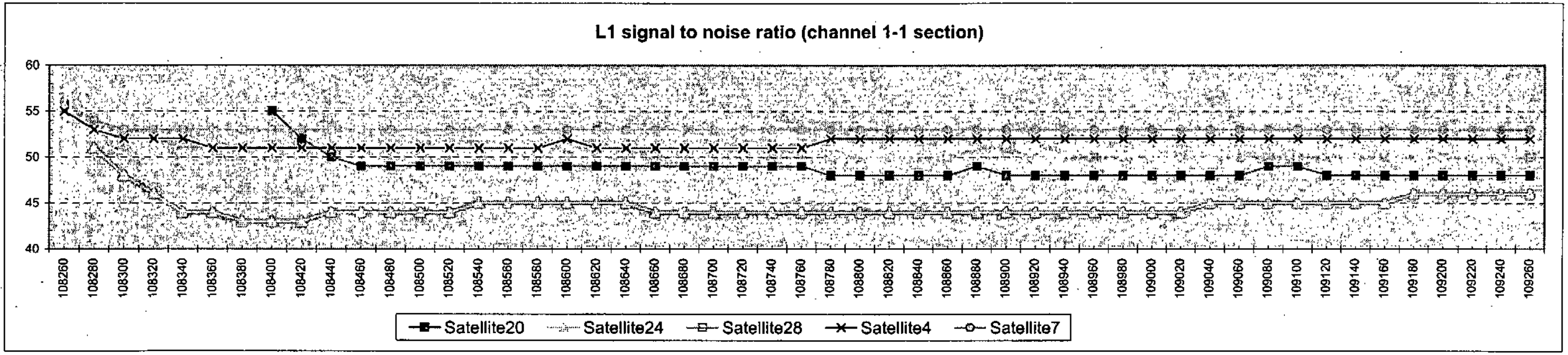


Figure 4.8 L1 signal to noise ratio (Channel 1-2 section)

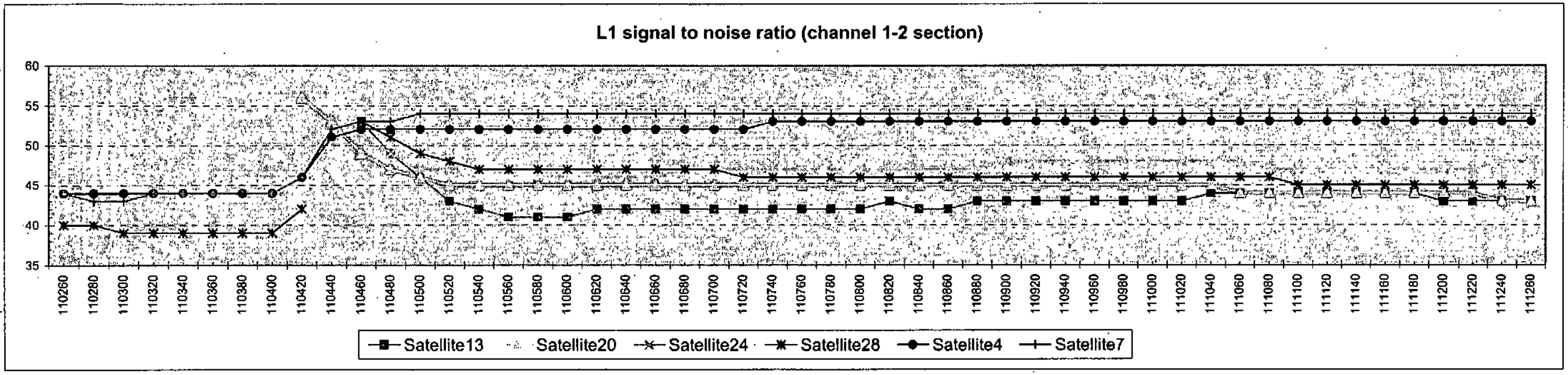


Figure 4.9 L1 signal to noise ratio (Channel 1-3 section)

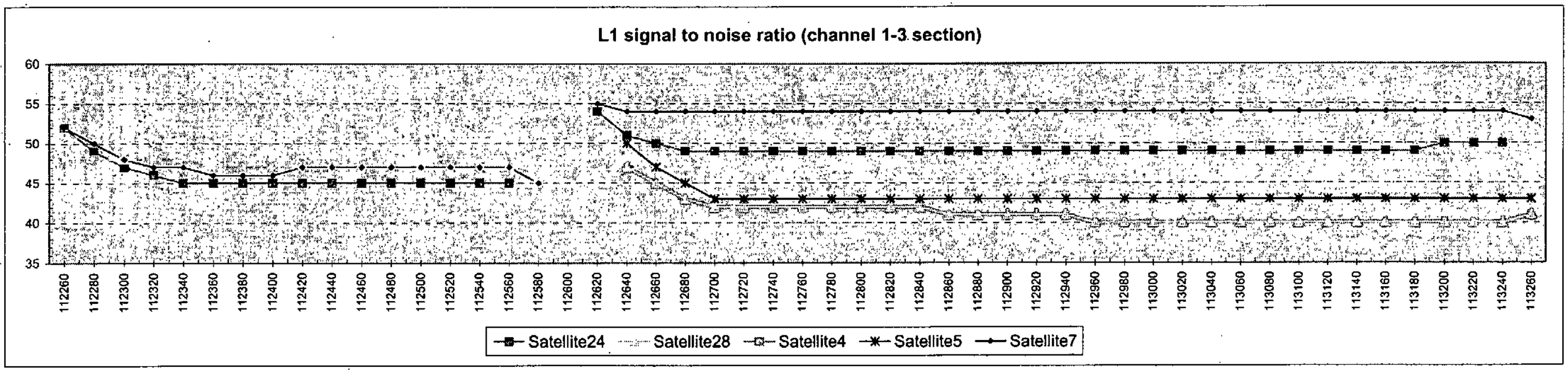
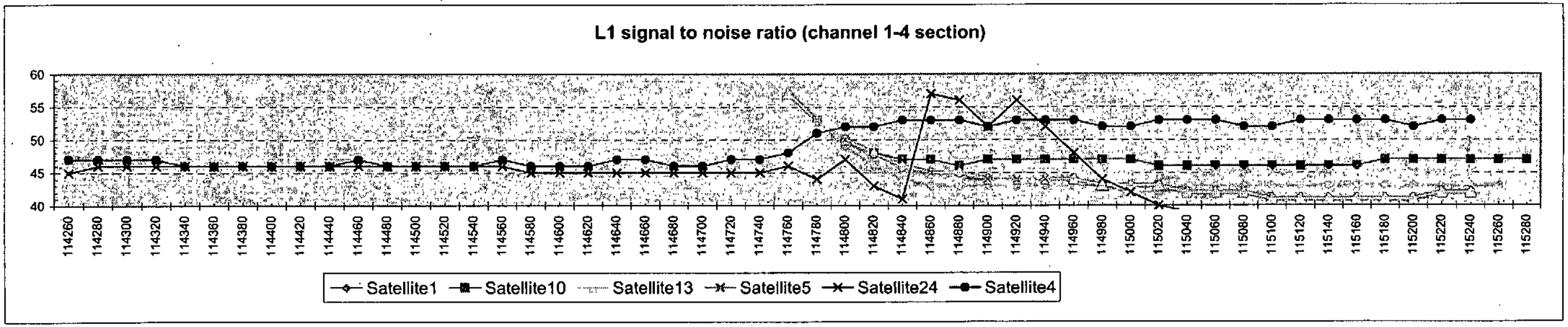


Figure 4.10 L1 signal to noise ratio (Channel 1-4 section)



# CHAPTER 5

# MULTIPATH EFFECT

## 5.1 Global Positioning System (GPS) and Multipath Effect

Global Positioning System (GPS) is a satellite-based positioning system where receiver uses pseudorange measurements to four (or more) satellites with known position to compute its own location. The satellite configuration consists of 24 satellites arranged in 6 orbital planes with 4 satellites per plane. In addition to these satellites, GPS has a *Control Segment* consisting of five Monitor Stations. The Control Segment is designed to track all GPS signals to compute satellite ephemeris and satellites clock errors. Together with other broadcast message data, these information are transmitted to the satellites to upload new ephemeredes and clock correction.

The satellites broadcast ranging codes and navigation data on two frequencies using a technique called Code Division Multiple Access (CDMA). The two frequencies are L1 frequency of 1575.42 MHz and L2 frequency of 1227.60 MHz. A pseudo-random noise (PRN) C/A or coarse/acquisition code of 1.023 MHz is modulated on L1 frequency and a PRN P or precision code of 10.23 MHz is modulated on both the L1 and L2 frequencies.

A GPS receiver can measure code pseudorange and carrier phase. A code pseudorange is the difference between the signal transmission time at the satellite and reception time at the receiver. It can be scaled to units of length using the speed of light. The pseudorange from a receiver to satellite is given as follows:

$R_L = R + c(dt-dT) + d_{ion} + d_{trop} + d_P + \varepsilon_p + M_c$

where

| | | |
|---|---|---|
| $R_L$ | : | measured pseudorange |
| $R$ | : | physical distance from receiver to satellite |
| $c$ | : | speed of light |
| $dt$ | : | satellite clock error |
| $dT$ | : | receiver clock error |
| $d_{ion}$ | : | ionosphere time delay |
| $d_{trop}$ | : | tropospheric time delay |
| $d_P$ | : | orbital error |
| $\varepsilon_p$ | : | code measurement noise |
| $M_c$ | : | multipath error |

The carrier phase observable, which is far more accurate than the code pseudorange observable, is being extensively used for surveying purpose. The measured carrier phase is equal to the fractional carrier phase plus the unknown integer cycle ambiguity (N).

Carrier phase observation can be scaled by their wavelength to convert them from cycles to units of length and is given is follows:

$\phi_L = R + c(dt-dT) + \lambda*N - d_{ion} + d_{trop} + d_P + \varepsilon_\phi + M_\phi$

where

$\phi_L$ : measured carrier phase

$\lambda$ : carrier wavelength

$\varepsilon_\phi$ : carrier phase measurement noise

$M_\phi$ : multipath error in carrier phase

The only differences between this equation and code pseudorange equation are the addition of integer cycle ambiguity and the reversal of signs for ionospheric delay term.

The accuracy of GPS measurements is affected by a number of factors, which are summarized as follows:

***a. Orbital errors***

They are the differences between the actual satellite positions and the position predicted by the broadcast ephemeredes. These discrepancies are the consequence of the inability to entirely model the forces acting on a satellite and the degradation due to Selective Availability (SA). Weigen (1993) pointed out that the errors could be reduced using single difference observation equation or precise ephemeredes, based on observations from globally distributed tracking stations. According to Vanicek et al. (1985), the orbital errors on baseline determination can be illustrated as follows:

$$dr/r = dp/p$$

where

| | | |
|---|---|---|
| dr | : | error in baseline; |
| r | : | baseline length; |
| dp | : | orbital error; |
| p | : | satellite-receiver range |

Table 5.1 below is the summary of the acceptable orbital error for a given relative accuracy in baseline determination explained by Seeber (1993).

| **Relative accuracy required** | **Acceptable orbital error** |
|---|---|
| 5ppm | 125m |
| 1ppm | 25m |
| 0.5ppm | 12.5m |
| 0.1ppm | 2.5m |

**Table 5.1 Orbital error for a baseline**

***b. Clock errors***

There are two types of clock errors, namely satellite clock error and receiver clock error. Satellite clock error is the difference between satellite time and true GPS time. While receiver clock error is the difference between receiver time and true GPS time. Satellite clock error can be eliminated by single-difference observation equation. Receiver clock error can be cancelled by double-difference observation equation. An alternative approach by Remondi (1984) was to leave the receiver and satellite clock errors as unknowns to be solved in parameter estimation.

*c. Ionospheric delay*

The ionosphere, which has free electrons surrounding the earth, is extending in various layers from about 50 km to 1000 km. Young et al. (1985) reported that a group delay and a phase advance occurred in the ionosphere. That means GPS code measurements are delayed and the carrier phase are advanced.

The ionospheric delay depends on the Total Electron Content (TEC) along the signal path and the frequency used. TEC is a function of sunspot activities, seasonal and diurnal variations, the line of sight and the position of the observation side. Nowadays, with the increasing use of dual frequency receivers, the delay can be solved by ionosphere-free linear combination of two frequency observations.

*d. Tropospheric delay*

The Troposphere is the lower part of the earth's atmosphere, which extends to a height of less than 9 kilometers over the poles and in excess of 16 kilometers over the equator. The pressure of neutral atoms and molecules in the troposphere affects electromagnetic signal propagation and eventually causes delay in a wave passing through the region. This is known as tropospheric delay. The Tropospheric delay depends on pressure, humidity and temperature. It can be separated into a dry and a wet component. The dry component, which reaches up to 90% of the total delay, is easier to estimate than the wet component.

Various models have been developed to estimate the delay, e.g. Davis et al. (1985), Hopfield (1969), Lanyi (1984) and Spilker (1996). Wells et al. (1987) explored that these models could precisely describe the dry component with an accuracy of ± 1% and also could model the wet component by surface weather data to within 3-4cm. Other approaches of determining the wet component include direct measurement with water vapor radiometers (Elgered et al. (1985)) and estimation of zenith delay in the least squares adjustment of the phase observations.

***e. Observation noise***

Observation noise can be classified into environmental noise and receiver internal noise. High noise level implies low signal-to-noise ratio (SNR) SNR refers to the ratio of signal power to noise power at the receiver output. This ratio is also referred to as the post detector or destination signal-to-noise. Roddy (1995) reported that SNR was different from the carrier-to-noise ratio at the detector input and the two ratios could be related through the receiver processing gain as follows:

$$10\log_{10}\frac{S}{N} = 10\log_{10}\frac{C}{N} + 10\log_{10} K_R \tag{5.1}$$

Where S/N is the signal-to-noise ratio, C/N is the carrier-to-noise ratio and $K_R$ is the processing gain of the receiver.

The SNR is an indication of the magnitude of the carrier phase signal. It is affected by atmospheric effect, antenna gain characteristics, satellite elevation angles and multipath effect.

*f. Multipath effect*

***Characteristics of Multipath effect***

Multipath effects occur when satellite signals arrive from more than one path. The effect is resulted from GPS signal reflected from ground and other objects causing the indirect paths. The effect can significantly distort the signal waveform's amplitude and phase. It also distorts the signal modulation and degrades accuracy in conventional systems. Moreover, Braasch (1996) reported that it was because the interferometric systems would employ pseudorange measurements for initialization (ambiguity reolution) purposes, multipath contamination of the pseudorange could increase the time required for initialization.

There are two types of multipath effects. They are the receiver multipath and the satellite multipath. We will mainly concern on receiver multipath in this study.

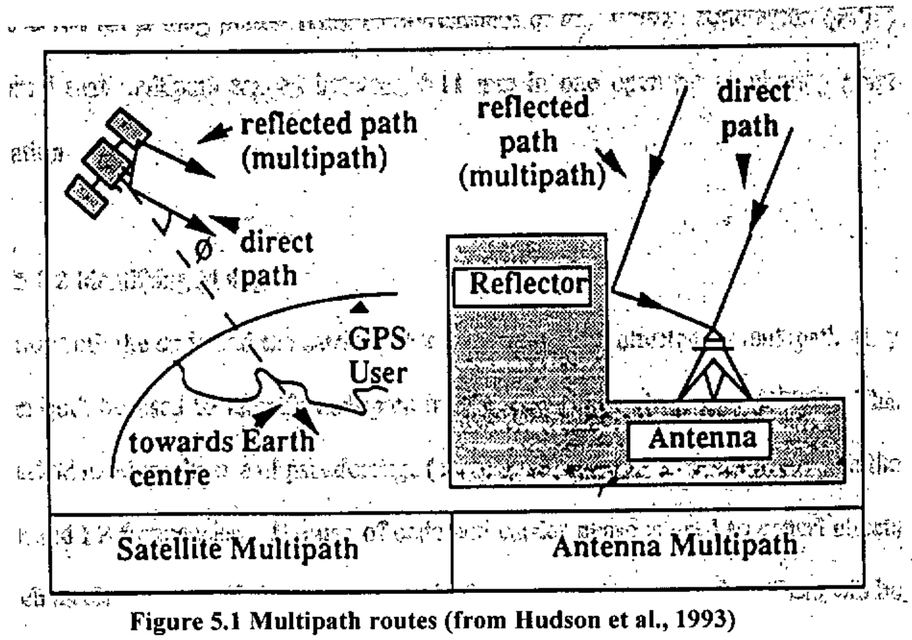



**Figure 5.1 Multipath routes (from Hudson et al., 1993)**

The characteristics of multipath effect are summarised as follows:

1. The multipath signal will always arrive after the direct path signal because it must travel a longer propagation path

2. The multipath signal will normally be weaker than the direct path signal since some signal power will be lost from the reflection. It can be significantly stronger if the reflecting surface has a significant area (reflecting building, for example) or if the Line Of Sight (LOS) is partially obstructed

3. The multipath signal depends on the direction to satellites, which is azimuth and elevation with respect to the reflector. If the satellite is directed toward the reflector or the elevation of the satellite is low, the multipath signal would become higher. Moreover, the magnitude of the signal is proportional to the SNR.

## 5.2 Reduction of Multipath Effect

As discussed in section 5.1, for short baseline observation, the effects of most of the GPS errors such as ionoshperic delays, orbital errors and clock errors are very small compared to multipath effect. Consequently, GPS multipath effect has become a dominant error source for high precision applications and extensive researches have been conducted to reduce the effect.

The most basic method is to place the GPS antenna in a low-multipath environment, away from any potential reflectors. Alternatively we can eliminate reflection from ground surface in GPS surveying by placing the receiver antenna on the ground instead of a tripod. Obviously, antenna relocation may not be practical in some cases, but it can be effective when feasible.

Tranquilla et al. (1994) suggested that equipping the antenna with a groundplane or a chokering. The groundplane could shield the antenna from any signals arriving from below the antenna, such as those reflecting from the ground. On the contrast, Weill (1997) argued that this scheme did not perform as well as expected because of a quirky characteristic of electromagnetic waves. When a signal wavefront arrived at the disk's edge from below, it induced horizontally traveling surface waves on the disk's top side, which then traveled to the antenna, thus compromising the disk's usefulness. The chokering, which contained a series of concentric circular troughs with one-quarter wavelength deep, was developed to eliminate surface waves and could replace groundplane. However, Weill (1997) further commented that the main drawback of the chokering was the circular troughs drive up its size, weight and cost. Most importantly, the chokering still could not effectively mitigate multipath signals arriving from above the horizontal, as might be experienced from a reflection off a tall building.

Another approach was to use improved receiver hardware to counter multipath effect. Townsend et al. (1995) developed the Multipath Estimating Delay Lock Loop or MEDLL to reduce the effect of multipath error. The MEDLL could estimates both line-of sight and multipath signal parameters, thereby reducing the influence of the multipath signals on the code and carrier estimates of the line-of-sight signal. The results showed that the MEDLL receiver reduced the effects of multipath by up to 90 % over a standard

NovAtel narrow-correlator receiver. Garin and Rousseau (1997) used the advanced technique of Enhanced Strobe Correlation™ to provide C/A carrier phase multipath rejection and even better C/A code rejection. This method led to better raw measurements in a real multipath environment and result in better performance in RTCM mode, with better 3D RMS errors.

Evans and Hermann (1990) reported that for initial research and development phase of GPS, a number of antennas were intentionally designed to have high gain at low elevation angles. The intended purpose of their design was to receive signals from satellites close to the horizon. However, multipath effect was easier to occur under their design. The reason was the reflected signals were more likely to interfere with the direct signal from the satellites. Therefore, they designed an antenna with low gain at low elevation angles to reduce multipath effect. Day-to-day repeated tests were carried out to confirm their assumption.

Some literatures had employed data processing techniques to solve the problem. Moelker (1997) proposed two new GNSS multipath direction finding algorithms to reduce multipath. The first one extended the MEDLL and the second one used Multiple Signal Classification (MUSIC). The feasibility of both techniques was demonstrated by measurements, which indicated an achievable direction estimation error of 4.9 degrees for the MEDLL-extension and 1.5 degrees for MUSIC. Ray et al. (1998) investigated the spatial correlation of the multipath error between multiple closely-spaced antennas to extract direct carrier phase from the multipath-corrupted carrier phase measurement. This technique estimated the parameters of the composite multipath signal and removed the error due to all multipath signals. It could be useful for reference stations, which transmitted carrier phase data for kinematic positioning application.

An alternative approach was given in (Raquet, 1996) which used multiple fixed receivers at known coordinates to estimate and reduce multipath for each code or carrier phase measurement at each receiver, using a network adjustment methodology. Then main strength of this method was that it used double differencing from receivers in very close proximity to each other, so all correlated errors (including multipath errors) were significantly reduced.

Multipath mitigation using the SNR is explored by Axelrad et al. (1994). He utilized the SNR and known antenna gain pattern to create a multipath correction profile. Therefore, a new correction profile was generated for each data set, eliminating the requirement that the environment remain unchanged. The effectiveness on real data was demonstrated with controlled static experiments, where the correction technique reduced multipath errors from 7.3 to 5.6 millimeters. Hartinger and Brunner (1998) suggested the original SNR data should be preserved in the RINEX conversion, and the SNR values should be used in the processing of the GPS data. Lawrence et al (1999) described an algorithm by using SNR to mitigate specular multipath as well as interference in GPS differential carrier phase measurement. Sleewaegen (1997) described in detail the relationship between multipath and SNR. Three important aspects of the SNR error were analyzed in function of the multipath delay, the signal-to-multipath ratio and the correlator spaceing: its envelope, its mean and its standard deviation.

*Formation of Multipath effect on slope surface*

According to Hofmann-Wellenhof, 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 interference with the indirect signal from the receiver surface can express as below:

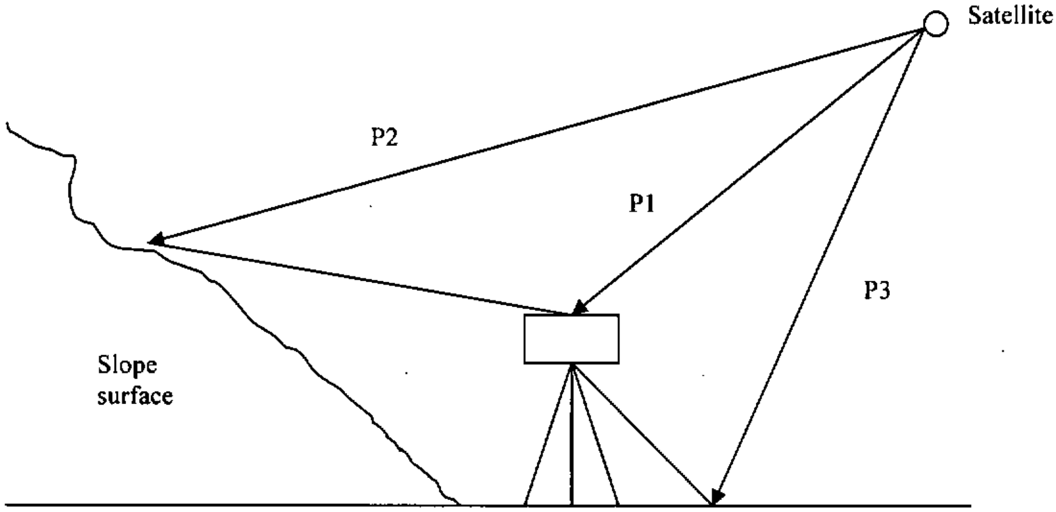



**Figure 5.2 Formation of multipath effect on slope surface**

$$P1 = a\cos\varphi$$

$$P2 = \beta\cos(\varphi + d\varphi) \qquad (5.2)$$

Where P1 denotes the direct signal from satellite, P2 denotes the indirect signal from the slope surface, $a$ and $\varphi$ are the amplitude and the phase of direct signal respectively. $\beta$ is the reduction factor and $d\varphi$ is the phase shift of the non-direct signal. The combined signals is represented by

$$P = P1 + P2 = a^d\cos(\varphi+\gamma) \qquad (5.3)$$

where the combined signal amplitude $a^d$ is

$$a^d = a(1+2\beta\cos\varphi + \beta^2)^{1/2} \tag{5.4}$$

and the carrier phase multipath delay $\gamma$ is

$$\gamma = \tan^{-1}\left[\frac{\beta\sin\varphi}{1+\beta\cos\varphi}\right] \tag{5.5}$$

$$\varphi = \frac{2h}{\lambda}\sin \mathrm{E} \tag{5.6}$$

where E is the elevation angle of the satellite, $\lambda$ 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

$$Ps_{multi} = \frac{\gamma}{2\pi}\lambda = \frac{\lambda}{2\pi}\tan^{-1}\left[\frac{\beta\sin\varphi}{1+\beta\cos\varphi}\right] \tag{5.7}$$

The maximum effect of multipath on phase measurements occurs when $\gamma = 90^0 = 1/4$ cycle. Thus, the maximum error in L1 signal ($\lambda$=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

$$\begin{aligned} \mathrm{P}_c &= \mathrm{P}_1 + \mathrm{P}_2 + \mathrm{P}_3 + \cdots + \mathrm{P}_n \\ &= \mathrm{P} + \mathrm{P}^d = a_c\cos\left(\varphi + \gamma + \gamma^d\right) \end{aligned} \tag{5.8}$$

$$\mathrm{P} = \mathrm{P}_1 + \mathrm{P}_2 = a^d\cos(\varphi + \gamma) \tag{5.9}$$

(5.10)

where

$$\mathrm{P}^d = \mathrm{P}_3 + \cdots + \mathrm{P}_n = \beta^d a^d\cos\left(\varphi + \gamma + \gamma^d\right) \tag{5.11}$$

Applying the same principle of equations (5.2) and (5.3), the combined signal amplitude is

$$a_c = a^d(1+2\beta^d\cos\varphi + \beta^{d2})^{1/2} \tag{5.12}$$

and the carrier phase multipath delay $\gamma^d$ caused by $P_3 + \ldots P_n$ is

$$\gamma^d = \tan^{-1}\left[\frac{\beta^d \sin\varphi^d}{1+\beta^d\cos\varphi^d}\right] \tag{5.13}$$

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

$$P_{multi} = \frac{\gamma + \gamma^d}{2\pi}\lambda \tag{5.14}$$

where $P_3 + \ldots P_n$ 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.

If we compare 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 (5.14), 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

$$P^d{}_{multi} = \frac{\gamma^d}{2\pi}\lambda \tag{5.15}$$

Therefore, subtracting equation (5.15) from equation (5.14), the multipath effect caused by the slope surface can be found out

$$Ps_{multi} = \frac{\gamma}{2\pi}\lambda \tag{5.16}$$

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 this chapter, experiments will conduct 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 estimate the effect on GPS survey.

## 5.3 Multipath Experiment

Experiments were carried out to analyze the multipath effect in monitoring survey. The objectives of the experiments were to investigate the following factors:

a. The magnitude of the multipath effect on coordinates computations.

b. The effect of multipath on displacement measurements.

c. The magnitude of the multipath effect on observation 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 session and were mounted on before next observation session. More than three hours observations were taken for each experiment. The experiments lasted 9 days, however only 6 days were recorded due to poor weather condition. The results of the experiments were listed in table 5.2.

| **Experiment No.** | **Date** | **Location** | **Observation Period (pm)** | **Type** |
|---|---|---|---|---|
| 1 | 12/1/2000 | C-D cores roof | 2:33 - 7:42 | No special reflector was placed (static mode - 30 min) |
| 2 | 13/1/2000 | C-D cores roof | 2:29 - 6:01 | Special reflector was placed (static mode - 30 min) |
| 3 | 14/1/2000 | C-D cores roof | 2:18 - 8:07 | Special reflector was placed (static mode - 1 hr 30 min) |
| 4 | 15/1/2000 | C-D cores roof | 2:14 - 8:03 | No special reflector was placed (static mode - 1 hr 30 min) |
| 5 | 17/1/2000 | C-D cores roof | 4:19 - 5:38 | No special reflector was placed (a pole was located in a tripod) |
| 6 | 19/1/2000 | C-D cores roof | 4:11 - 5:33 | Special reflector was placed (a pole was located in a tripod) |

**Table 5.2 The experiment result for analyzing the multipath effect**

In order to examine the effect of multipath caused by a slope surface, two observation conditions were used. The first one was the normal observation condition, that meant, no special reflected surface was placed. The other was the condition that a special reflected surface was established. We selected a large digitizer as the reflected surface (See figure 5.3) and place it near the receiver antenna. To ensure the signal from satellite could reflect from 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.

**Figure 5.3 Experiment set up at the roof top of the HKPU**

In order to compare the change caused by multipath, we used the same satellite geometry of two successive days. For instance, if we want to determine the multipath change between 12 January (exp. 1) and 13 January (exp.2), we 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). In order to compare the multipath effect on coordinates in the two observation conditions, the day time difference of each satellite was considered respectively and the generally the mean value 240 s was adopted.

The result of each experiment was discussed in the paragraph below.

***A. The magnitude of the multipath effect on coordinates computations***

Experiments 1 and 2 were used to investigate the effect of multipath on coordinate computations. In these two experiments, the receiver antenna occupied the rover station for five times respectively and approximately 30 min observations were taken in each time. The effects of multipath on coordinate computation were examined by comparing the coordinate difference in these two experiments.

Coordinate differences were computed between successive points as follows:

$$d = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2} \tag{5.17}$$

Where $d$ is the magnitude of coordinate differences, $x$, $y$, $z$ are coordinates in Conventional Terrestrial (CT) System.

As GPS accuracy in static mode is up to 1-2 mm, we could compare the coordinate differences between experiments 1 and 2 to estimate the magnitude of the multipath effect. Having examined the result, we concluded that for short observation time (30 min.), the magnitude of multipath on coordinate computation is about 8 mm (average value).

In experiment 3 and 4, we performed a KOF (Kinematic surveying on the fly (OTF)) mission individually. In these missions a very short occupation time (a single epoch - 1s) was used for baseline solution after the initial ambiguities were resolved by OTF technique. As the occupation time was very short, the averaging method would not remove multipath effect. Therefore, we can examine the effect by comparing the coordinates differences between these two experiments. The result is shown in figure 5.4:

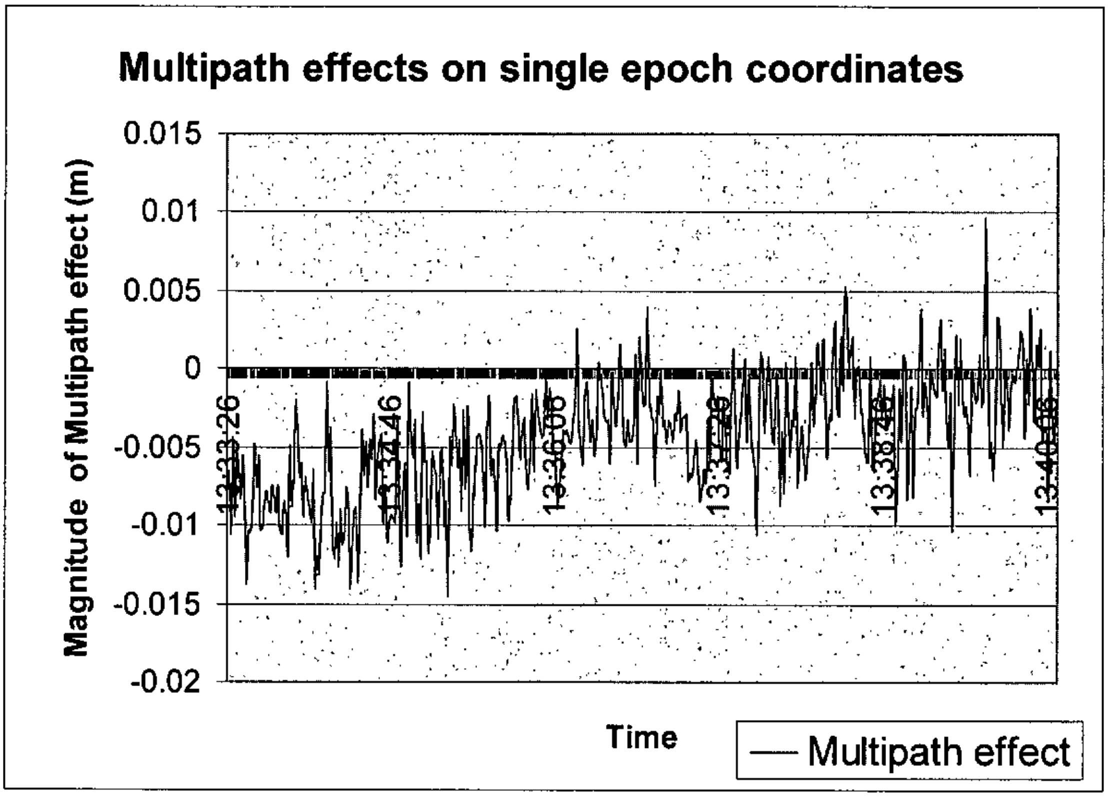



**Figure 5.4 Multipath effects on single epoch (1s) coordinates**

As seen from the above result, the multipath effect is fluctuating between -0.015m and 0.01m. The mean value of the effect is approximately -0.005m. This agreed with the above static observation result.

***B. The effect of multipath on measurement of displacements***

Additionally, in experiments 1 and 2, the horizontal position of the receiver antenna was moved to see whether GPS could detect small horizontal deformation. While in experiments 5 and 6, the vertical position of the receiver antenna was moved to see whether GPS could detect small vertical deformation. Details of these experiments were listed as follows:

a. Horizontal Movement - the position of the antenna was moved alone a well-marked precise ruler (See figure 5.5). It was moved by 5mm, 1cm, 3cm and 5cm in the two observation conditions. The reason of doing these was to determine the effect of multipath on GPS accuracy both in low and high multipath environment. The designed procedure for this experiment was listed in figure 5.6 below:

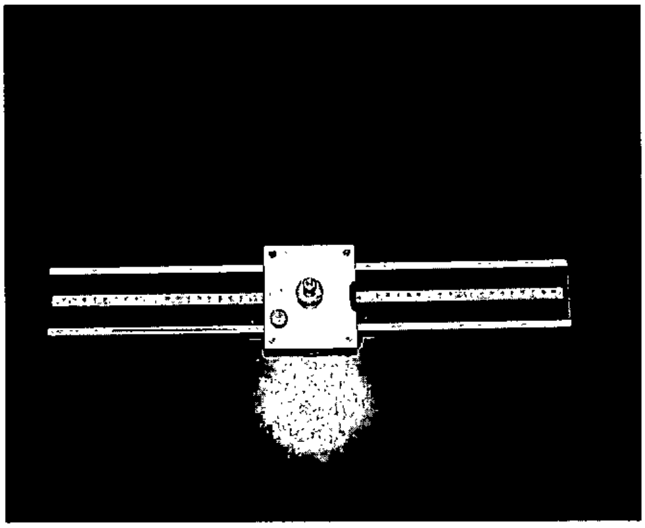


**Figure 5.5 A well-marked precise ruler**

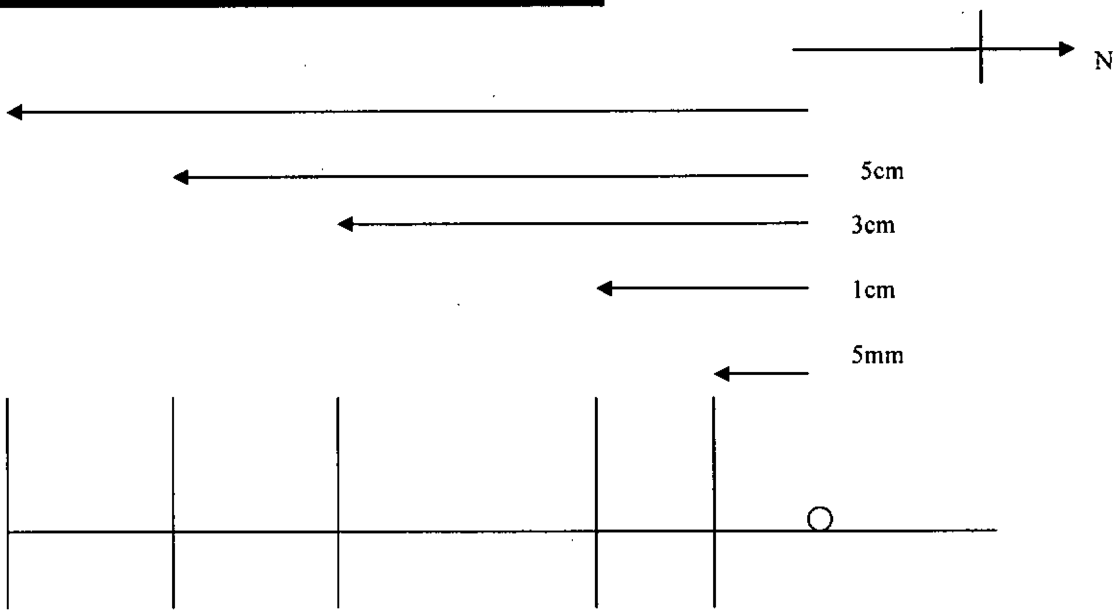


**Figure 5.6 Horizontal deformation experiment (not to scale)**

Displacements were computed using equation 5.17 by comparing the differences in GPS's coordinates. The survey results of experiment no. 1 on 12/1/2000 (no special reflector was placed) and experiment no. 2 on 13/12000 (a special reflector was placed) were summarized in tables 5.3 and 5.4. The computed coordinates' differences were compared with the movements of the well-marked precise ruler. The survey result concluded that under low multipath environment, the accuracy of the GPS on displacement was about 4mm. While under high multipath environment, the accuracy of GPS on displacement was about 9mm. That meant multipath effect reduced the accuracy of GPS displacement determination significantly.

**Table 5.3 The survey result of the experiment no. 1 on 12/1/2000**

| **Terminal** | **Experiment 1 – 12/1/2000** | | | **Displacements Value in (mm)** | | |
|---|---|---|---|---|---|---|
| **Session** | **Coordinate Value in Conventional Terrestrial (CT) System** | | | | | |
| Coordinates | X | Y | Z | Computed by using GPS coordinates | Movements of the well-marked precise ruler | Differences |
| 1 st. session (initial value) | *02.6784 | *10.3126 | *92.6425 | 0 | 0 | 0 |
| 2 nd. session | *02.6795 | *10.3157 | *92.6387 | 3.3 | 5 | 1.7 |
| 3 rd session | *02.6801 | *10.3185 | *92.6345 | 6.1 | 10 | 3.9 |
| 4 th session | *02.6634 | *10.2926 | *92.6138 | 25.0 | 30 | 5 |
| 5 th session | *02.6554 | *10.2736 | *92.5969 | 45.3 | 50 | 4.7 |

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

**Table 5.4 The survey result of the experiment no. 2 on 13/1/2000**

| **Terminal** | **Experiment 2 – 13/1/2000** | | | **Displacements Value in (mm)** | | |
|---|---|---|---|---|---|---|
| **Session** | **Coordinate Value in Conventional Terrestrial (CT) System** | | | | | |
| Coordinates | X | Y | Z | Computed by using GPS coordinates | Movements of the well-marked precise ruler | Differences |
| 1 st. session (initial value) | *02.6796 | *10.3192 | *92.6428 | 0 | 0 | 0 |
| 2 nd. session | *02.6836 | *10.3282 | *92.6410 | 9.8 | 5 | -4.8 |
| 3 rd session | *02.6906 | *10.3362 | *92.6370 | 20.2 | 10 | -19.2 |
| 4 th session | *02.7046 | *10.3502 | *92.6382 | 39.8 | 30 | -9.8 |
| 5 th session | *02.7176 | *10.3662 | *92.6412 | 60.4 | 50 | -10.4 |

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

b. Vertical Movement - in experiments 5 and 6, the vertical positions of the receiver antenna were moved to see whether GPS could detect small vertical deformation. Another rover station was established and a prism rod was used to fix the horizontal position of this rover. (See figure 5.7) Vertical movement was then performed by changing the rod height. Rather than using the other prism rod, the rod designed by the without hands; therefore this can avoid random error generated by the rod holder. The amount of vertical movement were then referenced to the readings on the rod.

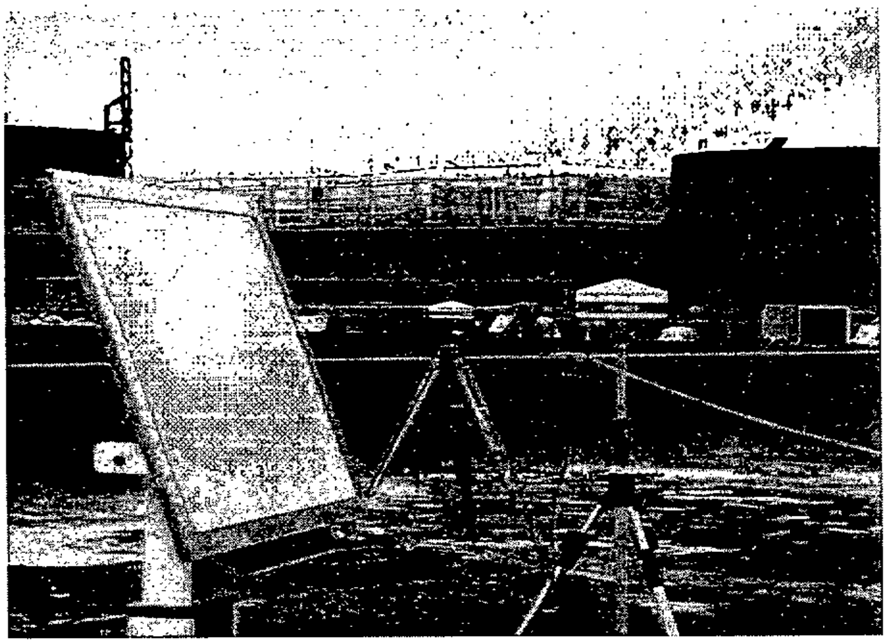


**Figure 5.7 The horizontal position of the rover was fixed by a prism rod**

**Table 5.5 Experiment no. 5 - 17/1/2000 (no special reflector was placed)**

| Point ID | Elli Height | Time |
|---|---|---|
| er21612 | 40.6297 | 16:19 |
| er1612a | 40.6362 | 17:06 |
| er1612b | 40.6342 | 17:38 |

**Table 5.6 Experiment no.6 - 19/1/2000 (a special reflector was placed)**

| Point ID | Elli Height | Time |
|---|---|---|
| er19120 | 40.6258 | 16:11 |
| er1912a | 40.6328 | 16:58 |
| er1912c | 40.6383 | 17:33 |

**Table 5.7 Vertical deformation result - 17/1/2000**

| Height Interval | Vert. Dis. | True Value | Deviation | Time |
|---|---|---|---|---|
| er21612- er1612a | 0.65 cm | 1 cm | 0.35 cm | 16:19 |
| er1612a - er1612b | 0.2 cm | 2 cm | 1.8 cm | 17:06 |

**Table 5.8 Vertical deformation result -19/1/2000**

| Height Interval | Vert. Dis. | True Value | Deviation | Time |
|---|---|---|---|---|
| er19120 - er1912a | 0.7 cm | 1 cm | 0.3 cm | 16:11 |
| er1912a - er1912c | 0.58 cm | 2 cm | 1.42 cm | 16:58 |

where Ell. Height is the elliptical height and Vert. Dis. is the vertical displacement. As seen from the results, the accuracy of GPS on vertical displacement is nearly the same in both low multipath environment (experiment 5) and high multipath environment (experiment 6).

c. The magnitude of the multipath effect on observation residuals - apart from comparing the coordinate differences, the observation residuals of L1 and L2 signals were also compared to examine the multipath effect. To obtain a reliable result, the same satellite geometry must be used. As mentioned before, 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. Based on a four-day experiment, they computed the periods for different satellites. In our experiment, the only two satellites (PRN 3 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 multipath effect caused by the special reflector. These two satellites were listed in table 5.9.

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

**Table 5.9 Sidereal day time difference of satellites**

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

$$Ps_{multi} = \frac{\gamma}{2\pi}\lambda = DL(t) = V_{15} - V_{14}(t + n\alpha) \tag{5.18}$$

where $DL(t)$ was the differences of observation residuals, $V_{15}$ denoted the observation residuals of 15 January in experiment 4, $V_{14}$ denoted the observation residuals of 14 January in experiment 3 and $\alpha$ was the sidereal day time difference.

The results of these experiments were shown in the following figures:

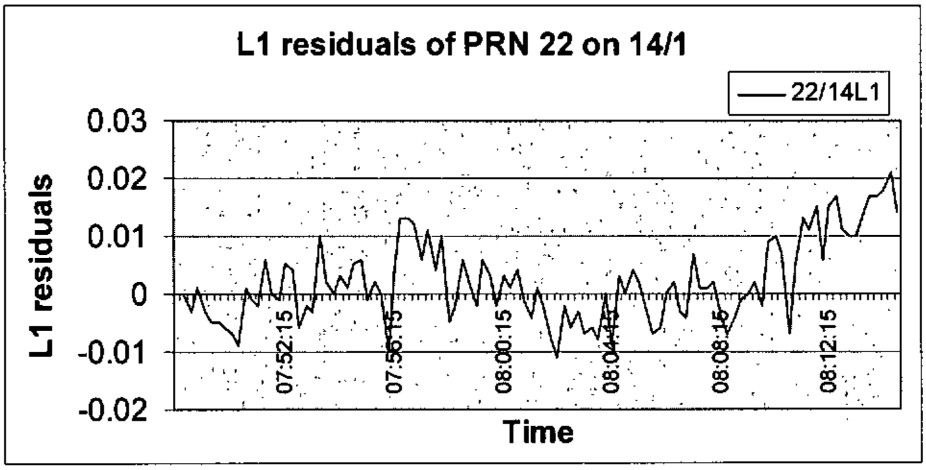



**Figure 5.8 The L1 residuals of PRN 22 on 14/1 (special reflector)**

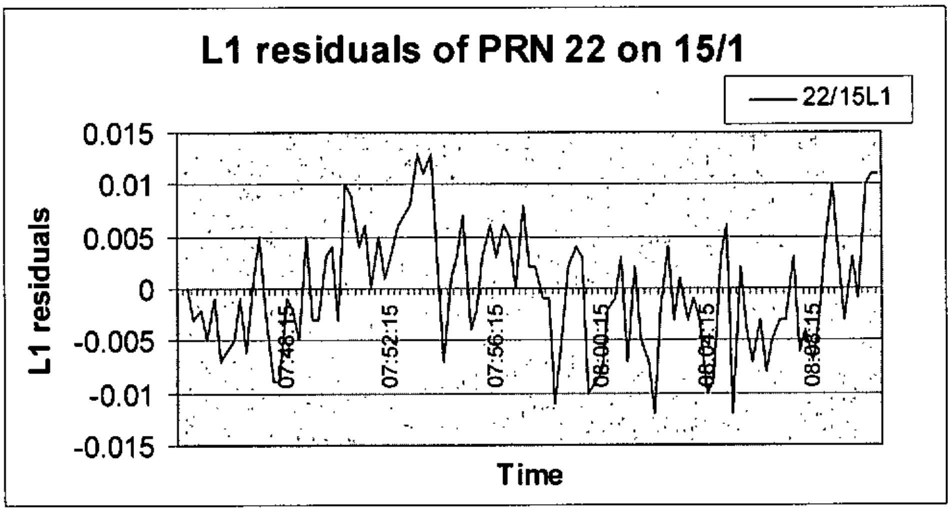



**Figure 5.9 The L1 residuals of PRN 22 on 15/1 (no special reflector)**

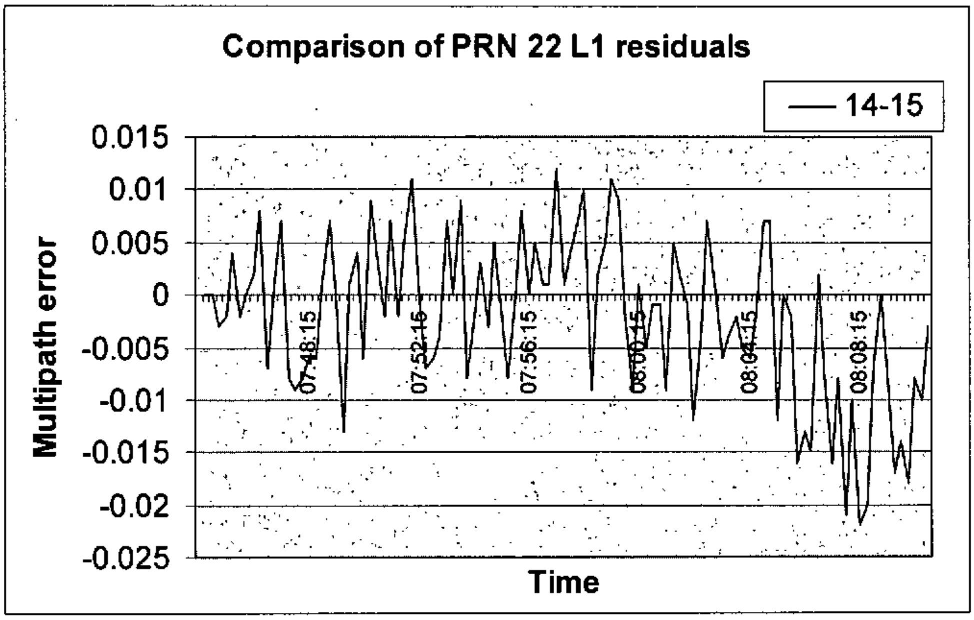



**Figure 5.10 Comparison of L1 residuals of PRN 22 between 14/1/2000 and 15/1/2000**

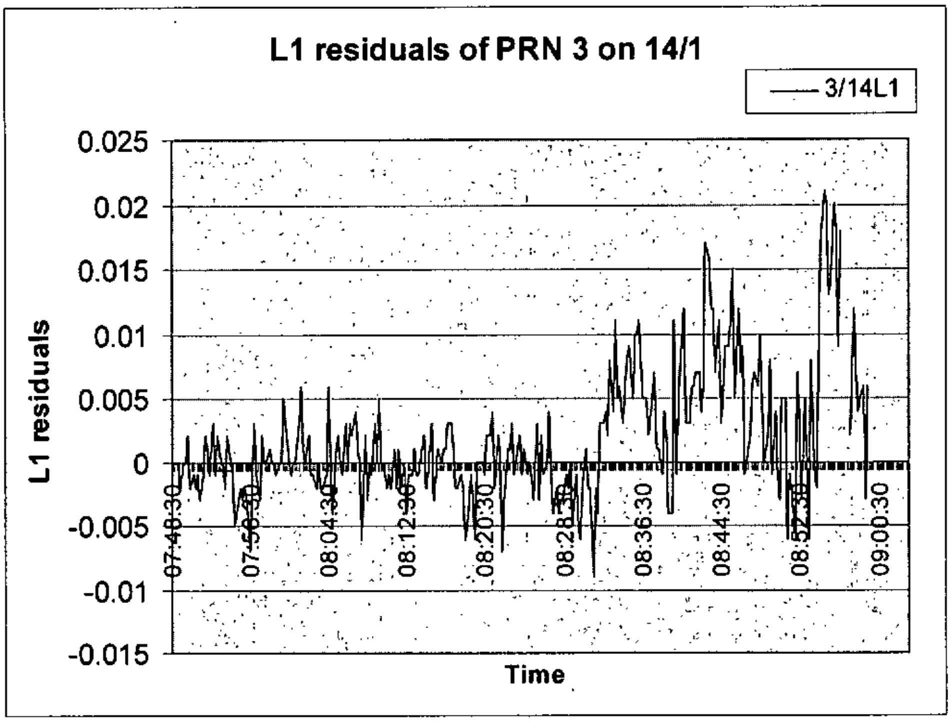



**Figure 5.11 The L1 residuals of PRN 3 on 14/1 (special reflector)**

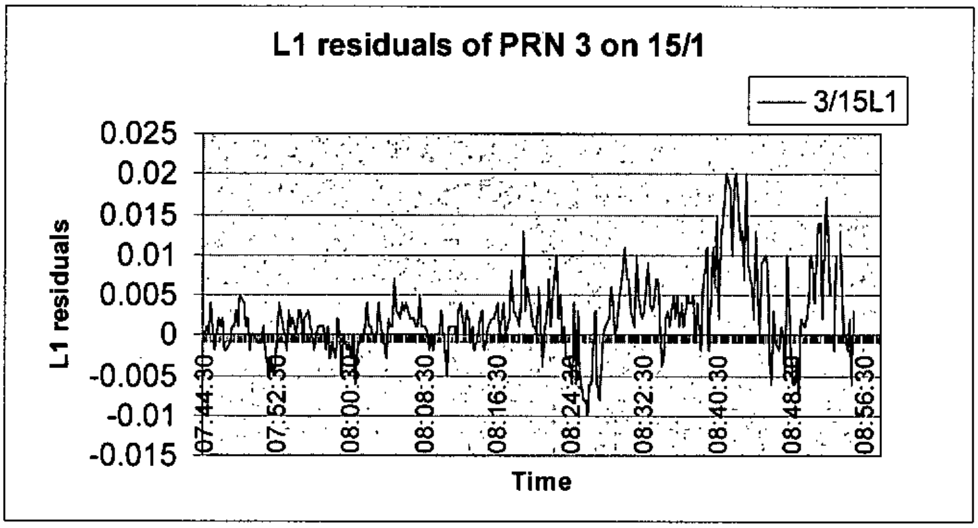



**Figure 5.12 The L1 residuals of PRN 3 on 15/1 (no special reflector)**

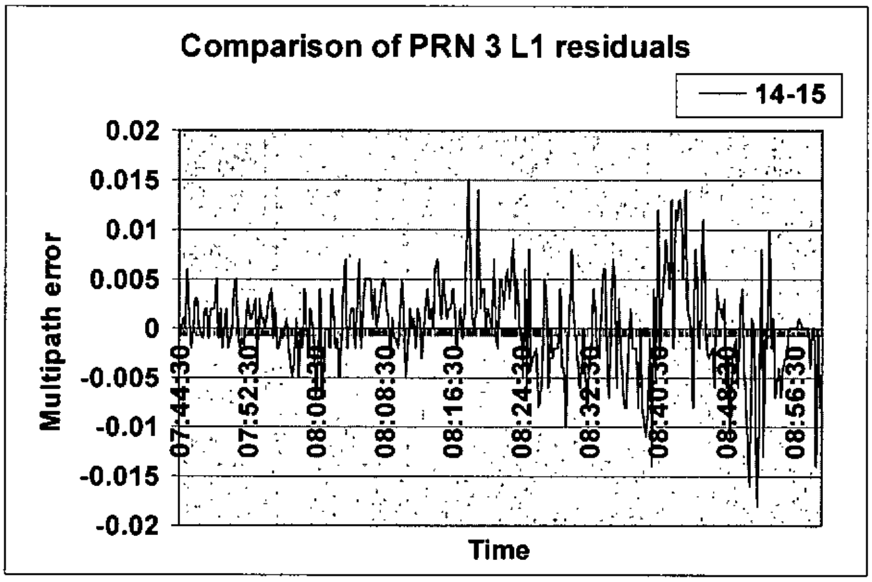



**Figure 5.13 Comparison of L1 residuals of PRN 3 between 14/1/2000 and 15/1/2000**

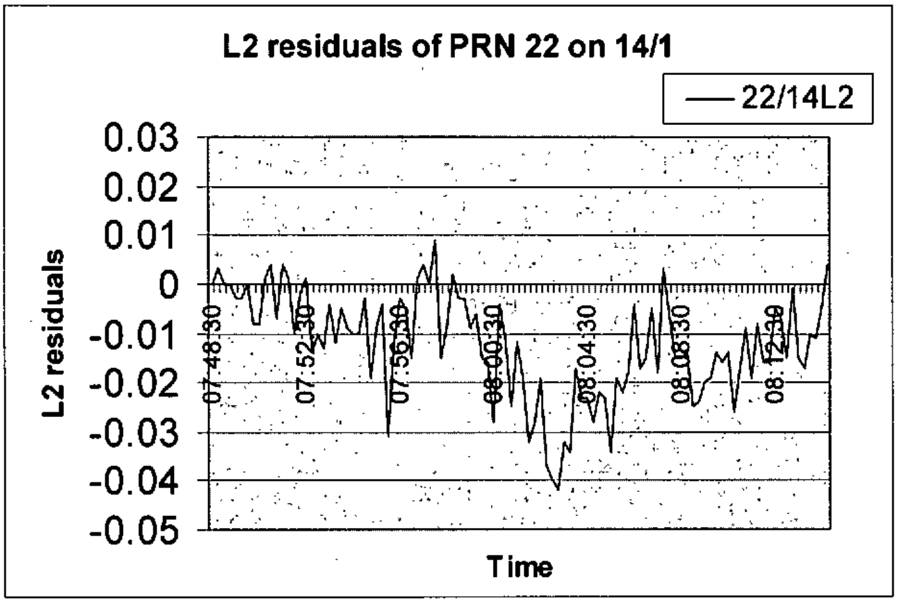



**Figure 5.14 The L2 residuals of PRN 22 on 14/1 (special reflector)**

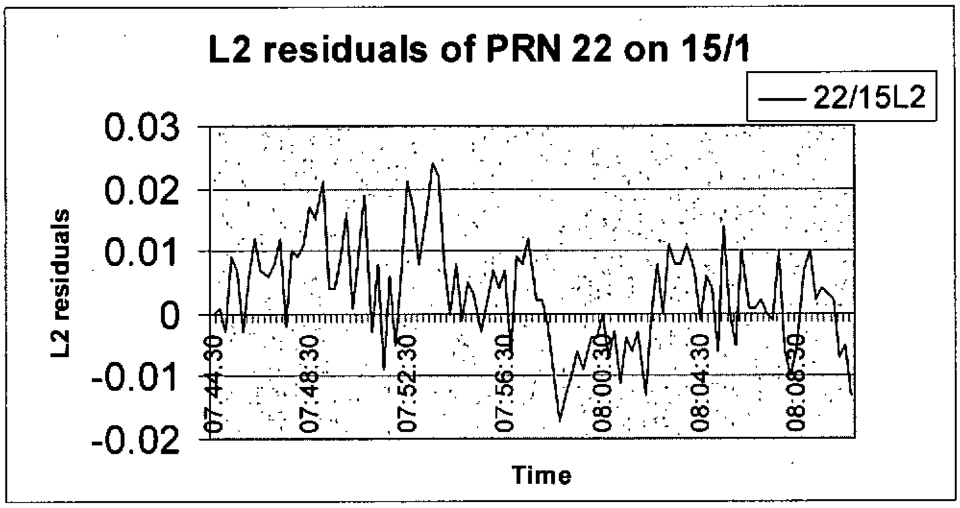



**Figure 5.15 The L2 residuals of PRN 22 on 15/1 (no special reflector)**

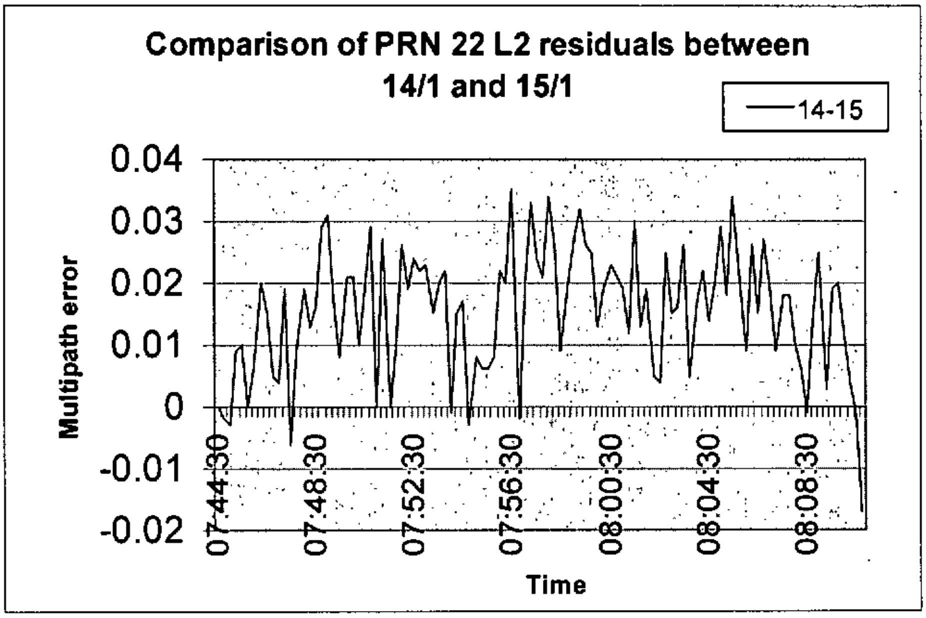



Figure 5.16 Comparison of L2 residuals of PRN 3 between 14/1/2000 and 15/1/2000

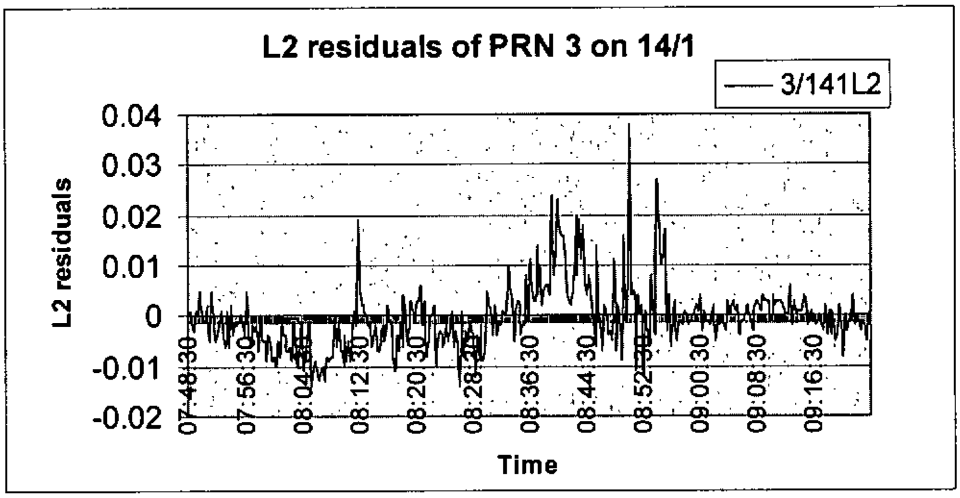



Figure 5.17 The L2 residuals of PRN 3 on 14/1 (special reflector)

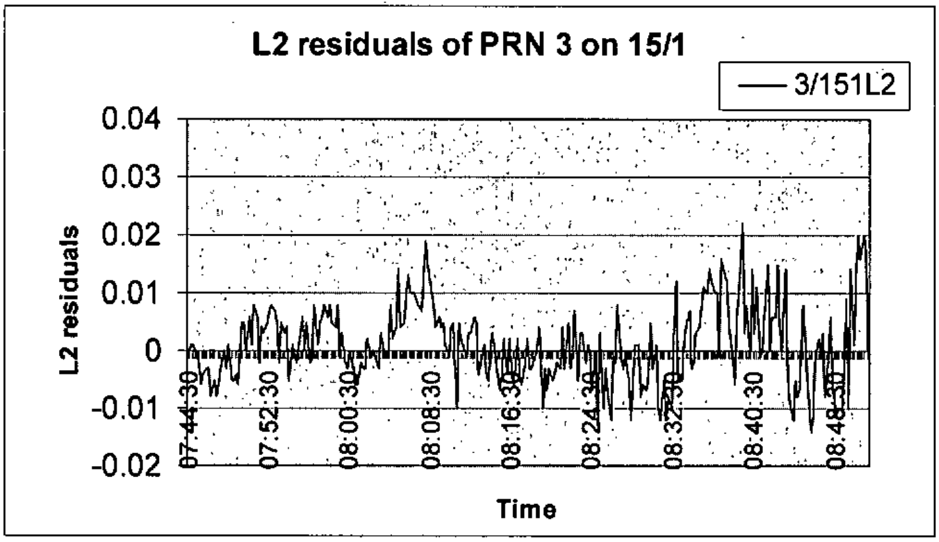



**Figure 5.18 The L2 residuals of PRN 3 on 15/1 (no special reflector)**

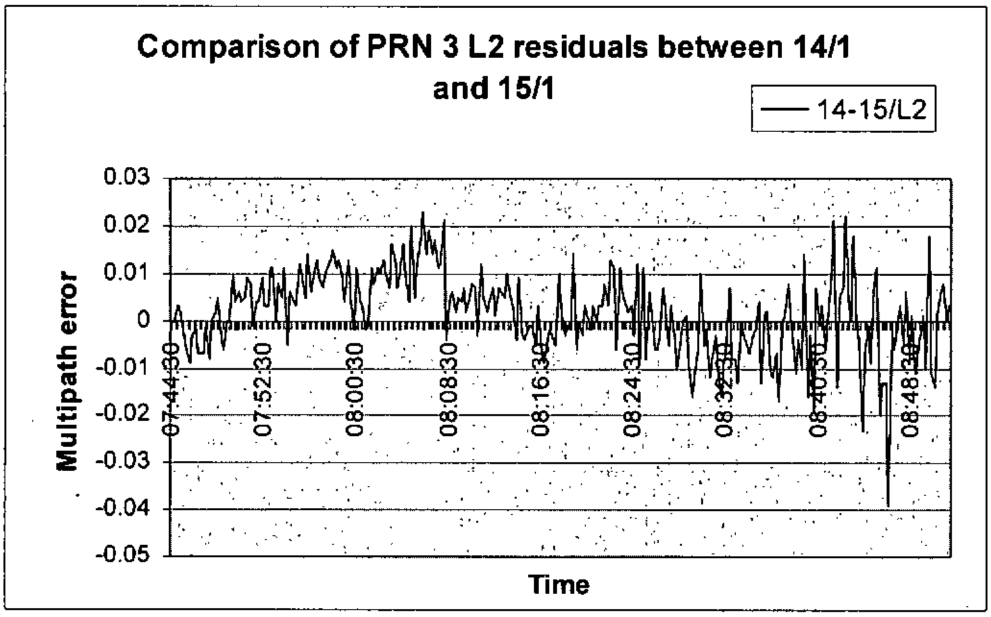



**Figure 5.19 Comparison of L2 residuals of PRN 3 between 14/1/2000 and 15/1/2000**

These figures illustrated the effect of multipath on observation residuals and the magnitude of the effect could be estimated in the differences of residuals. We here took figures 5.8, 5.9 and 5.10 as examples to demonstrate the results. As mentioned before, in these tests, the major source of error contained in observation residuals was multipath effect and observation noise. Consequently, the fluctuation of the observation residuals would reflect the changing of the multipath effect. By comparing figure 5.8 with figure 5.9, we could see that as a result of multipath effect caused by the special reflector, L1 residuals of PRN 22 on 14/1 had larger fluctuation than that on 15/1. Furthermore, the peak value of the residuals on 14/1 was 0.022 m while that on 15/1 was only 0.015 m. This resulted from the larger influence of multipath effect on 14/1 than 15/1. According to equation 5.18, we could also estimate the magnitude of multipath effect by comparing the differences of the L1 residuals between the two days. Figure 5.10 illustrated the changing of the effect with time and we could use it as estimation of the effect. In addition, the roof mean square values of the L1 residuals of PRN 22 on 14/1 (figure 5.8 where special reflector was placed) and that of the L1 residuals of PRN 22 on 15/1 (figure 5.9 where no special reflector was placed) were computed and they were 8 mm and 5 mm respectively. Examination of other figures indicated that the multipath effects did not show systematic errors except figure 5.16 where there might be a bias, but did generate larger fluctuations in the time series of the residuals. As mentioned, multipath effect had the characteristics of daily repeatability. This characteristic could be used in slope monitoring surveys to identify if significant multipath effect existed for a particular monitored point. This could be done by correlating the time series of the derived coordinates of a point or of the residuals to a satellite for two consecutive days. If the significant multipath effect did exist, we had to modify the antenna setup to minimize the effect, or to determine the location of reflecting object for the purpose of correction. Alternatively, multipath effects, when averaged over a long enough time, would be considerably reduced, this method was applicable for a slope with very slow movement.

# CHAPTER 6

# CONCLUSION AND RECOMMENDATIONS

## 6.1 Summary of the Thesis

This thesis studied the feasibility of using the GPS multi-antenna system in slope or structure deformation monitoring. Advantages and disadvantages of conventional geotechnical and land surveying techniques of deformation monitoring were elaborated in Chapter 1. The application of GPS in deformation monitoring and the objectives of this research were also discussed in the same chapter.

Chapter 2 introduced the implementation of the GPS multi-antenna system. The software and hardware components of the system were reviewed.

Three main areas of the GPS multi-antenna system were evaluated in Chapters 3, 4 and 5, namely the application algorithms and software, system configuration design and the study of GPS multipath effect in slope monitoring. In Chapter 3, two software programs were specifically developed by the author to enhance the application of the system. One was the automatic alarming system, which was capable to check and verify the GPS monitoring data collected from the GPS multi-antenna system. And, the other was the automatic data extraction program which was used to subdivide the single GPS rinex data file into different data files in accordance to the predefined time intervals and the occurrences of the cycle spilt effect. Different methods of data transmission from the antenna to the receiver by using long cable with signal amplifier were studied in Chapter 4. Experiments in Hong Kong and Nanjing were conducted to evaluate the techniques engaged and to compare the operation cost of the system for enhancement. Results from different experiments in Hong Kong and Nanjing were summarized and analyzed in the same chapter. Furthermore, the characteristics of the GPS multipath effect were examined in Chapter 5 with an aim to estimate the effect on GPS survey.

## 6.2 Discussion and Conclusion

Attempts were made to improve the reliability and effectiveness of the GPS multi-antenna system in terms of the software, the hardware and the GPS multipath effect. Experiments reported in Chapter 4 demonstrated the noticeable improvement in the overall performances of the GPS multi-antenna system. The automatic alarm system was set up to provide real-time monitoring and to alert the relevant control centre so that any potential tragedies could be prevented. To facilitate the application of the GPS multi-antenna system in large area monitoring survey, the alarm system was designed to support the operation of 16 antennas in any monitoring network simultaneously. While the automatic data extraction program was specifically developed to subdivide the single GPS rinex file containing the data collected from the GPS multi-antenna system into different data files. This program would facilitate the data computation process of the system. Furthermore, a relatively low cost data transmission method by connecting a 200m long cable with a low noise 40 dB GPS signal amplifier was introduced. The approximate cost of the improved long cable set up in Nanjing was only $8000 which was relatively economical compared with the high-ended products, costing $20,600, currently used in Hong Kong.

Experiment in the Ho Hai University in Nanjing demonstrated the effectiveness of the set up in conjunction with the GPS multi-antenna system. Finally, the GPS multipath effect caused by slope surface reflection and its day-to-day repeatability were examined for the estimate of the magnitude of the effect.

In conclusion, the enhanced GPS multi-antenna system can provide fast and precise checking and warning functions for the users. It also facilitates the data computation process of the GPS data. Moreover, the enhanced system reduces the cost of GPS hardware in comparison with the standard GPS systems used for monitoring landslides and structure deformation, which broadens the application of GPS multi-antenna system in other types of engineering surveying.

## 6.3 Limitation of the Project

There are merits and drawbacks of the GPS multi-antenna system in monitoring slope or structure deformation. The system provides accurate information on point positions in a global reference framework that is not affected by the local deformation. Besides, the system assists in reducing the hardware cost sharply. In addition, the system operates 24 hours a day, 7 days a week under any weather conditions. With the implementation of the enhanced GPS multi-antenna system, it becomes fully automatic, highly reliable and cost-effective.

However, it is noted that the GPS multi-antenna system also has its limitation. The primary one is that the hardware components of the system are bulky and heavy in weight, especially with long cable. This will limit the use of the system in remote or inaccessible areas. Nevertheless, it is more suitable to set up the system on site for long term monitoring survey.

## 6.4 Recommendations

In view of the above shortcomings, two aspects are suggested to further improve the enhanced GPS multi-antenna system. The first one is to alleviate the transportation problem due to the heavy weight of the long cable. It is anticipated that a lower weight long cable which is manufactured in Nanjing is proposed but the cost should be limited to less than $6000 to maintain the competitiveness of the system. The heavy weight will then be reduced and the application of the system will become more feasible.

The second one is to enhance the system in real time application. The observation epoch will then be set as 1 second in order to detect the instant movement of features. On the contrast, time delay in the system may create errors in identifying the true movement. In view of this problem, a time model should be developed for modeling the continuous deformation movement.

# Appendix I

# GPS Processing Report of Nanjing Experiment

# Adjusted Vectors

Session1

**Vector Stage:** Adjusted **Date:** 03/05/03
**Horizontal Coordinate System:** World Geodetic Sys. 1984 **Project file:** Session1.spr
**Height System:** Ellips. Ht.
**Linear Units of Measure:** Meters

| Vector Identifier | Test | Vector Length | Radial Resid. | | Vector Components | Tau Resid. |
|---|---|---|---|---|---|---|
| 1 **BA_1-R_11** | **3/03 6:04** | 27.197 | 0.000 | X | 25.674 | 0.000 |
| | | | | Y | 7.970 | 0.000 |
| | | | | Z | -4.120 | 0.000 |
| 2 **BA_1-R_12** | **3/03 6:40** | 27.191 | 0.000 | X | 25.667 | 0.000 |
| | | | | Y | 7.976 | 0.000 |
| | | | | Z | -4.118 | 0.000 |
| 3 **BA_1-R_13** | **3/03 7:16** | 27.194 | 0.000 | X | 25.669 | 0.000 |
| | | | | Y | 7.979 | 0.000 |
| | | | | Z | -4.117 | 0.000 |
| 4 **BA_1-R_14** | **3/03 7:52** | 27.191 | 0.000 | X | 25.668 | 0.000 |
| | | | | Y | 7.969 | 0.000 |
| | | | | Z | -4.122 | 0.000 |

# Site Positions

**Session1**

**Horizontal Coordinate System:** World Geodetic Sys. 1984 **Date:** 03/05/03
**Height System:** Ellips. Ht. **Project file:** Session1.spr
**Desired Horizontal Accuracy:** 0.020m + 1ppm
**Desired Vertical Accuracy:** 0.040m + 2ppm
**Confidence Level:** 95% Err.
**Linear Units of Measure:** Meters

| Site ID | Site Descriptor | Position | | 95% Error | Fix Status | Position Status |
|---|---|---|---|---|---|---|
| 1 BA_1 | | Lat. | 32° 03′ 34.85422″ N | 0.000 | Fixed | Adjusted |
| | | Lon. | 118° 45′ 11.33770″ E | 0.000 | Fixed | |
| | | Elv. | 82.549 | 0.000 | Fixed | |
| 2 R_11 | | Lat. | 32° 03′ 34.83328″ N | 0.002 | | Adjusted |
| | | Lon. | 118° 45′ 10.33348″ E | 0.002 | | |
| | | Elv. | 75.817 | 0.005 | | |
| 3 R_12 | | Lat. | 32° 03′ 34.83319″ N | 0.002 | | Adjusted |
| | | Lon. | 118° 45′ 10.33361″ E | 0.002 | | |
| | | Elv. | 75.826 | 0.004 | | |
| 4 R_13 | | Lat. | 32° 03′ 34.83318″ N | 0.002 | | Adjusted |
| | | Lon. | 118° 45′ 10.33346″ E | 0.002 | | |
| | | Elv. | 75.827 | 0.004 | | |
| 5 R_14 | | Lat. | 32° 03′ 34.83318″ N | 0.002 | | Adjusted |
| | | Lon. | 118° 45′ 10.33370″ E | 0.002 | | |
| | | Elv. | 75.817 | 0.004 | | |

| | Site ID | Site Descriptor | Elevation Factor |
|---|---|---|---|
| 1 | BA_1 | | 0.99998704 |
| 2 | R_11 | | 0.99998810 |
| 3 | R_12 | | 0.99998809 |
| 4 | R_13 | | 0.99998809 |
| 5 | R_14 | | 0.99998810 |

Number of vectors processed: 4 of 4.
Performing adjustment . . .

**FILLNET - Ashtech Network Adjustment Package**



2003年03月05日 10:46:40

**Network connectivity test:** passed
Number of sites: 5
Number of vectors: 4

**Adjustment type: Minimally constrained**

| Control sites | Constraints |
|---|---|
| BA_1 | Latitude Longitude Elevation |

**Adjustment Tests**

Confidence level: 95.0%
Number of
obs. equations 16
unknowns 16
degrees of freedom 0
Chi-square test: failed
Lower limit: 1.000000
Upper limit: 1.000000
Chi-square: 0.000000
Variance of Unit Weight: 1.000000
Standard Error of Unit Weight: 1.000000
Critical value for Tau-test: 0.000000
Scale factor for a-priori vector sigmas: 1.00

**Reference Ellipsoid Parameters**

Equatorial radius (semi-major axis): 6378137.000
Reciprocal of flattening: 298.257224000

**Adjusted Datum Bias Parameters**

*Bias Parameters In Geocentric Cartesian System*

| Rotation angle (seconds) | Value | Sigma |
|---|---|---|
| X | 0.000 | fixed |
| Y | -0.000 | fixed |
| Z | 0.000 | fixed |
| Scale correction (ppm) | 0.000 | fixed |

*Bias Parameters In Mapping Plane Horizontal System*

| Rotation angle (seconds) | Value | Sigma |
|---|---|---|
| Northing | 0.000 | fixed |
| Easting | 0.000 | fixed |
| Height | 0.000 | fixed |
| Scale correction (ppm) | 0.000 | fixed |

```
Processing started.
Processing Summary:
Number of vectors processed: 4 of 4.
Possible blunder: IDs 'R_11' and 'R_12' have been used for the same site.
Possible blunder: IDs 'R_11' and 'R_13' have been used for the same site.
Possible blunder: IDs 'R_11' and 'R_14' have been used for the same site.
Possible blunder: IDs 'R_12' and 'R_13' have been used for the same site.
Possible blunder: IDs 'R_12' and 'R_14' have been used for the same site.
Possible blunder: IDs 'R_13' and 'R_14' have been used for the same site.
Performing adjustment . . .
```

**FILLNET - Ashtech Network Adjustment Package**



2003年03月05日 10:56:08

**Network connectivity test:** passed

Number of sites: 5

Number of vectors: 4

**Adjustment type: Minimally constrained**

| Control sites | Constraints |
|---|---|
| BA_1 | Latitude Longitude Elevation |

**Adjustment Tests**

Confidence level: 95.0%

Number of

obs. equations 16

unknowns 16

degrees of freedom 0

Chi-square test: failed

Lower limit: 1.000000

Upper limit: 1.000000

Chi-square: 0.000000

Variance of Unit Weight: 1.000000

Standard Error of Unit Weight: 1.000000

Critical value for Tau-test: 0.000000

Scale factor for a-priori vector sigmas: 1.00

**Reference Ellipsoid Parameters**

Equatorial radius (semi-major axis): 6378137.000

Reciprocal of flattening: 298.257224000

**Adjusted Datum Bias Parameters**

*Bias Parameters In Geocentric Cartesian System*

| Rotation angle (seconds) | Value | Sigma |
|---|---|---|
| X | 0.000 | fixed |
| Y | -0.000 | fixed |
| Z | 0.000 | fixed |
| Scale correction (ppm) | 0.000 | fixed |

*Bias Parameters In Mapping Plane Horizontal System*

| Rotation angle (seconds) | Value | Sigma |
|---|---|---|
| Northing | 0.000 | fixed |
| Easting | 0.000 | fixed |
| Height | 0.000 | fixed |
| Scale correction (ppm) | 0.000 | fixed |

# Appendix II

# GAA Setting Configuration File

**GAA Setting Configuration File:**

**Line1:** [*no of devices*]

**Line2:** [*Identifier Name*]|[*Data File Location*]|[*Initial Latitude*][*Lat.Direction*]|[*Longitude*]|[*Lng.Direction*]|[*Orthometric height*]|[*Orth.Height Units*]|[*Factor*][*Per Unit*]

**Line3:** [*Lng.Minus Alarm*]|[*Lng. Minus Alert*]|[*Lng. Minus Action*]|[*Lng. Plus Alarm*]|[*Lng. Plus Alert*]|[*Lng. Plus Action*]

**Line4** [*Lat.Minus Alarm*]|[*Lat. Minus Alert*]|[*Lat. Minus Action*]|[*Lat. Plus Alarm*]|[ *Lat. Plus Alert*]|[*Lat. Plus Action*]

**Line5** [*Height.Minus Alarm*]|[ *Height. Minus Alert*]|[ *Height. Minus Action*]|[ *Height. Plus Alarm*]|[ *Height. Plus Alert*]|[ *Height. Plus Action*]

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