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THE INTEGRATION OF GLOBAL POSITIONING SYSTEM (GPS) AND METEOROLOGICAL OBSERVATIONS FOR TROPOSPHERIC MODEL DEVELOPMENT IN MALAYSIAN REGION

(INTEGRASI SISTEM PENENTUDUKAN SEJAGAT (GPS) DAN CERAPAN METEOROLOGI BAGI PEMBANGUNAN MODEL TROPOSFERA DALAM WILAYAH MALAYSIA)

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TAJUK PROJEK : **THE INTEGRATION OF GLOBAL POSITIONING SYSTEM (GPS) AND METEOROLOGICAL OBSERVATIONS FOR TROPOSPHERIC MODEL DEVELOPMENT IN MALAYSIAN REGION**

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ABSTRACT

(keywords: Global Positioning System (GPS), troposphere, meteorological data)

The use of satellite based Global Positioning System (GPS) is normal in engineering and surveying for a wide range of applications as the accuracy capability increases. Global Positioning System (GPS) satellites provide precise all weather global navigation information to users equipped with GPS receivers on or near the earth's surface. The GPS satellites transmit signals that are received by the receivers on the earth's surface to determine the position. The effects of other different error sources on the computed position have to be removed from the data. The principal limiting error source is incorrect modeling of the delay experienced by GPS signal propagating through the electrically neutral atmosphere, usually referred to as the tropospheric delay.

The integration of ground based meteorological observations and GPS lead to a better understanding of the tropospheric delay to the GPS signal and improve the GPS height accuracy. The study conducted by integrating the Malaysian Active GPS Station (MASS) data and ground based meteorological observations to analyze the variation occur to the GPS height determination due to the tropospheric delay. The introduction of the Saastamoinen tropospheric model to the data shows a delay variation for up to 20 meter in pseudorange which causes an error up to 5 meter of height component. Processing with certain tropospheric delay correction model using synchronizes ground meteorological and GPS data at the same point can provide better accurate baseline.

ABSTRAK

(katakunci: Global Positioning System (GPS), data kajicuaca (meteorology),troposfera)

Penggunaan teknik Global Positioning System (GPS) berasaskan satelit adalah meluas dalam kerja kejuruteraan dan pengukuran yang memerlukan kejituan tinggi. Satelit GPS memberikan informasi navigasi global berkejituan tinggi sepanjang masa kepada pengguna yang mempunyai alat penerima GPS di atas atau hampir permukaan bumi. Isyarat yang dipancarkan oleh satelit GPS akan diterima oleh alat penerima GPS untuk penentuan kedudukan. Walau bagaimana pun kesan dari sumber ralat ralat yang terdapat dalam pengukuran perlu dihapuskan semasa pemprosesan pada data. Sabagai contoh, kesilapan memodelkan kelewatan isyarat GPS yang melalui atmosfera bumi adalah salah satu daripada ralat utama yang juga di kenali sabagai kelewatan troposfera.

Integrasi cerapan meteorologi dan GPS memberikan kefahaman yang jelas mengenai kelewatan troposfera. Kajian yang dilaksanakan mengabungkan data daripada stesen MASS (Malaysian Active GPS Station) dan cerapan meteorologi untuk menganalisis perubahan ketinggian GPS disebabkan oleh kelewatan troposfera. Model troposfera Saastamoinen yang di kenakan kepada data menunjukkan ralat sehingga 20 meter bagi data pseudorange. Ianya menyamai ralat sehingga 5 meter bagi komponen ketinggian. Pemprosesan menggunakan model kelewatan troposfera yang serasi berserta data meteorologi dan GPS pada titik tertentu dapat meningkatkan kejituan pengukuran garis dasar.

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TABLE OF CONTENTS

		Page
	TITLE	i
	DECLARATION	ii
	ABSTRACT	iii
	ABSTRAK	iv
	DICLOSURE FORM	v
	ACKNOWLEDGEMENT	vi
	TABLE OF CONTENTS	viii
	LIST OF FIGURES	xii
	LIST OF TABLES	xiv

CHAPTER 1

INTRODUCTION

1.0	Overview	2
1.1	The Current State of Measuring Atmospheric Water Vapor	3
1.2	Problem Statement	6
1.3	Objectives	7
1.4	Scope of Research	7
1.5	Contribution	8
1.6	Outline Treatment	9

CHAPTER 2

THE APPLICATION OF GNSS FOR ATMOSPHERIC STUDIES IN MALAYSIA

	Abstract	13
2.0	Introduction	14
2.1	Total Electron Content (TEC) from GPS	14

2.2 Application in Atmospheric Studies 16
2.2.1 Universiti Teknologi Malaysia 16
2.2.2 Universiti Kebangsaan Malaysia 18
2.2.3 STRIDE Ministry of Defence 19
2.4 Conclusion 22
2.5 References 22

CHAPTER 3

EFFECTS OF TROPOSPHERIC ZENITH DELAY IN SINGLE BASELINE DETERMINATION

Abstract 25
3.0 Introduction 26
3.1 Background 26
3.1.1 The Atmospheric Effects on GPS Signals 26
3.1.2 GPS Error Budget 27
3.1.3 Residual Atmospheric Effects 28
3.1.4 The Correction Methods 28
3.2 The experiments 30
3.2.1 The Data 30
3.2.2 MASS Data 30
3.2.3 Baseline 30
3.2.4 Surface Meteorological Data 31
3.2.5 IGS data 31
3.3 Processing 31
3.3.1 The Model 32
3.3.2 Ionospheric Free Solution 32
3.4 Data Analysis 33

3.5	**Conclusion and Recommendation**	**37**
3.6	**Acknowledgements**	**38**
3.7	**References**	**38**
3.8	**Appendix**	**39**

CHAPTER 4

MULTIPATH ERROR DETECTION USING DIFFERENT GPS RECEIVER'S ANTENNA

	Abstract	**43**
4.0	**Introduction**	**44**
4.1	**GPS Multipath Error**	**45**
4.2	**Data Collection**	**46**
4.3	**Data Analysis**	**48**
	4.3.1 Comparing data quality	**48**
	4.3.2 Residual Analysis	**50**
4.4	**Conclusion**	**53**
4.5	**Acknowledgements**	**54**
4.6	**References**	**54**

CHAPTER 5

TROPOSPHERIC DELAY EFFECTS ON RELATIVE GPS HEIGHT DETERMINATION

	Abstract	**57**
5.0	**Introduction**	**58**

5.1	**GPS Observations**	**58**
5.2	**GPS Error Budget**	**59**
5.3	**Surface Meteorological Observations**	**60**
5.4	**Satellite Orbit Accuracy**	**60**
5.5	**Effects on GPS signals**	**61**
5.6	**Residual Tropospheric Effects**	**61**
5.7	**Delay Estimation**	**61**
5.8	**Data Analysis**	**63**
5.9	**The Models**	**63**
5.10	**Conclusions and Recommendation**	**74**
5.11	**Acknowledgements**	**75**
5.12	**References**	**75**

CHAPTER 6

SUMMARY AND CONCLUSIONS

6.0	**Summary**	**77**
6.1	**Conclusions**	**79**

REFERENCES **81**

APPENDIXES **85**

LIST OF FIGURES

Figures no		Page
1.1	Some of the different types of ground- or space-based systems for observing water vapor.	4
2.1	GPS MASS station at Universiti Teknologi Malaysia, Johor	17
2.2	GPS MASS Station at Ipoh, Perak	17
2.3	TEC plotted for the Peninsular Malaysia in April 2002	18
2.4	GPS TEC System	20
2.5	Geographic Coverage at Marak Parak Station for ionospheric pierce point of 400 km	20
3.1	Satellite elevation and azimuth in the Trimble Geomatic Office's Skyplot function.	32
3.2a	Morning variation of coordinate compared to control point.	34
3.2b	Morning variation of coordinate compared to control point.	34
3.3a	The TZD of SV05 during observation period in INSTUN	35
3.3b	The TZD of SV09 during observation	35
3.3c	The TZD of SV17 during observation period in INSTUN	36
3.3d	The TZD of SV24 during observation period in INSTUN	36
3.4a	Sensor module interface	39
3.4b	Meteorological sensor	39
3.4c	GPS receiver over GPS control point	40
3.4d	UTMJ MASS station	40
3.5	The processed baseline of the study area as in TGO	41
4.1	Two types of antenna used. a) ground plane antenna b) normal antenna	47
4.2	Residual for Station G11	51
4.3	Residual for Station G12	52
4.4	Correlation between two days observation based SV4 and SV7.	53
5.1	Satellite elevation and azimuth in the Trimble Geomatic Office's Skyplot function.	64

5.2a,b, c,d	**Hourly post-process GPS height component variation result of INSTUN**	**66**
5.3a,b, c,d	**Signal refraction delay of PRN05 on day 1 day 2 day 3 and day 4**	**68**
5.4a,b, c,d	**Signal refraction delay of PRN09 on day 1 day 2 day 3 and day 4**	**69**
5.5a,b c,d	**Signal refraction delay of PRN17 on day 1 day 2 day 3 and day 4**	**70**
5.6a,b c,d	**Signal refraction delay of PRN24 on day 1 day 2 day 3 and day 4**	**72**
5.7	**Position value differences to the control value of the point**	**74**

LIST OF TABLES

Table no		Page
1.1	Characteristics of Water Vapor Observing Systems	10
2.1	Location of five MASS station in Semenanjung Malaysia	16
2.2	TEC variation in year 2002	21
3.1	Satellite error propagation	27
3.2a	GPS point value for morning session and the Δ value compared to the fix point.	33
3.2b	GPS point value for evening session and the Δ value compared to the fix point	33
4.1	Observation session, station location and two types of antenna	47
4.2	Observation's quality for phase 1 and phase 2	49
5.1	Satellite error propagation	59

CHAPTER 1

INTRODUCTION

1.0 Overview

The most dense, lowest layer of the earth's atmosphere is known as the troposphere. The troposphere is composed of a mixture of several neutral dry gases, primarily nitrogen and oxygen, and possibly other traces of pollutants. The air of the troposphere is also contain variable amount of water vapour. The amount varies depending upon the content of the temperature and pressure of the air. The highest amount of water vapour can be observed in the Equatorial region like Malaysia. Knowing that a large amount and strong variation of water vapour is found in the Equator region, a better understanding of the effect on the Global Positioning System (GPS) positioning activities is needed. Furthermore, the information about of water vapour in this region is of special interest for meteorologists because its behaviour is vital for understanding the global climate, whereas a short term variation of water vapour is a very useful input to local weather forecasting.

As the GPS signals propagate from the GPS satellites to the receivers located on the ground, they are also delayed by the troposphere. The delay can be represented by a function of satellite elevation and altitude of the GPS receiver, and is dependent on the atmospheric pressure, temperature and water vapour pressure. The delay is a wavelength–dependent and thus can not be canceled out by observing multi-frequency signals. The delay can be evaluated by the integration of the tropospheric refractivity along the GPS signal path. For modeling purpose the refractivity is separated into two components, hydrostatic (dry) and wet components. The hydrostatic component is dependent on the dry air gasses in the atmosphere and it accounts for approximately 90% of the delay. The "wet" component depends on the moisture content of the atmosphere and it accounts for the remaining effect of the delay. Although the dry component has the larger effect, the errors in the models for the wet component are larger than the errors in the models for the dry because the wet component is more spatially and temporally varying.

Tropospheric water vapor plays an important role in the global climate system and is a key variable for short-range numerical weather prediction. Despite significant progress in remote sensing of wind and temperature, cost-effective monitoring of atmospheric water vapor is still lacking. Data from the Global Positioning System (GPS) have recently been suggested to improve this situation. The tropospheric delay consists of two components. Atmospheric scientists have shown that GPS determined integrated water vapor from ground-based observations can significantly improve weather forecasting accuracies (Kuo *et al.*, 1995). Scientists have reported a worldwide increase in atmospheric water vapor between the year 1973 to 1985 (see Gaffen *et al.*, 1991). The study was conducted with radiosonde data only, and similar studies in the future could greatly benefit from GPS Pressure Water Vapour (GPS PWV) estimates, because of the inherent homogeneity of the GPS data and their long-term stability. While data from ground based GPS stations typically provide integrated PWV, data from a GPS receiver in Low-Earth-Orbit (LEO) can be inverted to measure atmospheric profiles of refractivity, which in turn can provide tropospheric humidity profiles if temperature profiles are known. These space-based atmospheric measurements exploit the fact that a GPS signal that is traveling from a GPS satellite to a LEO is bent and retarded as it passes through the earth's atmosphere.

1.1 The Current State of Measuring Atmospheric Water Vapor

A multitude of systems exist for observing water vapor. Each has different characteristics and advantages. Figure 1.1 shows some of the different types of observational systems, while in Table 1.1 compares some of their characteristics. It is generally agreed that improved knowledge of the role of water vapor in the climate system hinges largely on closing observational gaps that currently exist.

To date, in most large-scale water vapor climatological studies have relied primarily on analysis of radiosonde data, which have good resolution in the lower troposphere in populated regions but are of limited value at high altitude and are lacking over remote oceanic regions.

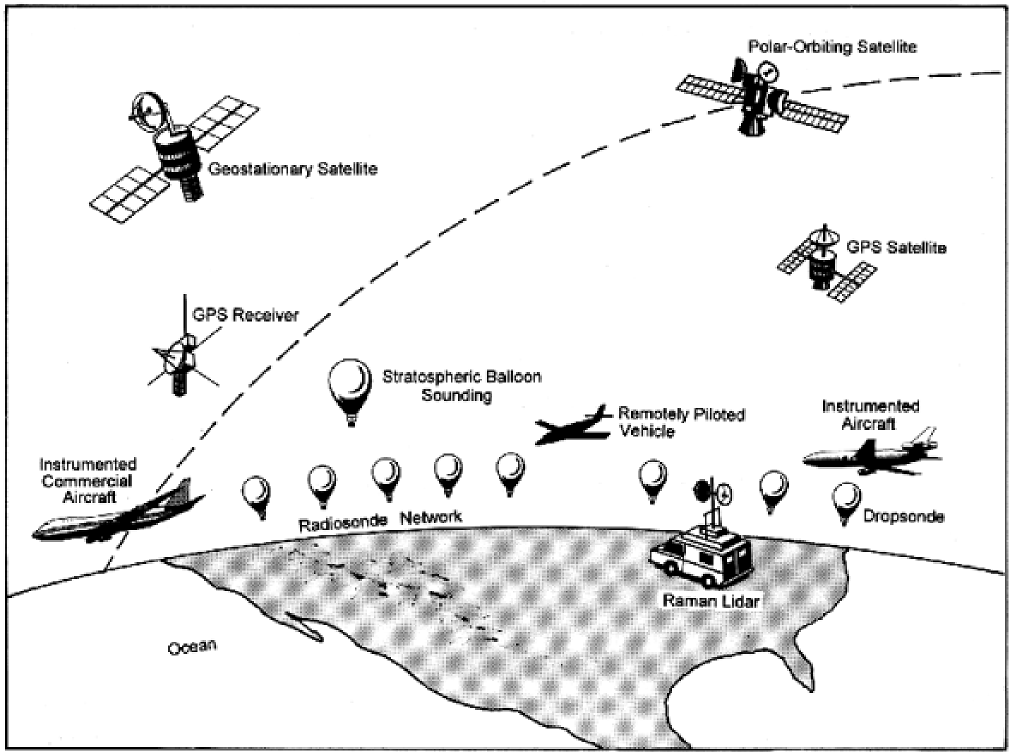

Figure 1.1 Some of the different types of ground- or space-based systems for observing water vapor.

Recently, substantial progress has been made using satellite observations to obtain total column water vapor and some low-resolution vertical profiles from infrared and microwave sensors. Satellite observations do not provide water vapor data in all weather conditions above all surfaces. Special processing of signals received from the Global Positioning System (GPS), a satellite-based navigational tool, has been receiving increased attention recently as a method for measuring water vapor, as it could give long-term measurements of the total column water vapor. New water vapor data sets can constructed for several years from a combination of satellite remote-sensing methods and direct observations to achieve improved spatial coverage and vertical resolution. Data assimilation systems, which combine information from observations and output from atmospheric models, also are being used to augment traditional observations and, in some instances, to take the place of data where no observations are available.

There are several efforts currently under way to observe, understand, and model the hydrological cycle and energy fluxes in the atmosphere, on the land surface, and in the upper ocean. The efforts will investigate variations of the global hydrological regime and their impact on atmospheric and oceanic dynamics. Variations in regional hydrological processes and water resources and their response to change in the environment such as the increase of greenhouse gases will be examined.

There are questions about how well the current models, both those used in climate studies and those used in forecasting the daily weather, treat water vapor. Modeling would be improved by systematic examination of models treatment of water vapor in light of what is now known of its distributions. Some of the questions arise because of the lack of good water vapor observations. The likely benefits of improved water vapor data include better weather forecasts as well as improved climate models.

Different types of measurements are complementary and useful. The challenge is how best to merge the available information on water vapor distribution into an improved description of the time and space variations of water vapor to enhance climate studies.

High accuracy GPS software estimates the total tropospheric delay in the zenith direction at regular time intervals. This delay is approximately 250 cm at sea level and has two components. Wet delay is caused by atmospheric water vapor, and dry or hydrostatic delay by all other atmospheric constituents. The hydrostatic delay of a zenith GPS signal traveling to an atmospheric depth of 1000 millibars is approximately 230 centimeter. Assuming hydrostatic equilibrium, this delay can be predicted to better than 1 mm with surface pressure measurement accuracies of 0.5 millibars. The error introduced by the assumption of hydrostatic equilibrium depends on winds and topology but is typically of the order of 0.01%. This corresponds to 0.2 mm in zenith delay. Extreme conditions may cause an error of several mm.

Wet GPS signal delay ranges from 0 to 40 centimeter in the zenith direction. The zenith wet delay (ZWD) is highly variable and cannot be accurately predicted from surface observations. The PWV is the depth of water that would result if all atmospheric water vapor in a vertical column of air were condensed to liquid. One centimeter of PWV causes approximately 6.5 centimeter of GPS wet signal delay.

1.2 Problem Statement

The atmospheric moisture fields that include the water vapour and clouds remains a difficult problem for improved weather forecasts. In modern weather prediction, short-term weather forecasts especially in severe weather and precipitation are essential. The Global Positioning System can be improved all-weather estimates of the atmospheric refractivity at very low cost compare with conventional upper-air observing systems.

The applications of GPS has led to a new and potentially significantly upper-air observing system for meteorological agencies and proposed in the estimation of integrated precipitable water vapour for the use in objective and subjective weather forecasting. This technique can be useful for Malaysia.

Continuous GPS satellite data incorporated with meteorological parameters can be use to study the effect of the lower part of the atmosphere.

1.3 Objectives

The main objectives of this project are as follows:-

1. To demonstrate the feasibility of using Global Positioning System (GPS) and that of ground based meteorological data to provide information for tropospheric model development.

2. To develop a model and mapping of precipitable water vapours useful for climate studies.

1.4 Scope of Research

The methodology for the project research involves several parts of investigations to develop an integrated troposhperic model from ground-based GPS and meteorological observations for the Malaysian region. The methodology of this research can be divided into five (5) phases which are:

Phase 1. Feasibility studies

The first phase that is required is the investigation and studies on existing techniques in order to provide additional information. This phase consists of identification of the factors to be considered and the derivation of the parameters used in the development of the algorithm.

Phase 2. Mathematical formalization and Real time data acquisition

The next phase is the extensive testing with various surface modelling simulated data will be carried out. Data will be collected from MASS GPS permanent stations in Malaysia maintained by JUPEM. The data collected by these stations are identified, evaluated and transferred for further processing. The meteorological data from several sites will be identified and collected.

Phase 3. Data analysis and processing

The meteorological and GPS data are processed for the quality of data. Then data analysis are carried out. The processing of these data are conducted at UTM.

Phase 4. Model Development

The modelling and testing of the model will be carried out to determine the suitable tropospheric model to be used and the capabilities of the model to be developed.

Phase 5. Verification of Model

Field verification of the tropospheric model which is obtained by integrated GPS data and that of the ground based meteorological data is required and carried out at several points. Most of the facilities that are needed in this phase are available in Universiti Teknologi Malaysia (UTM).

1.5 Contribution

As mentioned earlier, the applications of GPS has led to a new and potentially significantly upper-air observing system for meteorological agencies and proposed in the prediction of weather forecasting. This technique can be useful for Malaysia since the continuous GPS satellite data obtained from Jabatan Ukur & Pemetaan Malaysia (JUPEM) can be incorporated with meteorological parameters used to study the effect of the lower part of the atmosphere.

This study can provide benefits to government agencies, scientific researchers and even public who are interested in current information of weather forecast. Potential mapping system of any low lying areas can be obtained and the results can show the water level height as indicators for the planning and rescue purposes. The project is beneficial to researcher at UTM, JUPEM and Malaysian Meteorological Services since the real time data collected for surveying and navigation for future references and model developments can be acquired especially valuable information for short term weather broadcast and improved weather prediction in Malaysia. The Malaysian public especially the Navigation community can used this data for navigation purposes.

1.6 Outline Treatment

The integration of GPS and ground based meteorological data in this research shows the potential of combining the latest technology with some meteorological data can contribute towards model development. In this chapter the objectives and the methodology of the research as well as the GPS technology is introduced. Chapter 2 has been written to describe the research work carried out in Malaysia by different agencies and the application of atmospheric studies in Global Navigation Satellite System (GNSS).

In chapter 3, the used of Global Positioning System (GPS) technology in baseline determination is discussed. The meteorological data is considered to detect the error sources that resulted from effect of the troposhperic delay. In chapter 4 the detection of error due to different types of satellite antenna used in data collection is discussed. In chapter 5 , the test conducted is to detect the effect of the tropospheric delay in height determination. The meteorological data are considered in the test carried out. The results in all the studies obtained are presented at Seminar related to navigation and at International Symposium and Exhibition on Geoinformation in 2004 and 2005. Through this event the presentation of the ideas and many opportunities towards the betterment of the research carried out have been achieved.

Table 1.1 Characteristics of Water Vapor Observing Systems

Observing Platform	Measurement System	Advantages	Problems
Earth's surface	Routine surface meteorological observations. Instruments include wet- and dry-bulb psychrometer and dew point hygrometer	Long records of reasonably high quality global data are available. Observations are made at least daily and often more frequently.	Spatial coverage is non-uniform. Data are at the Earth's surface only.
Balloons	Routine radiosonde (weather balloon) observations. Humidity sensors include carbon and lithium chloride hygristors, capacitive sensors, goldbeater's skin, and human hair.	Instruments are expendable, so observations are relatively inexpensive. Method is in use since 1930s, so long data records are available. Global network of about 800 stations making one to four observations per day at each station. Data have relatively good vertical resolution in lower troposphere.	Data quality is variable quality in the upper troposphere and poor in the stratosphere. Quality of observations is poor at very high and low humidities. Differences in instruments and practices between countries, and changes over time, make data interpretation difficult. Spatial coverage is limited.
	Research soundings (using, e.g., frost point hygrometers)	Quality of humidity observations is high. Data extend beyond altitude limits of radiosondes.	Instruments are expensive, so soundings are made infrequently at limited locations.
	Reference radiosondes	High-quality observations could be used for comparison with operational measurement systems and for field experiments.	In development. Instruments are more expensive than expendable radiosondes.
Satellites	Infrared sensors	Sensors provide total column water vapor and some vertical profile information over large areas.	Data are limited to cloud-free regions and can exhibit regional biases. Vertical resolution is poor
	Microwave sensors	Sensors provide total column water vapor data over large regions and are not highly influenced by clouds.	Data are limited to ice-free ocean regions, and vertical resolution is poor.
	Solar occultation methods	Global humidity data at very high altitudes in the stratosphere and above. High accuracy and vertical resolution.	Coverage is limited by clouds. Sampling is poor in tropical regions.
	Global Positioning System	Global water vapor soundings would use	Methods are in research and development stage.

		existing and planned navigational satellites.	
Aircraft	Instruments mounted on special research airplanes or commercial aircraft. The research instruments include dew point and lyman alpha hygrometers, differential absorption lidars, capacitive sensors	Research aircraft can make measurements at almost any location at any time desired. Measurements with commercial aircraft could provide good data coverage over much of the globe.	Research missions are expensive, so data collection is limited. Programs involving commercial aircraft have not been widely implemented.
Ground-based remote sensors	Raman lidar, Differential absorption lidar	Sensors provide high-quality data with high vertical and temporal resolution.	The systems are expensive and require highly skilled operators. Usefulness is limited in daytime and in cloudy conditions.

CHAPTER 2

THE APPLICATION OF GNSS FOR ATMOSPHERIC STUDIES IN MALAYSIA

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THE APPLICATION OF GNSS FOR ATMOSPHERIC STUDIES IN MALAYSIA

Abstract

(keywords: Global Positioning System, atmosphere, total electron contents)

Global Positioning System (GPS) satellites provide precise all weather global navigation information to users equipped with GPS receivers on or near the earth's surface. The effects of different error sources on the computed position have to be removed from the data. In this paper, research work that carried out by universities and agencies on the atmospheric studies in Malaysia are presented.

Key Researcher:

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2.0 Introduction

The ionoshpere is a layer of the atmosphere between 50 km and 1000 km above the surface of the earth. The ionopshere is made up mostly of O_2 and N_2. Solar energy, in the form of ultraviolet light (UV) and x rays, ionize these gases, allowing electrons to float freely. The Faraday effect introduces phase distortions in the satellite positioning signals and can lead to large errors, purely due to the effects of the ionosphere.

Global Positioning System (GPS) satellites provide precise all weather global navigation information to users equipped with GPS receivers on or near the earth's surface. However, irregularities in the electron density of the equatorial ionosphere, with spatial extent from a few meters to many kilometers, can result in the performance of GPS receivers to be compromised.

2.1 Total Electron Content (TEC) from GPS

GPS satellites are located about 22,000 km from the earth's surface and they transmit signals that will be received by GPS receivers on the earth. The existence of the ionosphere is primarily due to the extreme ultraviolet radiation and X-rays from the sun. It is a shell of electrons and electrically charged atom and molecules that surrounds the earth, stretching from the heights of about 50 km to more than 1000km above the earth's surface. For signal frequency lower than 30 MHz, the ionosphere acts like a reflector. But ultra high frequency radio waves, like GPS signals, pass through the ionosphere they suffer an extra time delay as a result of the encounter with the electrons. This time delay is determined by the density of the electrons, that is characterized by the number of electrons in a vertical column with a cross-sectional area of one meter along a trans-ionospheric path to the receiver. This number is called Total Electron Content (TEC).

The TEC which is highly unpredictable depends on many parameter: local time, season, solar activity geomagnetic activity and latitude (geomagnetic). The electron density is a function of the amount of incident solar radiation.

TEC is measured in unit of 10^{16} electron per m^2.

$$1 \quad \text{TECU} = 10^{16} \text{ electrons} / m^2 .$$

Throughout the day, TEC at a location is dependent on the local time, reaching a maximum between 12.00 and 16.00. The dispersive nature of the ionosphere enables measurements of total electron content (TEC) using a dual-frequency GPS receiver.

One important application for TEC data is in automatic control of aircraft trajectories, which must be completely accurate. Information on TEC also provides a valuable tool for investigating global and regional ionospheric structures. Accurate information on TEC is essential for satellite navigation systems. The Global Positioning System provides global coverage by definition. If a suitable network of TEC stations could be established world-wide to use the GPS signals, TEC data could be available on a near real-time basis. This would provide near real-time feedback on communications propagation conditions across the globe.

In addition to instabilities, there are large diurnal and seasonal variations in the ionosphere in step with solar activity that is almost cyclical every 11 years. At the equator, such as variations of peaks up during equinoxes in March and September. These effects are more serious after sunset and during periods of high solar activity .

2.2 Application in Atmospheric Studies

In Malaysia, ionospheric studies is still a relatively new area of research. The participating from universities and organization to name a few such as Universiti Teknologi Malaysia, Universiti Kebangsaan Malaysia and STRIDE. In atmostspheric studies have increased.

2.2.1 Universiti Teknologi Malaysia

The research activities started in 1999 when a group of researchers studied on the atmospheric refraction effect on GPS positioning. The daily activities of tracking GPS signals for positioning and mapping purposes have increased the interest in studying the satellites signal ever since the establishment of Malaysian Actives Satellite Stations (MASS) in Peninsular Malaysia by Department of Surveying and Mapping Malaysia (DSMM). Table 2.1 shows the location of MASS stations used in the research.

GPS signals are obtained from five MASS stations are used to compute the TEC in the Peninsular region. Data downloaded from GPS receivers are used to compute the total electron content and the TEC values are plotted for the region.

Table 2.1 : Location of five MASS station in Semenanjung Malaysia.

Location of Stations	Latitude	Longitude	Height above MSL
Arau	6° 27' 00.57"	100° 16' 47".05	18.12 m
Kuala Lumpur	3° 10' 15.77"	101° 43' 3. "77	112.9 m
Ipoh	4° 35' 18.32"	101° 7' 35. "6	10.8 m
Geting	6° 13' 34.00"	102° 06' 20. "07	13.7 m
Skudai	1° 33' 56.43"	103° 38' 22. "13	87.6 m

In the following figures that is Figure 2.1 and Figure 2.2 show the antenna of the GPS receivers that are located at the MASS stations. In Figures 2.3 , the Total Electron Content (TEC) computed and plotted during the observation in April 2002.

Figure 2.1: GPS MASS station at Universiti Teknologi Malaysia, Johor

Figure 2.2:- GPS MASS Station at Ipoh, Perak

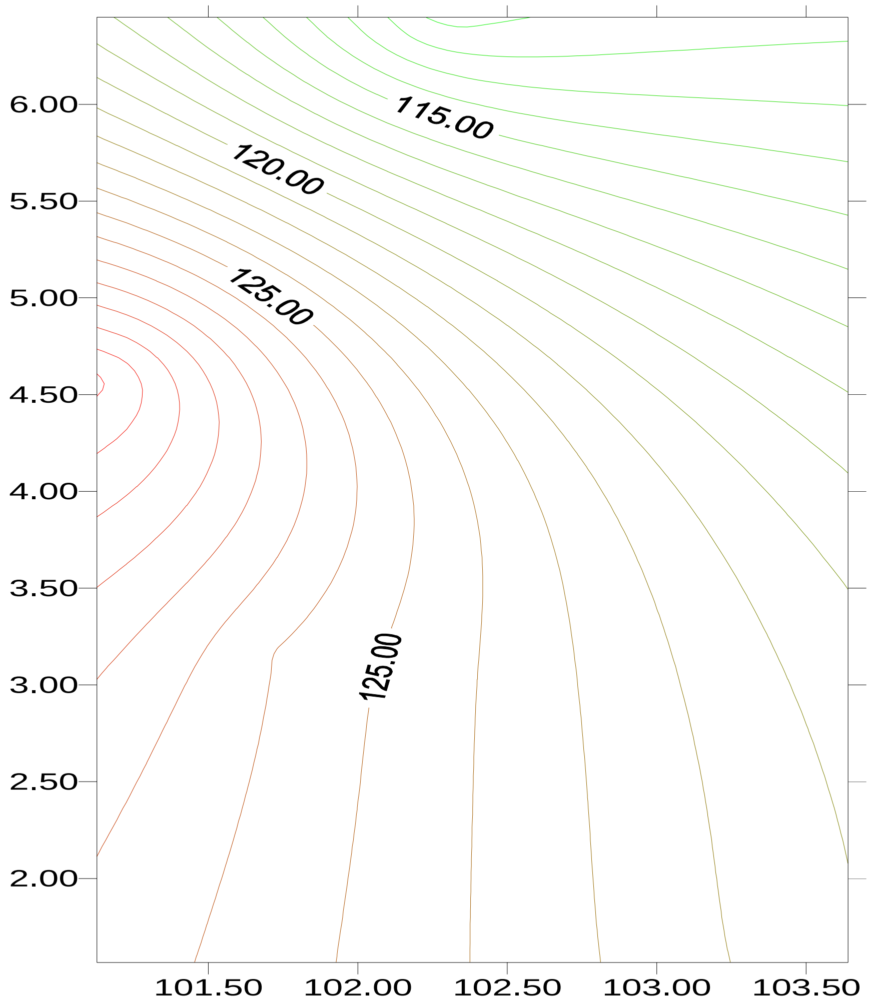

Figure 2.3 :- TEC plotted for the Peninsular Malaysia in April 2002

2.2.2 Universiti Kebangsaan Malaysia

A group of researcher in the university are engaged in the research using GPS receivers focusing on space weather sensing. The activities include:

1) Development of space GPS sensor for atmospheric radio occultation measurement aboard LEO satellite

2) Analysis and Modelling of Polar-Equatorial Ionospheric TEC using GPS sensing

3) Analysis and Modelling of Polar-Equatorial Ionopsheric Scintillation using GPS sensing

4) Analysis and Modelling of Polar-Equatrorial Slant Path Water Vapour using GPS sensing

2.2.3 STRIDE Ministry of Defence

In 1998, the Science and Technology Research Institute for Defence (STRIDE) participated a research through the co-operation with the Defence Science and Technology Organisation, Australia (DSTO) conducted a long-term study on the trend of equatorial TEC variations with increasing solar activity carried out at Marak Parak, Sabah, Malaysia (geographic co-ordinates : 6.31° N, 116.74° E ; geomagnetic lat 1.3° S, dip 3.8° S, declination 0.2°). Some of the analysis was carried out jointly with researchers from Universiti Kebangsaan Malaysia.

A GPS receiver system, housed in a cabin in Marak Parak, Sabah are used to study equatorial TEC ionospheric behaviour through continuous reception of trans-ionospheric GPS signals. The study covers a period near solar maximum activity in the current solar cycle 23 as it approaches its expected peak towards the end of 2000

Measurements of ionospheric TEC were done using a NovAtel MiLLennium GPSCard receiver with NovAtel 503 Survey Antenna and Choke Ring designed to minimize multipath interference. The dual frequency receiver has 12 channels permitting simultaneous collection of data from up to 12 satellites. The receiver is placed in a station located on a wide open space and allows all round clear horizon although on the southwest it is blocked at some spot by the peak of a mountain at 12°.

Figure 2 4:-GPS TEC System

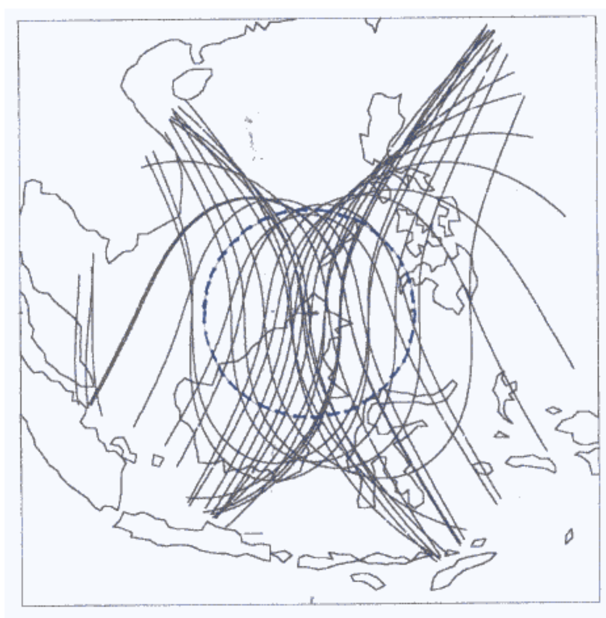

Figure 2.5:-Geographic Coverage at Marak Parak Station for ionospheric pierce point of 400 km

Observation are made from the year 1998 to 2000 indicates that the TEC increases with increasing solar activity peaking at equinoxes. It shows consistently, a deep pre-sunrise depression which becomes more prominent as TEC increases with the solar activity.

Daily charted of TEC activities reveals that the diurnal TEC variations are more complicated than initially anticipated. Although the general trend of increasing during the day and decreasing after sunset is observed, other abnormalities including multiple peaks during the day and secondary peaks after sunset are also present. Some interesting TEC variations are published for selected days as indicated in the table 2.2.

Date	**TEC behaviour**
23 June 2000	Moderate TEC values
5 Nov 2000	High TEC values
9 May 2000	Presence of night time secondary peak
15 May 2000	Presence of structure in day time peak
14 – 20 July 2000	Period of intense geomagnetic activity

Table 2.2 : TEC variation in year 2002

Throughout the work, various indicators of solar activity and representation of ionospheric TEC have been used. For solar activity Zurich SSN, $F_{10.7}$ and a local measurement of sunspot number have been used. For the ionospheric TEC, TECmax and TECday was chosen. TEC is the daytime maximum value of TEC, one value per day. It is an instantaneous value commonly used by most researchers. TECday is the integrated diurnal TEC, a summation of every minute TEC values, one value per day. This is a new indicator being introduced and used for the fist time in the work. The results indicate that $F_{10.7}$ is a better indicator of solar activity while TECday provides the best representation of TEC.

2.4 Conclusion

The research in the application of GNSS for atmospheric studies have increased with the participation of various universities and organization in Malaysia. From the research report obtained , it shows that the on-going activities conducted contribute to new information regarding the atmosphere in Malaysian region and can be recommended for future studies.

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CHAPTER 3

EFFECTS OF TROPOSPHERIC ZENITH DELAY IN SINGLE BASELINE DETERMINATION

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EFFECTS OF TROPOSPHERIC ZENITH DELAY IN SINGLE BASELINE DETERMINATION

ABSTRACT

(Keywords: GPS, Tropospheric zenith delay, MASS station)

In the global positioning system (GPS) surveying for baseline determination, the principal limiting error source is incorrect modeling of the delay experienced by GPS signal propagating through the electrically neutral atmosphere, usually referred to as the tropospheric delay. An experiment was conducted to determine the effect of tropospheric zenith delay in single baseline determination using Malaysian Active GPS (MASS) Station and GPS permanent point. The observations involved are the use of on-site ground meteorological data and satellite zenith angle information from the GPS data. The result from processed data was compared to the tropospheric delay corrections in GPS processing software such as Trimble Geomatics Office (TGO) that has certain limitation due to the default meteorological value. This paper shows that processing with certain tropospheric delay correction model using synchronizes ground meteorological and GPS data at the same point can provide better accurate baseline.

Key Researcher:-

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3.0 Introduction

The lower part of the atmosphere, called the troposphere, is electrically neutral and non-dispersive for frequencies as high as about 15GHz. In the global positioning system (GPS) surveying, the principal limiting error source is incorrect modeling of the delay experienced by GPS signal propagating through the troposphere, usually referred to as the tropospheric delay.

Within this medium, group and phase velocities of the GPS signal on both L1 and L2 frequencies are equally reduced. The resulting delay is a function of atmospheric temperature, pressure, and moisture content. Without appropriate compensation, tropospheric delay will induce pseudorange and carrier- phase errors that vary from roughly 2 meters for a satellite at zenith to more than 20 meters for a low-elevation- angle satellite (Hay.C and Wong, 2000). This delay affects mainly the height component of position and constitutes therefore a matter of concern in space geodesy applications (Mendes and Langley, 1998).

3.1 Background

3.1.1 The atmospheric effects on GPS signals

In this paper, GPS data are used to estimate the zenith tropospheric delay from measurement of the delay from each GPS satellite in view from a ground station. Typically four to six GPS satellites are in view at any given time over the study area.

GPS signals are affected while being transmitted through the ionosphere and troposphere (the neutral atmosphere). Normally, the global atmospheric models are use to correct for the atmospheric effect and these models are suitable for most GPS positioning. For high accuracy static and kinematic applications the global models are, however not sufficiently accurate (Jensen, 2002).

3.1.2 GPS Error Budget

There are several source of error in GPS and the error sources can be classified into three groups as

Table 3.1: Satellite error propagation

Source	**Effect**
Satellite	Clock bias
	Orbital errors
Signal propagation	Ionospheric refraction
	Tropospheric refraction
Receiver	Antenna phase center variation
	Clock bias
	Multipath

Both satellite and receiver clock bias can be fix by double differencing during the baseline processing. The ionospheric refractions is assume fixed by the dual frequency method of L1 and L2 signals. Multipath effect is minimize by a long hours observations, in this case is 3 hours for each session and the antenna phase center variation is ignored since the effect is too small. The remaining bias is the tropospheric refraction that can be predicted and corrected using models such as Saastamoinen, Hopfield, Black and others.

3.1.3 Residual atmospheric effects

Tropospheric layer is the most dynamic among other atmospheric layer because of the high variation of its water vapor content. This is a major task and an appropriate model has not yet been found.

Within the tropospheric layer, group and phase velocities of the GPS signal on both L1 and L2 frequencies are equally reduced. Without appropriate compensation, tropospheric delay will induce pseudorange and carrier phase errors that vary from roughly 2 meters for a satellite at zenith to more than 20 meters for a low elevation angle satellite.

3.1.4 The correction methods

The tropospheric delay is composed by two components; one is the dry part and the other is the wet part. The wet component is more difficult to model because of the heterogeneous distribution of the water vapor. The dry component correction is usually carried out using some atmospheric model. The surface pressure and temperature data are used to compute the dry component delay. In this experiment, an equation given by Saastamoinen's (Saastamoinen, 1973) is use to compute the tropospheric delay including the wet component.

Saastamoinen has refined this model by adding two correction terms, one being dependent on the height of the observing site and the other on the height and on the zenith angle. The refine formula is as follows (Hofmann-Wellenhof, 1994):

The equation is given below:

$$\Delta^{Trop} = \frac{0.002277}{\cos z}\left[P + \left(\frac{1255}{T} + 0.05\right)e - B\tan^2 z\right] + \delta R$$

where Δ^{trop} is propagation delay in terms of range,

z is zenith angle of the satellite,

P is the pressure at the site in milibar,

T is temperature in Kelvin and,

e is the partial pressure of water vapor in milibar.

B, δR is the correction term for height and zenith angle (Hofmann-Wellenhof, 1994).

In the above equation, partial pressure of water vapor is computed from the relative humidity as a fractional of 1. RH and the temperature, T measured at the surface. The following equation is used to calculate the partial pressure of water vapor (Murakami, 1989).

$$e = 6.108RH \times \exp\left[\frac{17.15T - 4684}{T - 38.45}\right]$$

RH is relative humidity at site

The pressure P at height above sea level h (in kilometers) is given in terms of the surface pressure Ps, and temperature Ts as mention by Murakami, 1989 as:

$$P = Ps\left[\left(\frac{Ts - 4.5h}{Ts}\right)\right]^{7.58}$$

The dry model is accurate to better than 1 cm (King et al 1985). This is more than sufficient for the purpose of the orbit determination.The radio signal delay through the tropospheric is dependent on the total amount of the water vapor existent along the path. It means that the delay depends on the distribution of water vapor. The geographical distribution of the clouds is difficult to model. As a result, a wet component correction using a model is less effective. Fortunately, the total magnitude of this effect is less than a meter in normal cases.

This level of error does not cause a serious problem in the practical application, especially, when the measured baseline length is short.

3.2 The experiment

3.2.1 The data

Several types of data are use in this experiment such as:

a. MASS station data
b. GPS point
c. Surface meteorological data
d. IGS data product (precise ephemeris)

3.2.2 MASS data

Malaysian Active GPS System (MASS) established Department of Survey and Mapping Malaysia (DSMM) in providing 24 hours GPS data for GPS users in Malaysia. This network containing 18 remote stations located strategically to cover the whole country including the Sabah and Sarawak. The data can be downloaded by user the day after the actual observations from the website provided by DSMM. Data from MASS station is use as a control point for the baseline.

3.2.3 Baseline

Baseline in GPS surveying refers to the position of one receiver relative to another. When the data from these two receivers is combined, the result is a baseline comprising a 3-Dimention vector between the two stations. In GPS processing, a baseline can overcome the effect from the satellite and receiver clock bias. In theory, this is what we call as double differencing. As the baseline length and observation periods increase, effects of the troposphere may become more significant and this leads to tropospheric zenith delay estimation for corrections purposes. In this case, the baseline length is 338,855.5255 meter.

The instrument used in this experiment is Leica GPS System 500 and MASS station data derived from UTMJ MASS Station located in Universiti Teknologi Malaysia.

3.2.4 Surface Meteorological Data

A Real time surface meteorological sensor (Davis GroWeather System) is stationed nearby the GPS receiver to collect the meteorological parameters needed in the tropospheric model correction algorithm.Surface values of meteorological data were taken every 10 minutes from 9am to 5pm to see the variations according to time.

3.2.5 IGS data

IGS precise final orbits is adopted to achieve cm level of accuracy and to give the exact location of the satellite at any given time. This is to ensure the value of azimuth and elevation angle of the satellite is corrected before the delay of each satellite can be determined.

3.3 Processing

Basically, all GPS data need to be processed before it can be used for high precision purposes. In this experiment, the data was collected using a Leica GPS receiver but the processing is done using Trimble Geomatic Office (TGO) v1.6. A baseline processing technique is used to eliminate errors such as clock biases, orbital errors, ionospheric refraction, cycle slips and multipath which cleaned and only the tropospheric refraction alone to be fixed.

3.3.1 The Model

A refined Saastamoinen model is used in this experiment to estimate the tropospheric delay in the study area. This has to do with the good reputation of the model (Saastamoinen) which is widely used for high accuracy GPS positioning (Jensen, 2002). The accuracy of the Saastamoinen model was estimated to be about 3cm in zenith (Mendes, 1999).

3.3.2 Ionospheric Free Solution

The ionospheric free solution uses a combination of L1 and L2 carrier phases to model and remove effects of the ionosphere on the GPS signals. This type of solution is often used for high-order control surveying, particularly when observing long baselines. The azimuth and elevation of the satellite after the use of precise ephemeris is derived from the sky plot function in TGO. These are essential parameters to determine the zenith angle of the satellite to be use in the Saastamoinen algorithm to estimate the signal delay. Figure 3.1 shows the azimuth and elevation of each single satellite due to time variation.

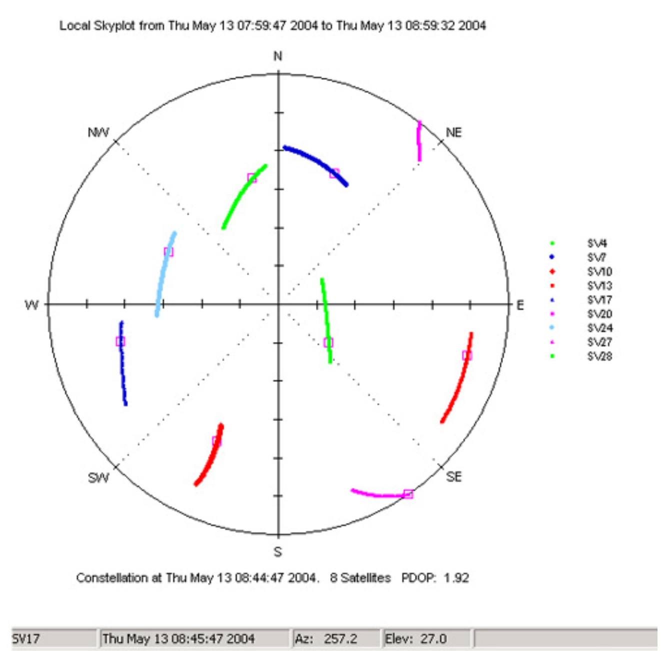

Figure 3.1: Satellite elevation and azimuth in the Trimble Geomatic Office's Skyplot function.

3.4 Data Analysis

Four satellites are to be track consistently in this experiment to derive the zenith delay of each single satellite for 8 hours of observations and 5 days temporal resolutions. The mentioned satellites are SV5, SV9, SV17 and SV24. The most critical parameters to be analyzed in this experiment is the elevation height, *h* of the observed point since the tropospheric delay mainly effected this components.

The tables below shows the Δ value of the point compared to a fix value of the point which is 416692.555N, 391589.087E and 72.038h.

Table 3.2a: GPS point value for morning session and the Δ value compared to the fix point.

Date	Northing (m)	ΔN (m)	Easting (m)	ΔE (m)	Elev. (m)	Δh (m)
13-05-04	416692.576	-0.037	391589.211	0.023	71.853	0.209
14-05-04	416692.548	-0.065	391589.088	-0.100	72.115	0.083
15-05-04	416692.543	-0.070	391589.376	0.188	71.874	-0.423
16-05-04	416692.583	-0.030	391589.146	0.311	71.644	-0.388
17-05-04	416692.853	0.240	391589.395	0.310	72.163	0.131

Table 3.2b: GPS point value for evening session and the Δ value compared to the fix point.

Date	Northing (m)	ΔN (m)	Easting (m)	ΔE (m)	Elev. (m)	Δh (m)
13-05-04	416692.543	-0.070	391589.067	-0.121	71.644	-0.388
14-05-04	416692.480	-0.133	391589.274	0.086	71.752	-0.280
15-05-04	416692.463	-0.150	391589.324	0.136	72.297	0.265
16-05-04	416692.497	-0.116	391588.835	-0.353	71.943	-0.089
17-05-04	416692.607	-0.090	391588.785	-0.103	71.777	-0.255

` The figure below shows the pattern of NEh value of the observed point in terms of time variation.

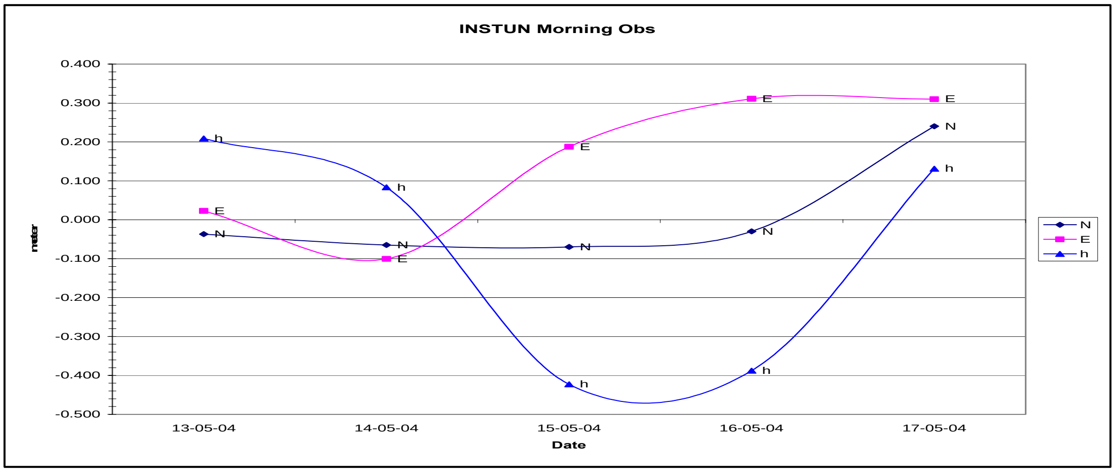

Figure 3.2a: Morning variation of coordinate compared to control point.

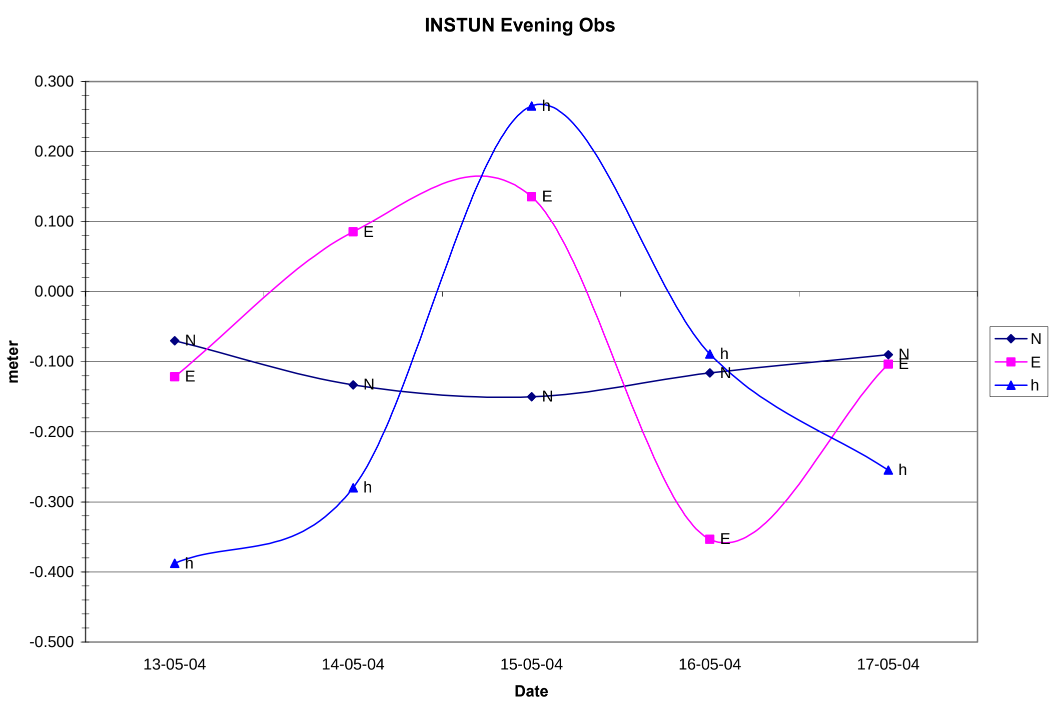

Figure 3.2b: Morning variation of coordinate compared to control point.

The tropospheric zenith delay (TZD) is estimated using Saastamoinen model to see the variation of the delay according to time. The result is shown in figure 3.3a, 3.3b, 3.3c and 3.3d.

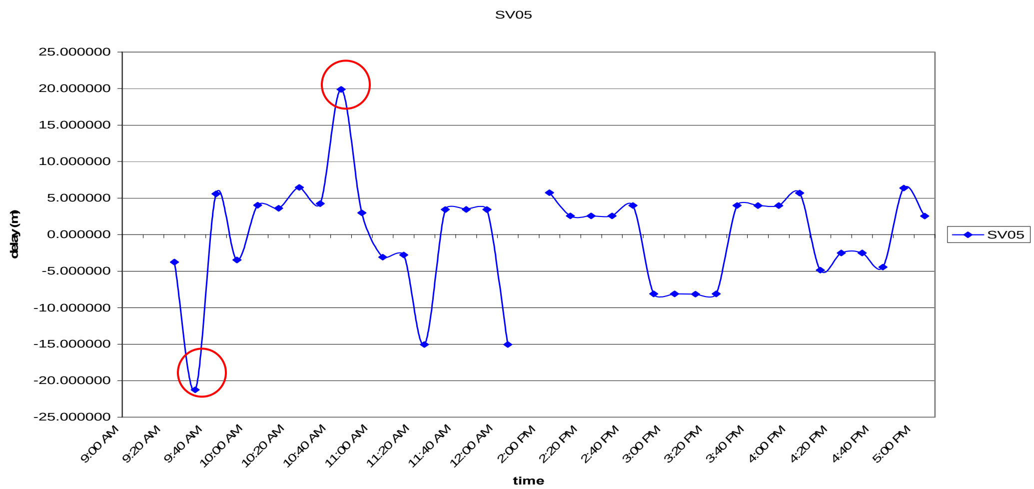

Figure 3.3a: The TZD of SV05 during observation period in INSTUN

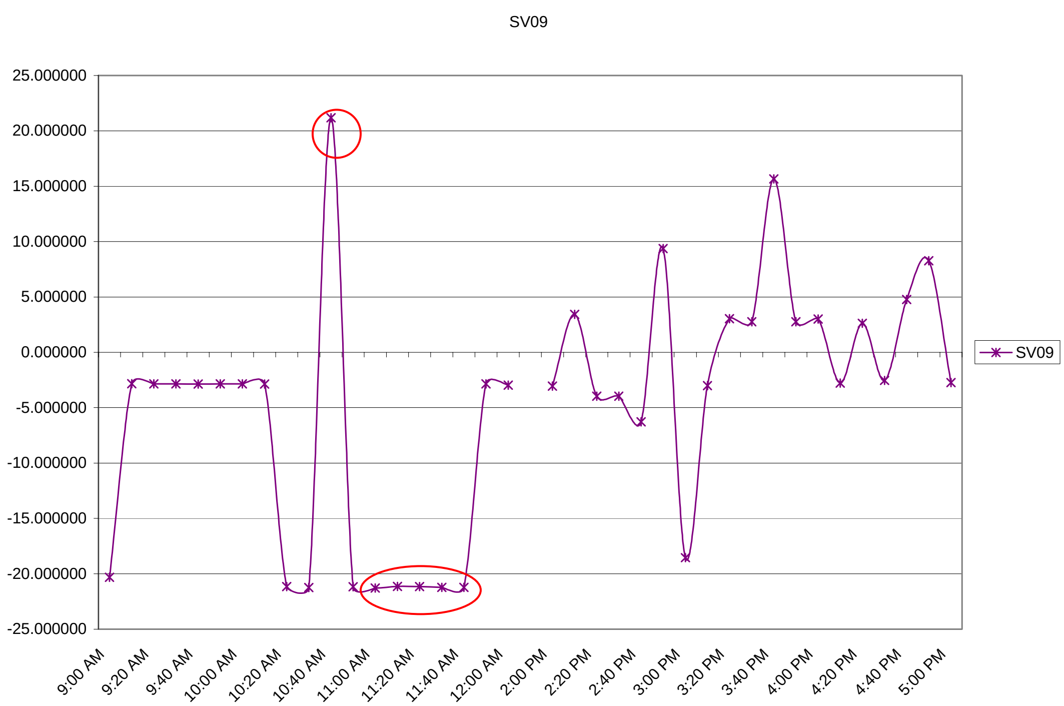

Figure 3.3b: The TZD of SV09 during observation

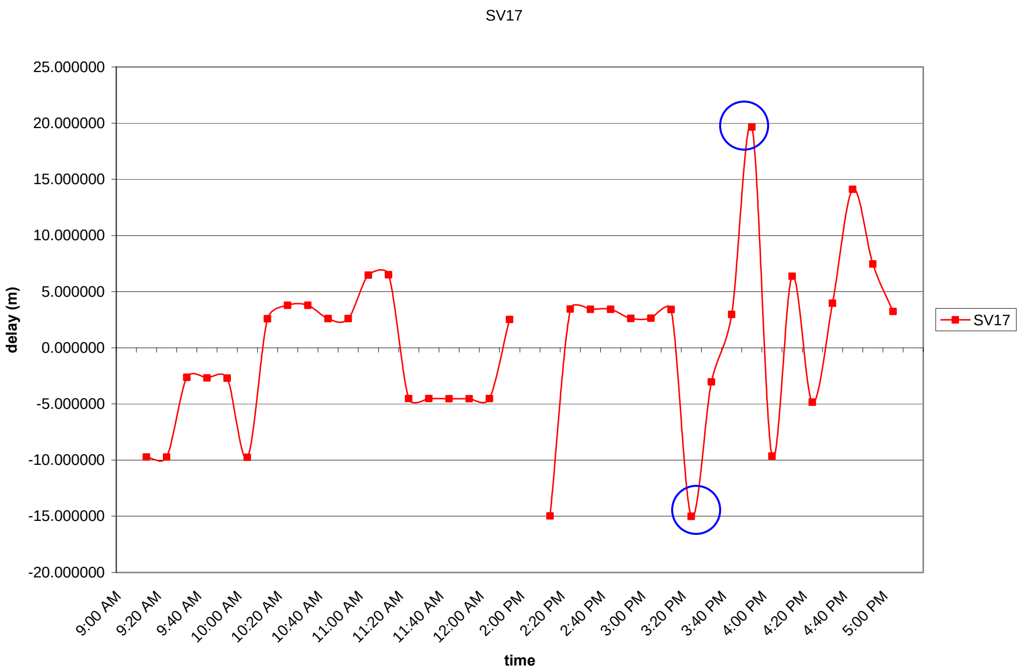

Figure 3.3c: The TZD of SV17 during observation period in INSTUN

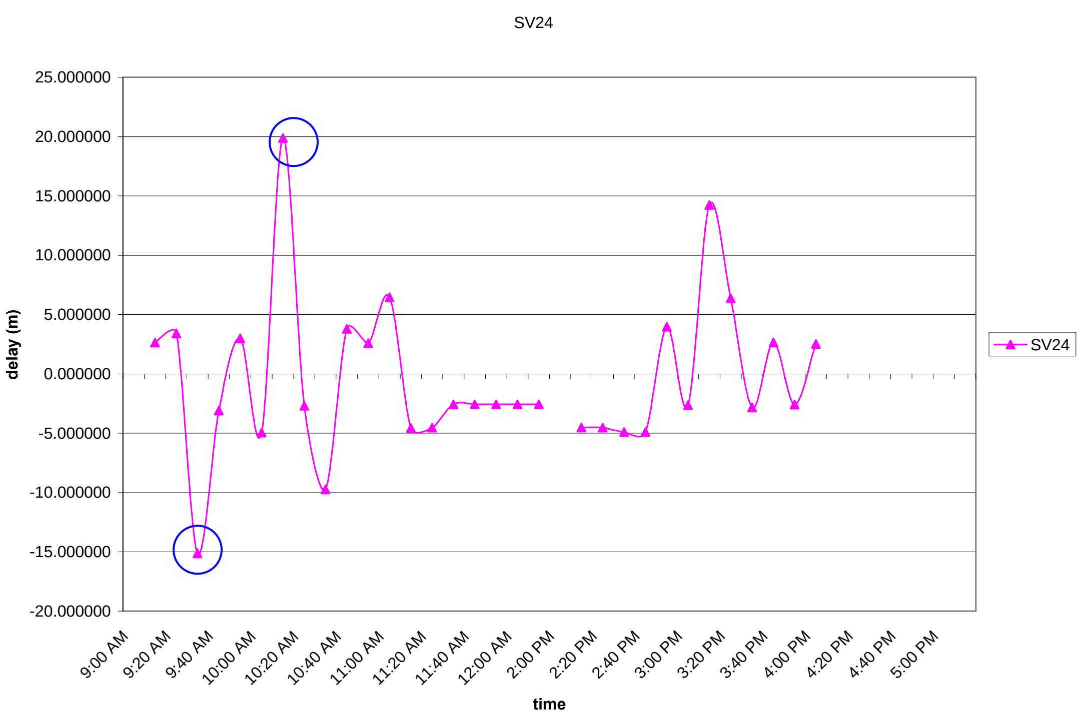

Figure 3.3d: The TZD of SV24 during observation period in INSTUN

The peak of the delay is mainly cause by the low elevation (10-40°) of the satellite and low humidity state (< 55%). The variation between positive and negative value is expected because there a no mapping function introduce in the study yet.

For example, the constant lower peak shown in Figure 3.3b for SV09 is caused by the constant satellite elevation of 10° and the humidity at that particular time is around 50-53%.

The results confirm that the tropospheric delay is such inconsistent and the effected is mainly due to the variation of the tropospheric component such as water vapor and the zenith angle of the satellite. It also shows that the tropospheric delay has resulted in pseudorange and carrier phase errors of about 20 meters for a low elevation satellite. The results are still at the preliminary stage for futher investigations.

3.5 Conclusions and Recomendation

From the study, the tropospheric delay can be estimated by using real time meteorological data and GPS observations for single baseline determination. An appropriate mapping function need to be identified and introduce into the calculation to get a more reliable result. A revision of the existing model need to be done base on local meteorological parameters to satisfy the humid tropical climate such as Malaysia before it can be applied for high accuracy GPS purposes.

3.6 Acknowledgements

We acknowledge the geodesy section of Institut Tanah dan Ukur Negara (INSTUN) and Department of Survey and Mapping Malaysia (DSMM) for their coorporation in this study. This study is funded by vote 74158 Research Management Centre (RMC)-UTM.

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APPENDIX

Figure 3.4a: sensor module interface

Figure 3.4b: Meteorological sensor

Figure 3.4c: GPS receiver over GPS control point

Figure 3.4d: UTMJ MASS station

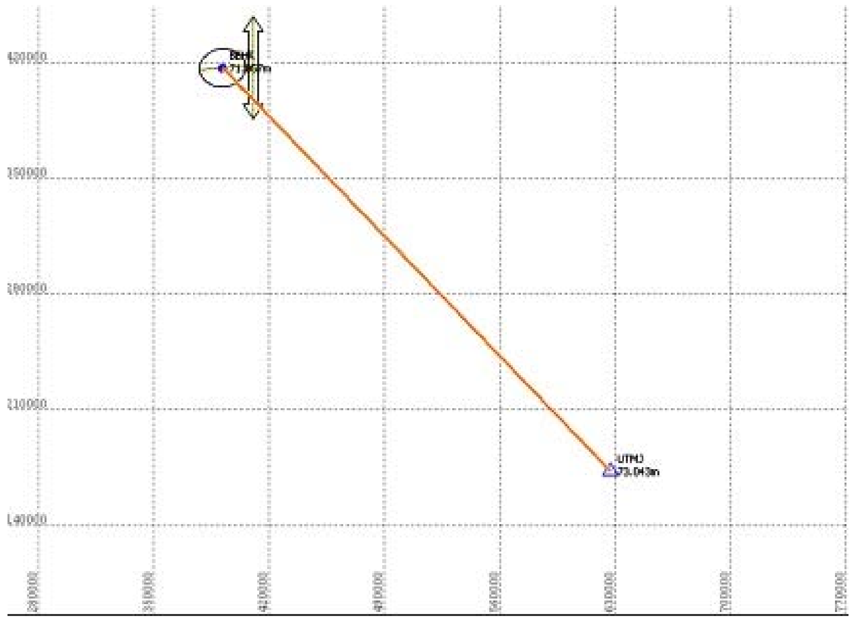

Figure 3.5: The processed baseline of the study area as in TGO

CHAPTER 4

MULTIPATH ERROR DETECTION USING DIFFERENT GPS RECEIVER'S ANTENNA

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MULTIPATH ERROR DETECTION USING DIFFERENT GPS RECEIVER'S ANTENNA

ABSTRACT

(Keywords: GPS, multipath error detection, antenna residual.)

The use of satellite based Global Positioning System (GPS) is normal in engineering and surveying for a wide range of applications as the accuracy capability increases. The GPS satellites transmit signals that are received by the receivers on the earth's surface to determine the position. As long as each satellite's signal travels along a direct path straight to the receiver's antenna, the unit can determine the satellite range quite accurately. However the ground and other objects easily reflect GPS signals, often resulting in one or more secondary paths, which are superimposed on the direct-path signals at the antenna and caused longer propagation time and can significantly distort the signals waveform's amplitude and phase. This paper will discussed the detection of the multipath errors from test carried out using two different types and design of GPS antenna. The existence of the multipath is analyzed.

Key Researcher:-

Md. Nor Kamarudin
Zulkarnaini Mat Amin

4.0 Introduction

Global Positioning System (GPS) is a satellite-based navigation system that revolutionizes tasks in navigation and surveying. GPS offers several advantages such as it allows high accuracy in relative positioning, each signal will pass through the clouds, rains and it can be used day and night regardless weather condition and also it can be operate 24 hours daily. GPS also gives coordinate information's in three dimensional (3D) position of any point.

Every GPS satellite transmits unique navigation signals base on dual-frequency electromagnetic band which L1 is at 1575.42 MHz and L2 is at 1227.60 MHz. So the frequency of the signal will reflect to the direction when it hit objects called multipath. Somehow, it still can penetrate the clouds but the signal will hinder when it pass through heavy fog and thick wet leaves. Basically, GPS satellite signals consists (Hoffman-Wellenhof et.al., 1997, Leick, 1995 and Wells et. al., 1987):

i. Dual band frequency – L (L1 and L2)
ii. Modulated frequencies carrier of distance measurement code
iii. Navigation message

All signal components is produced from atomic clock output in high stabilization. Every satellite is equipped with two cesium atomic clock and two atomic rubidium clock. These clocks will generate the sinus wave at f_o = 10.23 MHz frequency. This frequency is known as basic frequency. Although GPS has been a great helper in navigation and surveying, but there is situation where the GPS solution is unreliable and unreachable. The first case happened for bad satellite's geometry and GPS multipath error that introduced multiple signals. The second case happened when the antenna could not receive GPS signals since it affected from high buildings and other objects in urban areas. This paper will describe the GPS multipath error and several GPS observations have been conducted using two different antennas; one antenna used to overcome the GPS multipath (ground plane antenna) problem and another usual antenna supplied by the manufacturer. Data analysis has been carried out on GPS observation residual with carrier phase (especially L1 double difference residuals) by calculating the statistic value and graphically data comparison.

4.1 GPS Multipath Error

Multipath error happens when part of the transmitted signals from satellite is reflected by the earth surface or any surface that have high power of reflection before the signals reach to the receiver. This scenario also happen when the receiver received more secondary path signal from various directions, which resulted from ireflection from earth surface or any high objects for instance buildings around the observation station. This interfering signal is neither coded translated or understandable by GPS receiver.

Magnitude from these multipaths is depends on few factors:

i. Position and types of reflected surface that located near the antenna
ii. The height of antenna from earth surface
iii. GPS wave distance signals

Base on these factors, it clearly shows that received signals from low altitude satellite have more tendencies to multipath error rather than signals from higher altitude satellite. Apart from that, range code is more influenced by this consequences compare to carrier phase. For single reading epoch this error affected up to 10-20m for pseudo range code (Evans, 1986 and Wells et.al, 1987). While for carrier phase, this error affected for shorter base line is around 1 cm (for good satellite's geometry and longer observation period). Various methods have been conducted to decrease the errors for example by choosing the antenna that have signals polarization or by filtering signal and applying ground plane antenna or choke ring. However, the effective method to overcome these errors is by avoiding the areas or surrounding that may cause multipath problems such as buildings and other reflected surface.

4.2 Data Collection

The data collection for this study is divided into two phases. In the first phase, comparison of the observation results at two different areas; one is located in an open area and the other in an area that has obvious tendencies in causing the multipath errors. Meanwhile, for the second phase, the data is collected for evaluating the existing multipath errors in two days consecutively.

In phase 1, the observation has been conducted at station G11 (an open area), station G12 (area with obvious multipath) and station G13. Station G01 was chosen as reference station since the position is known. For two consecutive days (25th January 2003 and 26th January 2003) the observation has been carried out for 2 hours at about the same period of time in order to obtain the same satellite geometry. Using the same stations, the second phase observation was continued but an additional station (G13) was observed with a normal antenna to see the significant change of the multipath error in two days.

In both phases, the data are collected using the receiver of Trimble GPS 4700 with ground plane antenna and Trimble GPS 4800 with normal antenna. Generally, there are 4 GPS receivers in collecting data simultaneously. The observation are conducted when GDOP (Geometric Dilution of Precision) value is less than 3.0 and 15 minutes time interval for 2 hours observation. The GDOP value indicate the satellite's geometry with the reference of observation location. Table 4.1 shows observation session, station location and types of antennas used for phase 1 and 2. While Figure 1 shows the two types of antenna used in data collection for this study.

Observation day	**Station LocationSEN**	**Antenna**
25 Jan. 2003	G01 (Reference Station)	**Ground Plane**
	G11	*Ground Plane*
	G12	*Ground Plane*
	G13	Biasa
26 Jan. 2003	G01 (Reference station)	Normal
	G11	Normal
	G12	Normal
	G13	Normal

Table 4.1 Observation session, station location and two types of antenna

a) Ground Plane antenna **b) Normal antenna**

Figure 4.1: Two types of antenna used.

4.3 Data Analysis

All observation have been processed with Trimble Geomatic Office (TGO) software. This software can be used to process baseline and other additional modules such as for network adjustment and coordinate transformation. In this study case, the data are processed to the observation accuracy and observation data residual for every satellite.

The data analysis are carried out in three stages:

i. Compare the quality of the observation due to the surroundings factor between two different stations.
ii. To identify the residual of every satellite with reference to other existing antenna in ideal area (zero multipath errors) and area with multipath errors factors.
iii. Day to day residual analysis for two consecutively days of observation.

4.3.1 Comparing data quality

The analysis is based on the quality of observation from two different receivers. The parameters involved are ratio value, variance reference and error in root mean square (RMS) for every observation. The ratio is a relationship between two variances that was generated from the integer in the processing and high ratio shows high difference between two choices. Base line processing is more reliable with high accuracy integer value. Other factors that are relevant with ratio:

- Higher ratio value is more reliable to every observation.
- Ratio value shows quality point for every quality GPS observation.
- Fixed integer solution produces ratio value.

The baseline processing will only solve for ratio value that is more than 1.5. However, this ratio can possibly varies to higher value or lower value. Reference variance shows how collected data could fulfill the base line requirement. Base line processing will predict the error before continue data processing and comparing the predicted error and actual error obtained during the processing data. The reading from reference variance should be at 1.000 if the error is equivalent. The quality for base line solution mostly depends on noise measurement and satellite's geometry. RMS uses noise measurement for observation distance satellite to show solution quality. It also depends on satellite's geometry and smaller RMS value.

Table 4.2 shows the comparison between ratio value, reference variance and obtained RMS from processed data in two days observation. From the table, it clearly shows that by using ground plane antenna (25^{th} January 2003) gives more reliable result compared to usual antenna (26^{th} January 2003). For instance, base line from G01 to G11 contain ratio value up to 23.335, while on second day observation (26^{th} January 2003) is only at 22.034. For base line processing from G01 to G12, gives smaller ratio value at 3.656 for the first day and 3.629 on the second day, which resulted from multipath error factor as the G12 station located near buildings while G11 station located in an open and clear area.

Date	**Baseline**	**Ratio**	**Reference variance**	**RMS**	**ANTENNA**
25/01/03	G01 ke G11	23.335	5.252	0.006	*Ground Plane*
	G01 ke G12	3.656	15.552	0.015	*Ground Plane*
26/01/3	G01 ke G11	22.034	5.838	0.008	normal
	G01 ke G12	3.629	21.287	0.016	normal

Table 4.2: Observation's quality for phase 1 and phase 2

4.3.2 Residual Analysis

Apart from ratio factor, reference variance and RMS, the observation quality can be distinguished through residual observation for every involved satellite during data collecting process. Residual is a difference value between observation quantity and calculated value for the quantity, which is carrier phase value. Residual values have been analyzed to determine the consequences of multipath error occurred to carrier phase measurement. This study case only used residual from observation in carrier phase L1. The residual had been plotted verses time for two different areas.

Figure 4.2 shows observation residual value between first day and second day for integration SV4 and SV7 satellite at observation station G11 (no interference). On top of that, the residual difference is being calculated from both SV. Figure 3 shows comparison between two days observation that comprises areas with multipath error factors, G12 where this area situated near the buildings. As described in Section 4.2, station surrounding plays an important role to every GPS observation. In the figure also shows L1 phase value for observation residual for both satellite on the observation day, SV8 and SV24. Standard deviation value for Figure 4.2 is 0.451 cm, while in Figure 4.3 the value is 0.933 cm.

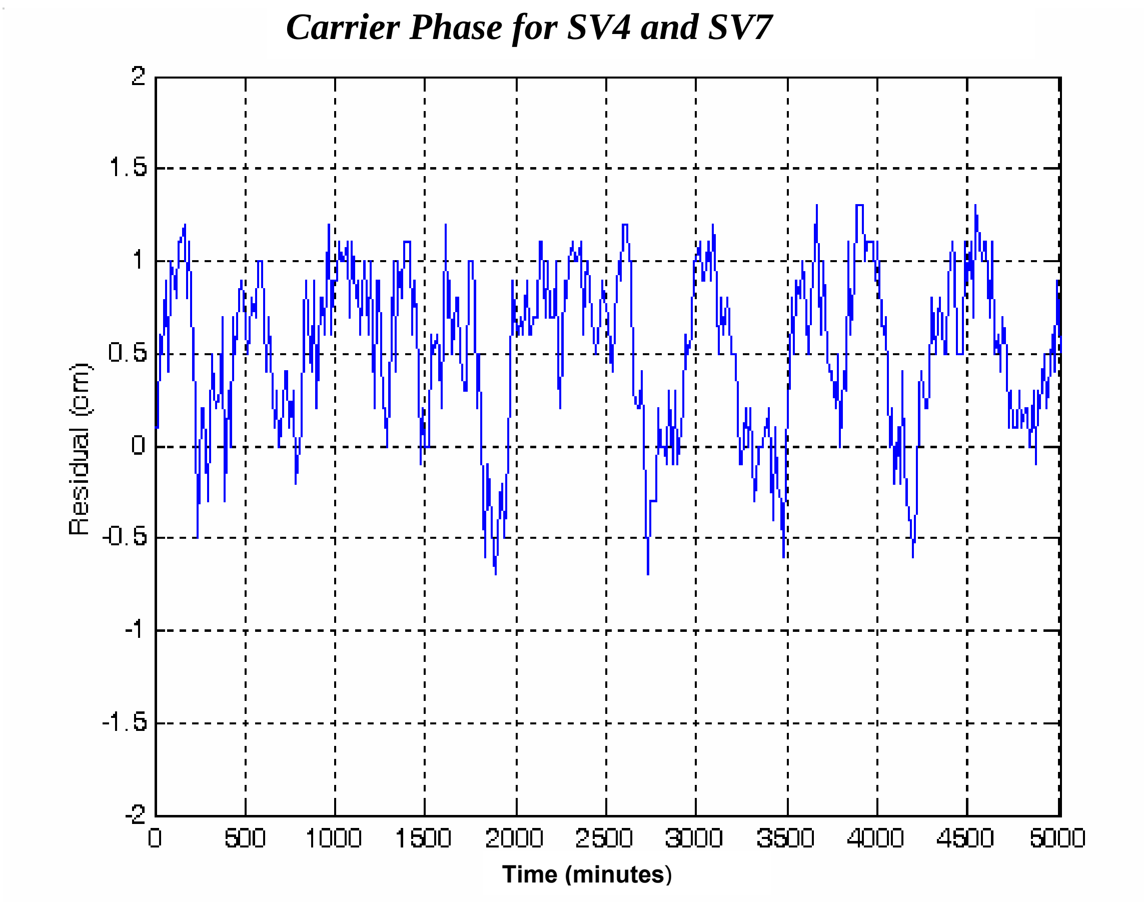

Figure 4.2: Residual for Station G11

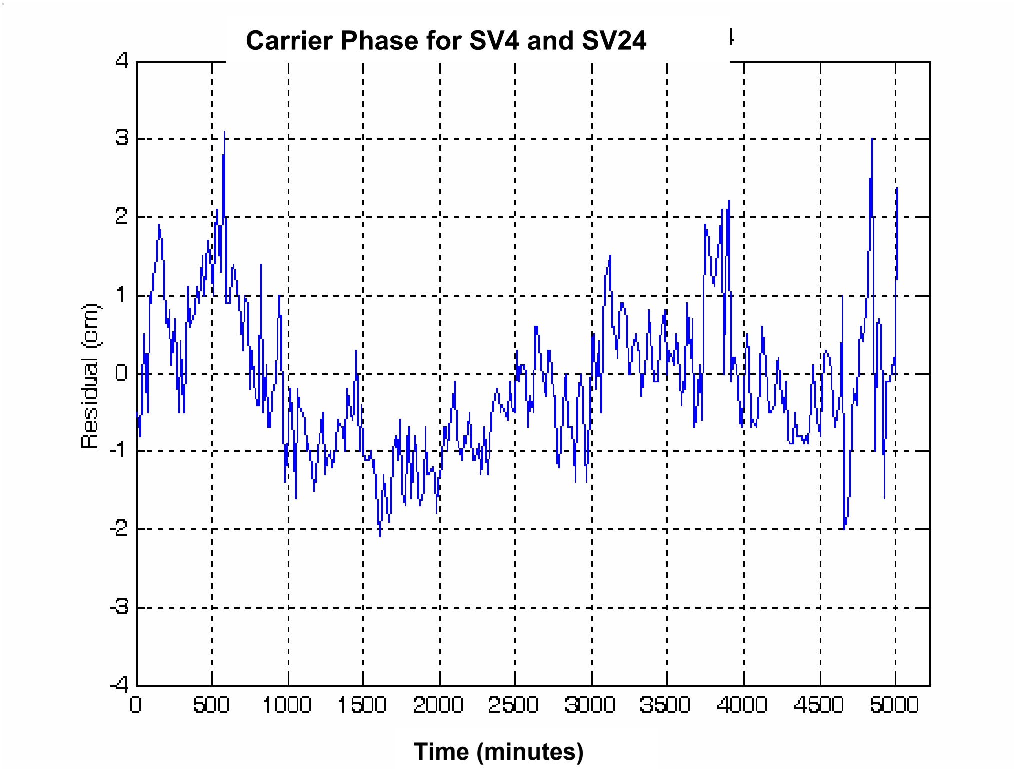

Figure 4.3:Residual for Station G12

Beside these two figures, analysis also has been done on observation residual for two days consecutively. Figure 4 shows residual for different satellite SV4 and SV7 during observation days. Both observations has been carried out at the same day, time and using the same tools. It can be seen that multipath errors occured on the same time for those two days. (It shows when the dark line redundant with the light line). Correlation value for both observation set is 0.548. Day to day correlation can be used to remove the multipath errors occurred. For example, observation for two days non-stop able to remove the multipath error and the difference observation value represents the actual criteria for observed objects.

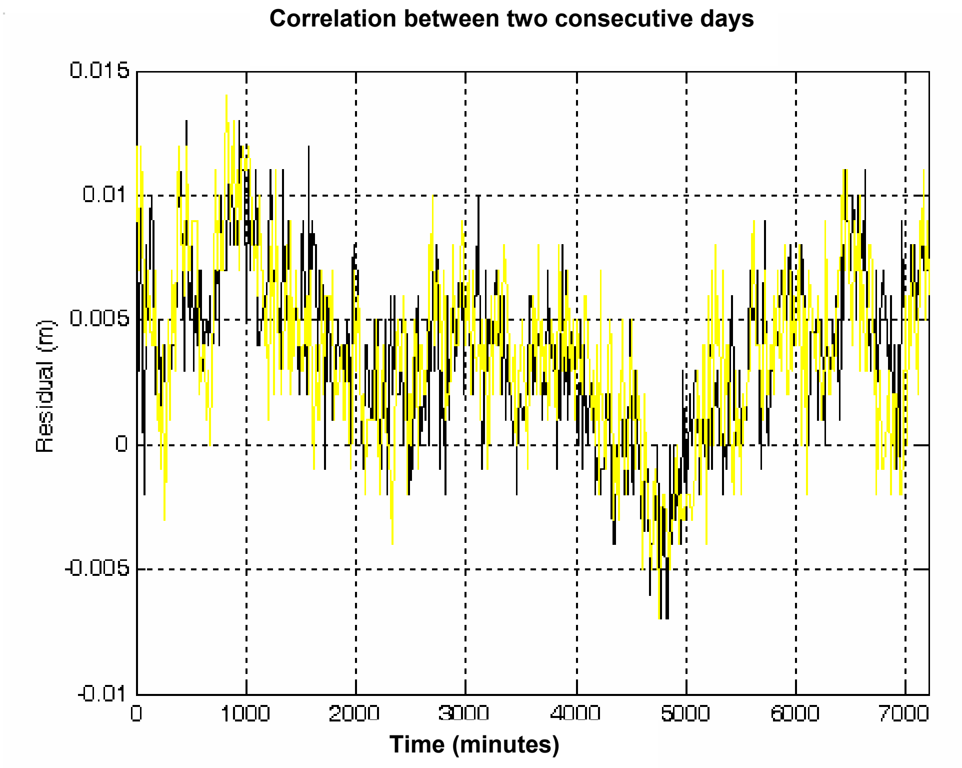

Figure 4.4 Correlation between two days observation based SV4 and SV7.

4.4 Conclusion

This research paper described the multipath error detection using two different GPS receiver's antennas such as the ground plane and normal antenna. From the analysis of the GPS observations, it shows that multipath error exist in the observation. Multipath error can be detecting in areas with reflected GPS signals at station G12. For an open and clear area such as at station G11, the residual value being influenced by other errors such as high noisy frequency. It also shows the ground plane antenna is capable to reduce the multipath errors as shown in Table 2.

As conclusion, in this study the reliable technique for reducing the multipath errors was successfully been done by different observation for two days consecutively. Day to day correlation is useful to apply GPS for observation tasks such as structural continuous observation. From GPS continuous observation such as Real Time Kinematics (RTK), the observation output for those two days has to be differentiated between them in order to obtain the actual object position in observed area.

4.5 Acknowledgements

Our gratitude goes to En. Jumali Mohd Ismail for his help throughout this research and Research Management Centre, Universiti Teknologi Malaysia, 81310, Universiti Teknologi Malaysia, Skudai, Johor.

4.6 References

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CHAPTER 5

TROPOSPHERIC DELAY EFFECTS ON RELATIVE GPS HEIGHT DETERMINATION

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TROPOSPHERIC DELAY EFFECTS ON RELATIVE GPS HEIGHT DETERMINATION

ABSTRACT

In the global positioning system (GPS) surveying for point positioning, one of the principal limiting error source is incorrect modeling of the delay experienced by GPS signal propagating through the electrically neutral atmosphere, usually referred to as the tropospheric delay. This paper concentrates on showing the result of an experimental work that has been conducted by integrating the Malaysian Active GPS Station (MASS) data and ground meteorological observations to analyze the variation occur to the GPS height determination due to the tropospheric delay. Four individual satellites are selected to assist the analysis due to their availability during the observations period. The result of introducing a Saastamoinen tropospheric model to the data shows a delay variation for up to 20 meter in pseudorange which causes an error up to 5 meter of height component. This paper verify that the integration of ground meteorological observations and GPS lead to a better understanding of the tropospheric delay to the GPS signal and improve the GPS height accuracy.

Key Researcher:

Md. Nor Kamarudin,

Mohd. Zahlan Mohd. Zaki

5.0 Introduction

The troposphere is a part of the earth atmosphere which is situated in its lower region. It is where all weather occurs, electrically neutral and non-dispersive for frequencies as high as about 15GHz. In the global positioning system (GPS) surveying, the principal limiting error source is incorrect modeling of the delay experienced by GPS signal propagating through the troposphere, usually referred to as the tropospheric delay.

Within this medium, group and phase velocities of the GPS signal on both L1 and L2 frequencies are equally reduced. The resulting delay is a function of atmospheric temperature, pressure, and moisture content represented by relative humidity. Without appropriate compensation, tropospheric delay will induce pseudorange and carrier- phase errors that vary from roughly 2 meters for a satellite at zenith to more than 20 meters for a low-elevation- angle satellite (Hay.C and Wong, 2000). This delay affects mainly the height component of position and constitutes therefore a matter of concern in space geodesy applications (Mendes and Langley, 1998).

5.1 GPS Observations

The constellation of activies GPS satellites consist of 24 satellites. These satellites are distributed in six orbital planes inclined at 55°, with a nodal separation of 60°. The orbits are circular with 12 hour period. Each satellite broadcasts navigation signals on two L band frequencies: 1.57542 GHz (L1) and 1.2276 GHz (L2) carrier phase observations that are used to form ionospheric-free double differences (Gutman et al., 2003). Sources of initial measurement error include receiver noise, site-dependant multipath, and antenna phase delays.

5.2 GPS Error Budget

There are several sources of error in GPS and can be classified into three major groups which are satellite, signal propagation and receiver as shown in table 5-1.

Table 5-1: Satellite error propagation

Source	Effect
Satellite	Clock bias
	Orbital errors
Signal propagation	Ionospheric refraction
	Tropospheric refraction
Receiver	Antenna phase center variation
	Clock bias
	Multipath

In this experiment, both satellite and receiver clock bias is eliminated by applying double differencing during the processing. Since the measurements are taken on both the L1 and L2 frequencies, an ionosphere-free (IF) double difference observable can be obtained by combining the observations. Using this observation during positioning removes the first-order effects of the ionosphere (99% of this error source), allowing for the removal of this error to the centimeter-level even with low elevation observations and high atmospheric electron content (*Brunner and Gu*, 1991). Multipath effect is minimize by a long hours observations, in this case is 3 hours for each session and the antenna phase center variation can be neglected as long as the system is well maintain and calibrated. The remaining bias is the tropospheric refraction which value can be estimated and corrected using existing empirical models such as Saastamoinen, Hopfield, Black and others.

5.3 Surface Meteorological Observations

Surface observations are required to parse the tropospheric signal delay into its wet and dry components. Surface temperature measurements can be used to estimate the mean temperature of the atmosphere with an error of about 2%. In general, surface pressure measurements with accuracy of about 0.5 hPa, and surface temperature measurements with accuracy of about 2 degrees are sufficient (Saastamoinen, 1972). A Real time surface meteorological sensor (Davis GroWeather™ System) is stationed nearby the MASS Station to collect the meteorological parameters needed in the tropospheric model correction algorithm. Parameters taken are surface temperature, pressure and relative humidity. These surface values of meteorological data were taken within a 10 minutes interval from 9am to 5pm to identify the variations.

5.4 Satellite Orbit Accuracy

IGS precise final orbits are adopt to achieve cm level of accuracy and to give the exact location of the satellite at any given time. This is to ensure the value of azimuth and elevation angle of the satellite is corrected before the delay of each satellite can be determined. Precise orbits are available with about 13 days latency, and are determined from hundreds of ground tracking stations' measurements. The accuracy of precise orbits is <5 cm [*IGS*, 2005]. If the application permits, most processing is done with precise orbits due to the fact that it provides very complete ephemeris (if a certain satellite ephemeris is not available at the time the rapid orbit is available, an effort is made to make it available in the precise ephemeris) and there is enough time to correct blunders which may have made their way into other orbital products.

5.5 Effects on GPS signals

In this research, GPS data are used to estimate the tropospheric delay from measurement of the delay from each GPS satellite in view from a ground station. Typically four to six GPS satellites are in view at any given time over the study area.

GPS signals are affected while being transmitted through the ionosphere and troposphere (the neutral atmosphere). Normally, the global atmospheric models are use to correct for the atmospheric effect and these models are suitable for most GPS positioning. For high accuracy static and kinematic applications the global models are, however not sufficiently accurate (Jensen, 2002).

5.6 Residual Tropospheric Effects

Tropospheric layer is the most dynamic among other atmospheric layer because of the high variation of its water vapor content. This is a major task and an appropriate model has not yet found.When the satellite signals are transmitted through the troposphere they are refracted, and the refraction is a function of meteorological conditions. The refraction causes a signal delay has a size of 2-3 meters in zenith depending on meteorological conditions and the altitude of the GPS receiver. Within the tropospheric layer, group and phase velocities of the GPS signal on both L1 and L2 frequencies are equally reduced. Without appropriate compensation, tropospheric delay will induce pseudorange and carrier phase errors that vary from roughly 2 meters for a satellite at zenith to more than 20 meters for a low elevation angle satellite (Hay.C and Wong, 2000).

5.7 Delay Estimation

The tropospheric delay is actually composed by two components; one is the dry part and the other is the wet part. The wet component is more difficult to model because of the heterogeneous distribution of the water vapor.

The dry component correction is usually carried out using some atmospheric model. The surface pressure and temperature data are used to compute the dry component delay. In this experiment, an equation given by Saastamoinen's (Saastamoinen, 1973) is use to compute the tropospheric delay including the wet component. Saastamoinen has refined this model by adding two correction terms, one being dependent on the height of the observing site and the other on the height and on the zenith angle. The refine formula is as follows (Hofmann-Wellenhof, 1994):

The equation is given below:

$$\Delta^{Trop} = \frac{0.002277}{\cos z}\left[P + \left(\frac{1255}{T} + 0.05\right)e - B\tan^2 z\right] + \delta R$$

where Δ^{trop} is propagation delay in terms of range,

z is zenith angle of the satellite,

P is the pressure at the site in milibar,

T is temperature in Kelvin and,

e is the partial pressure of water vapor in milibar.

B, δR is the correction term for height and zenith angle (Hofmann-Wellenhof, 1994).

In the above equation, partial pressure of water vapor is computed from the relative humidity as a fractional of 1. RH and the temperature, T measured at the surface. The following equation is used to calculate the partial pressure of water vapor (Murakami, 1989).

$$e = 6.108RH \times \exp\left[\frac{17.15T - 4684}{T - 38.45}\right]$$

RH is relative humidity at site

The pressure P at height above sea level h (in kilometers) is given in terms of the surface pressure Ps, and temperature Ts as mention by Murakami, 1989 as:

$$P = Ps\left[\left(\frac{Ts - 4.5h}{Ts}\right)\right]^{7.58}$$

The dry model is accurate to better than 1 cm (King et al 1985). This is more than sufficient for the purpose of the orbit determination.

The radio signal delay through the tropospheric is dependent on the total amount of the water vapor existent along the path. It means that the delay depends on the distribution of water vapor. The geographical distribution of the clouds is difficult to model. As a result, a wet component correction using a model is less effective. Fortunately, the total magnitude of this effect is less than a meter in normal cases.

5.8 Data Analysis

The data use this experiment is a relative positioning connecting UTMJ and INSTUN within 300km baseline. The data processing is done in Trimble Geomatic Office (TGO) v1.6. During baseline processing, errors such as clock biases, orbital errors, ionospheric refraction, cycle slips and multipath were eliminated and leave out the tropospheric refraction alone to be fix.

5.9 The Models

A refined Saastamoinen model is used in this experiment to estimate the tropospheric delay in the study area. This has to do with the good reputation of the model (Saastamoinen) which is widely used for high accuracy GPS positioning (Jensen, 2002). The accuracy of the Saastamoinen model was estimated to be about 3cm in zenith (Mendes, 1999).

The ionospheric free solution uses a combination of L1 and L2 carrier phases to model and remove effects of the ionosphere on the GPS signals. This type of solution is often used for high-order control surveying, particularly when observing long baselines. The azimuth and elevation of the satellite after the use of precise ephemeris is derived from the skyplot function in TGO. These are essential parameters to determine the zenith angle of the satellite to be use in the Saastamoinen algorithm to estimate the signal delay. Figure 5-1 shows the azimuth and elevation of each single satellite due to time variation.

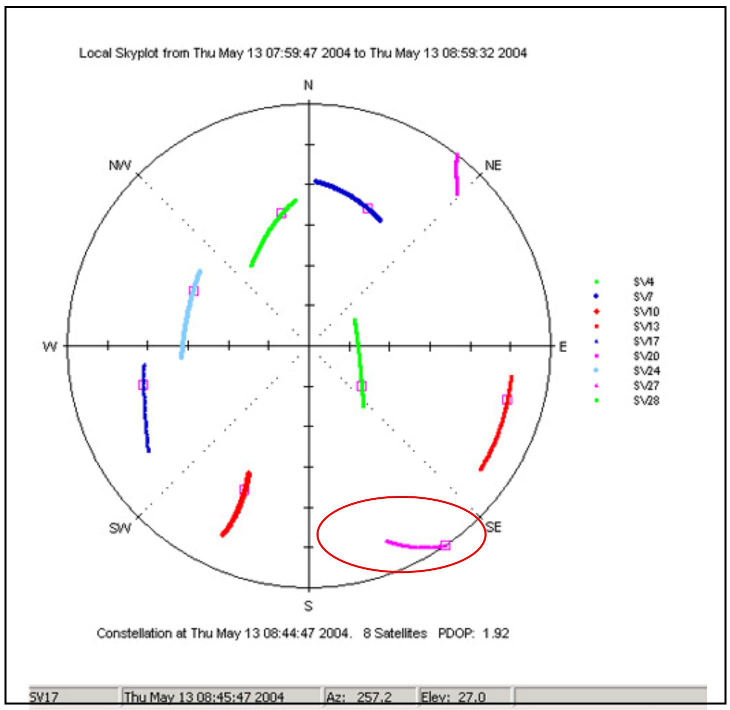


Figure 5-1: Satellite elevation and azimuth in the Trimble Geomatic Office's Skyplot function.

Four satellites has been chosen to represent the observations. The satellites are PRN05, PRN09, PRN17 and PRN24. The most critical parameters to be analyzed in this experiment is the elevation height, *h* of the observed point since the tropospheric delay mainly effected this components. Figure 5-2 below shows the variations of the height components:-

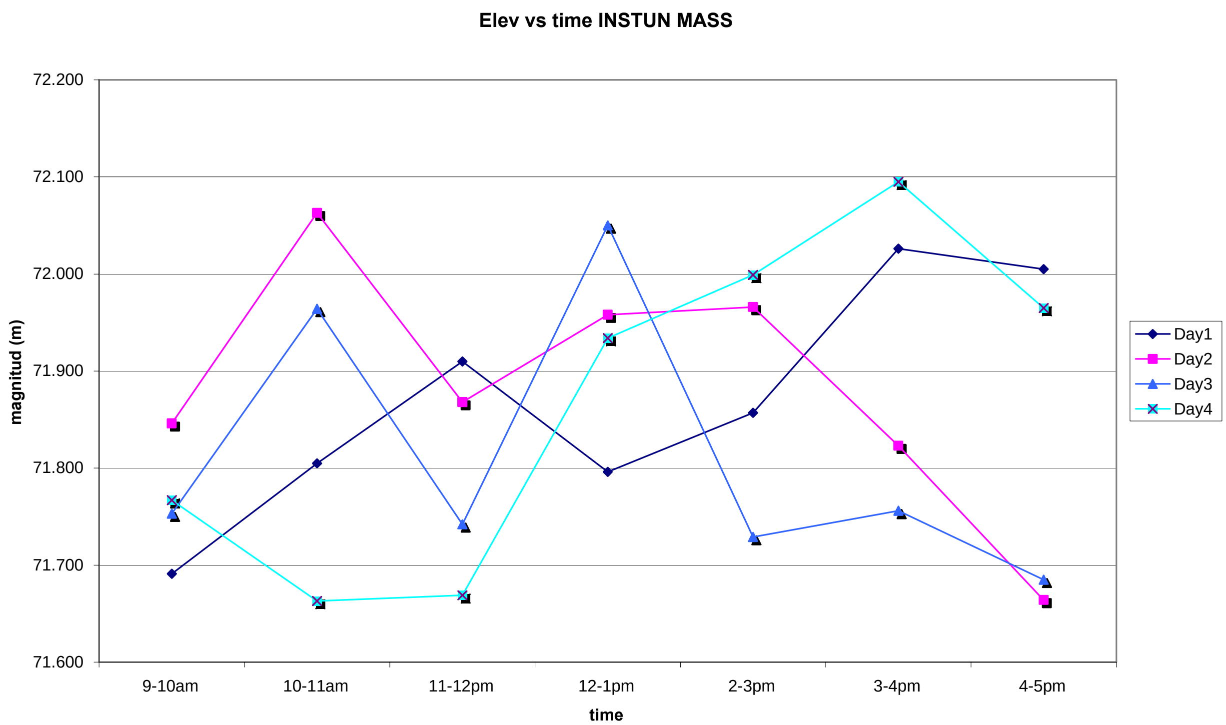
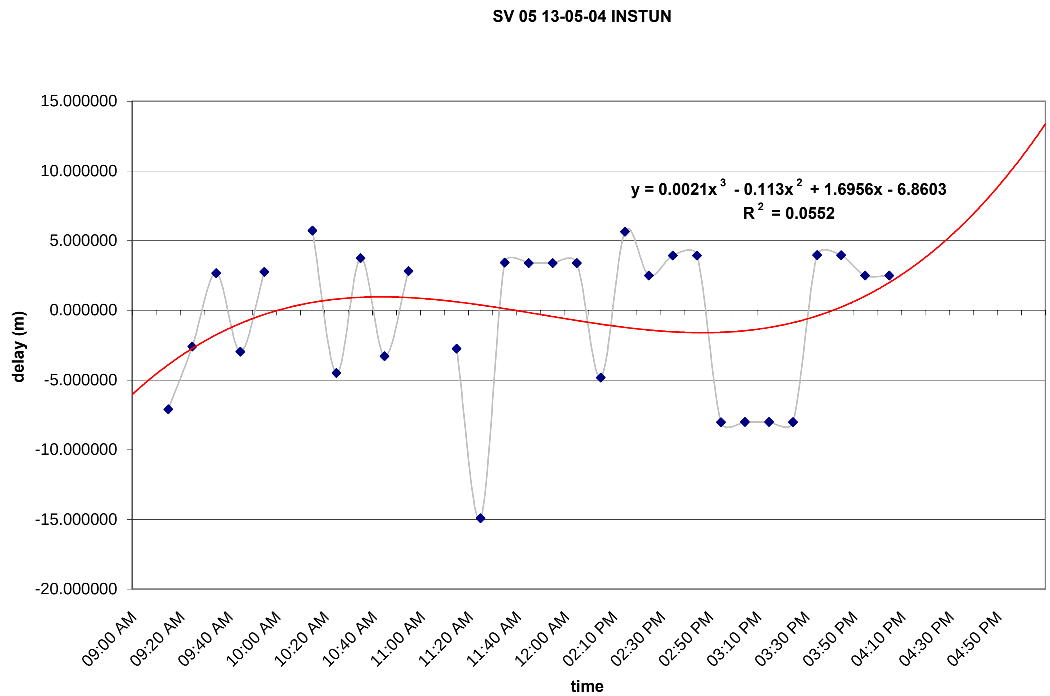


Figure 5-2: Hourly post-process GPS height component variation result of INSTUN

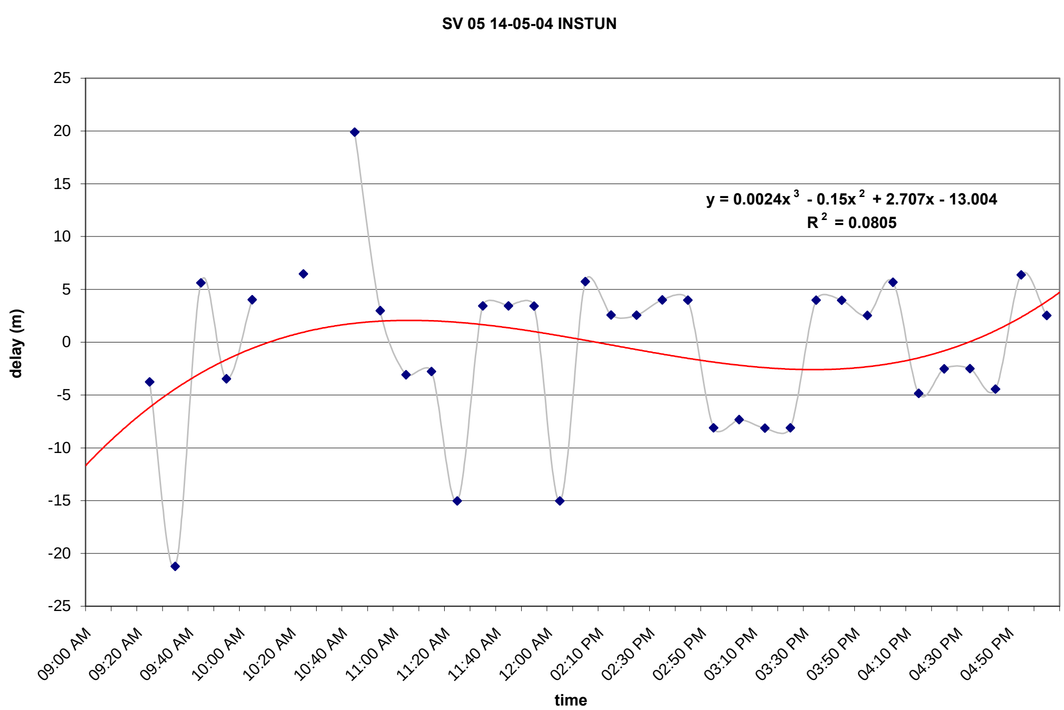
The result as shown in figure 5-2 shows the variations of height component value up to 0.5m after baseline processing and adjustment using a precise orbit and ionospheric free solutions. This variation is expected due to the tropospheric delay since the entire major error source has been eliminated.

To determine each individual satellites range delay, a Saastamoinen empirical model is introduce to the data using a computer program develop specially for purpose.

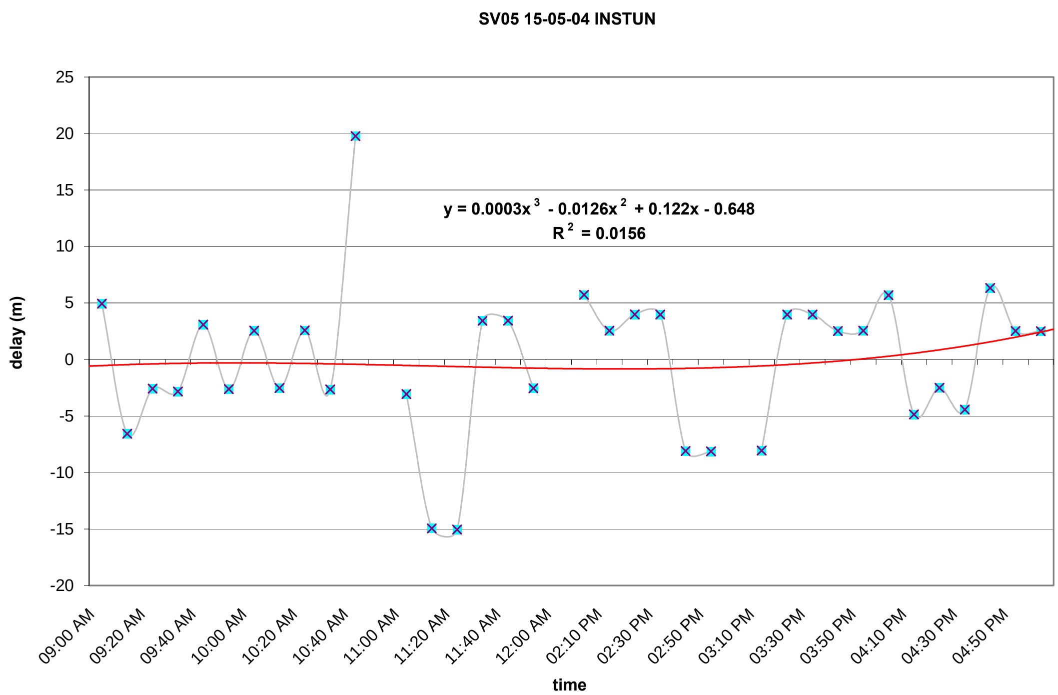
The results are shown in Figures 5.3 to figure 5.6 as follows.



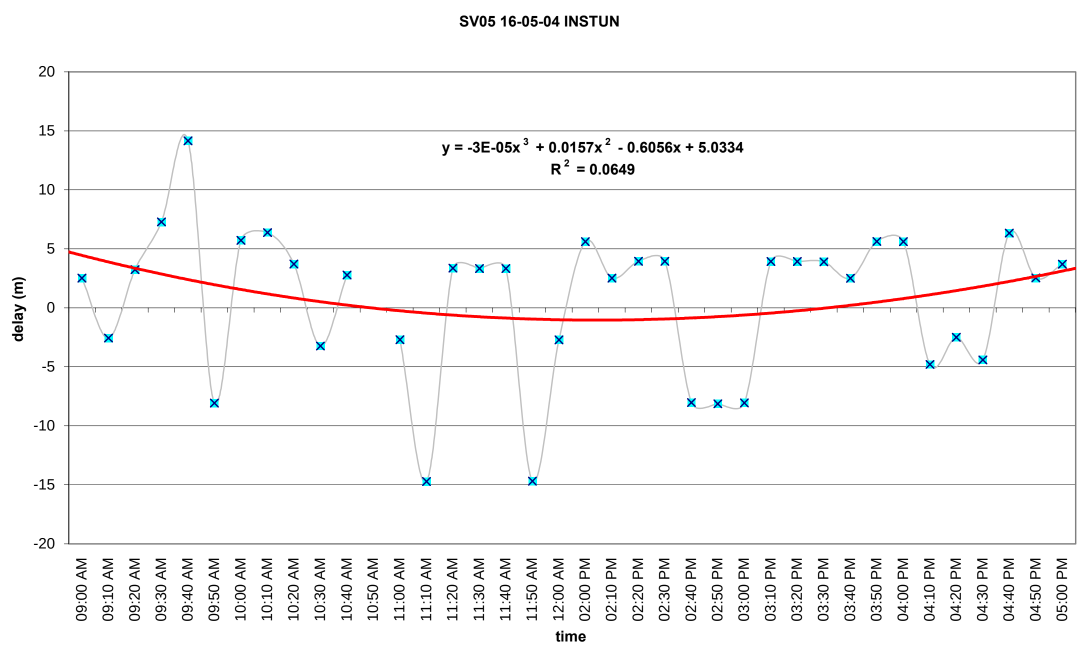
(a)



(b)

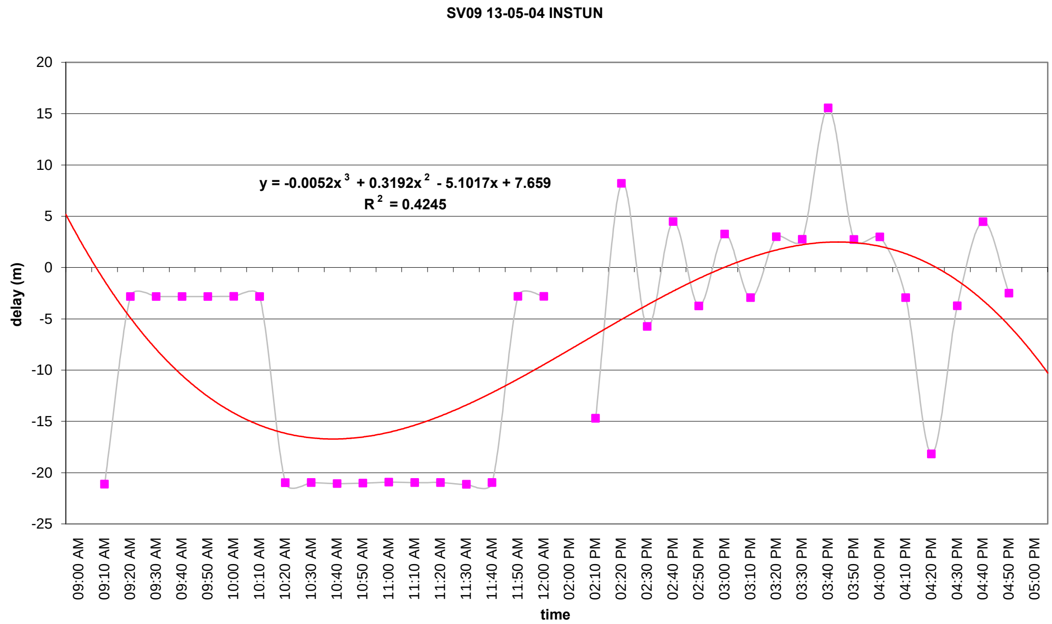


(c)



(d)

Figure 5-3: Signal refraction delay of PRN05 on day 1 day 2 day 3 and day 4


SV09 13-05-04 INSTUN
y = -0.0052x³ + 0.3192x² - 5.1017x + 7.659
R² = 0.4245
delay (m)
time
20
15
10
5
0
-5
-10
-15
-20
-25
09:00 AM
09:10 AM
09:20 AM
09:30 AM
09:40 AM
09:50 AM
10:00 AM
10:10 AM
10:20 AM
10:30 AM
10:40 AM
10:50 AM
11:00 AM
11:10 AM
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03:30 PM
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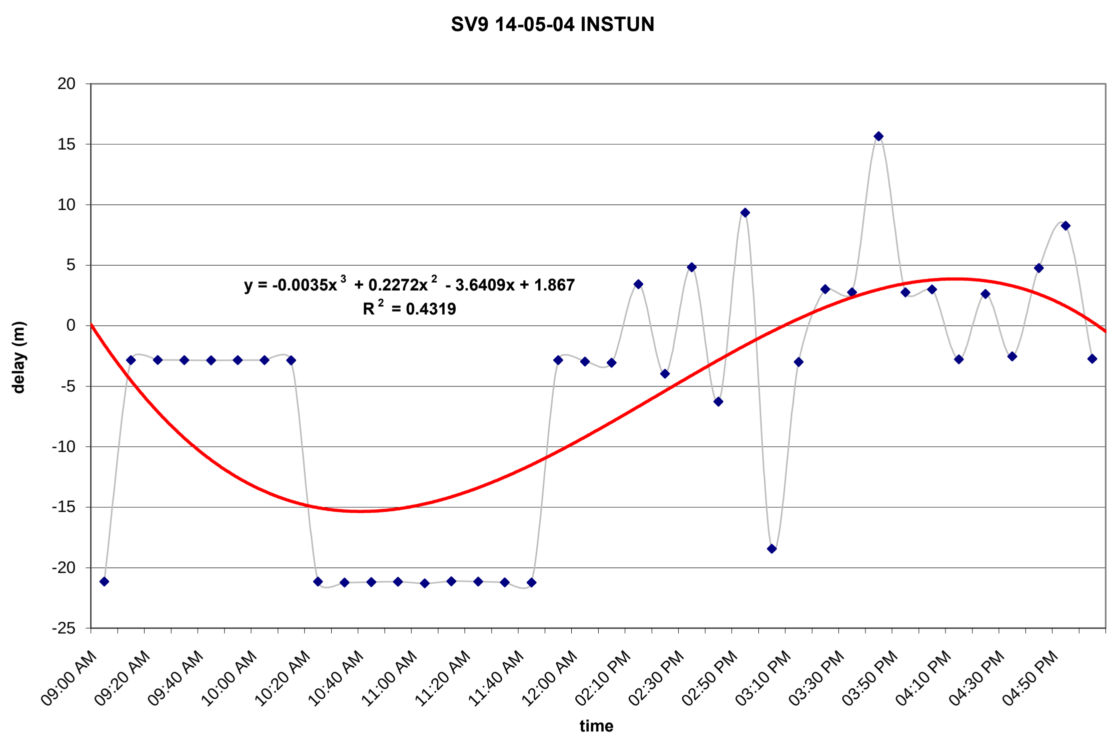
04:00 PM
04:10 PM
04:20 PM
04:30 PM
04:40 PM
04:50 PM
05:00 PM

(a)


SV9 14-05-04 INSTUN
y = -0.0035x³ + 0.2272x² - 3.6409x + 1.867
R² = 0.4319
delay (m)
time
20
15
10
5
0
-5
-10
-15
-20
-25
09:00 AM
09:20 AM
09:40 AM
10:00 AM
10:20 AM
10:40 AM
11:00 AM
11:20 AM
11:40 AM
12:00 AM
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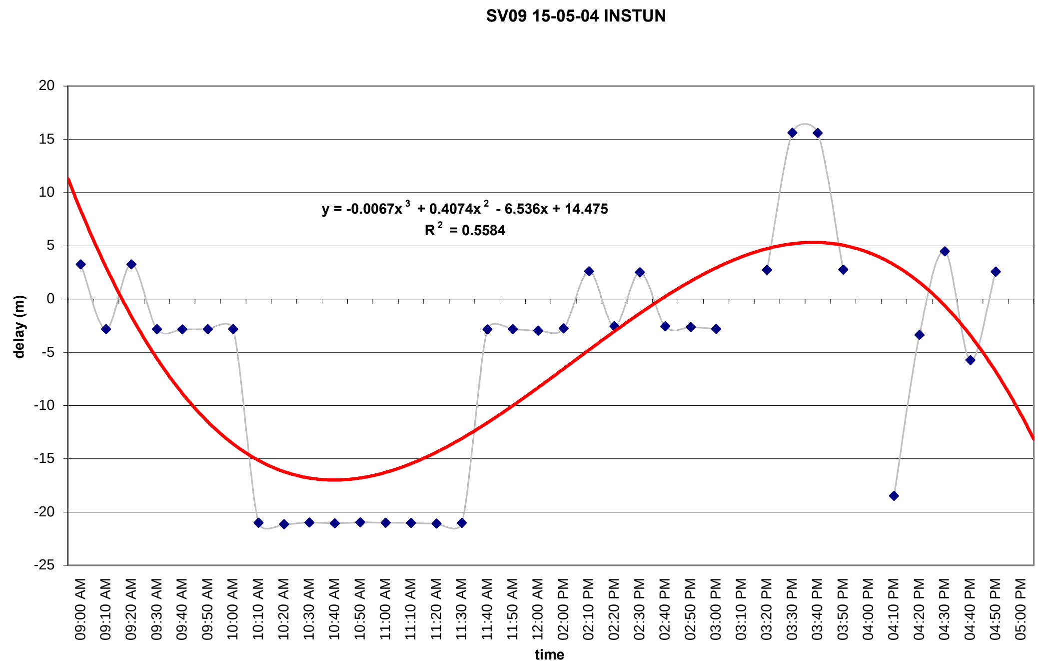
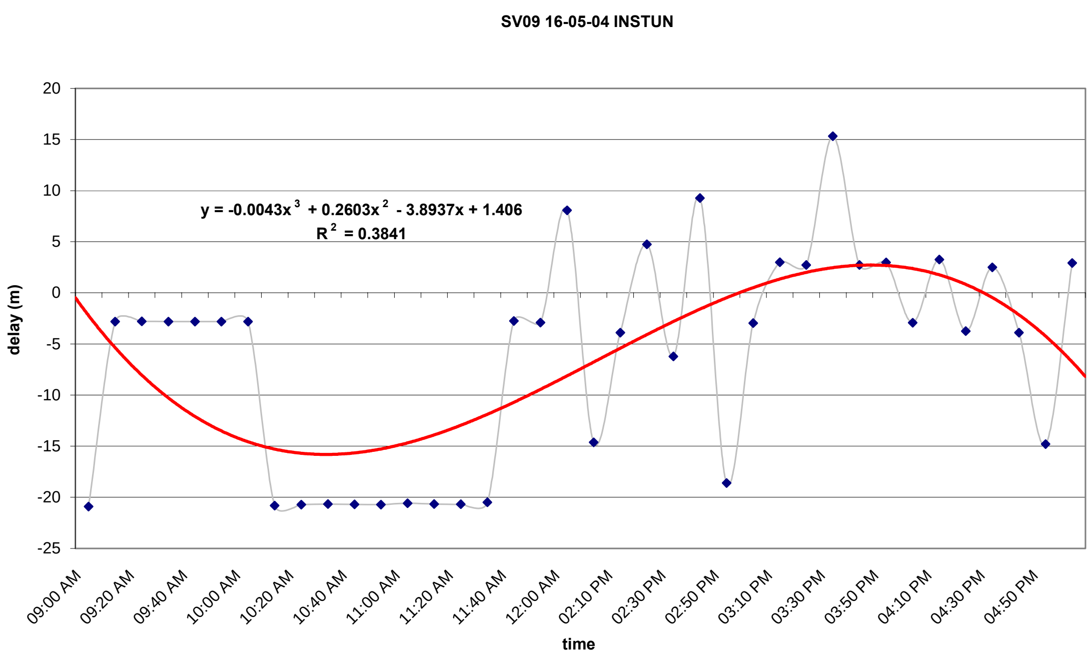
04:30 PM
04:50 PM

(b)

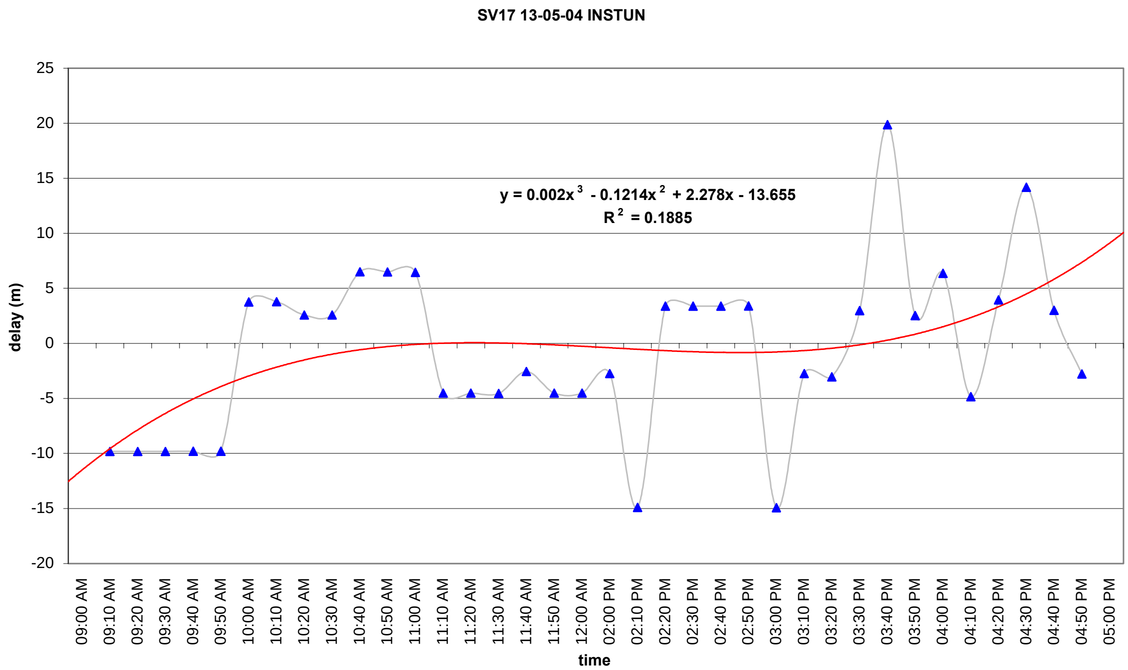


(c)



(d)

Figure 5-4: Signal refraction delay of PRN09 on day 1 day 2 day 3 and day 4


SV17 13-05-04 INSTUN
y = 0.002x^3 - 0.1214x^2 + 2.278x - 13.655
R^2 = 0.1885
delay (m)
time
25
20
15
10
5
0
-5
-10
-15
-20
09:00 AM
09:10 AM
09:20 AM
09:30 AM
09:40 AM
09:50 AM
10:00 AM
10:10 AM
10:20 AM
10:30 AM
10:40 AM
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03:30 PM
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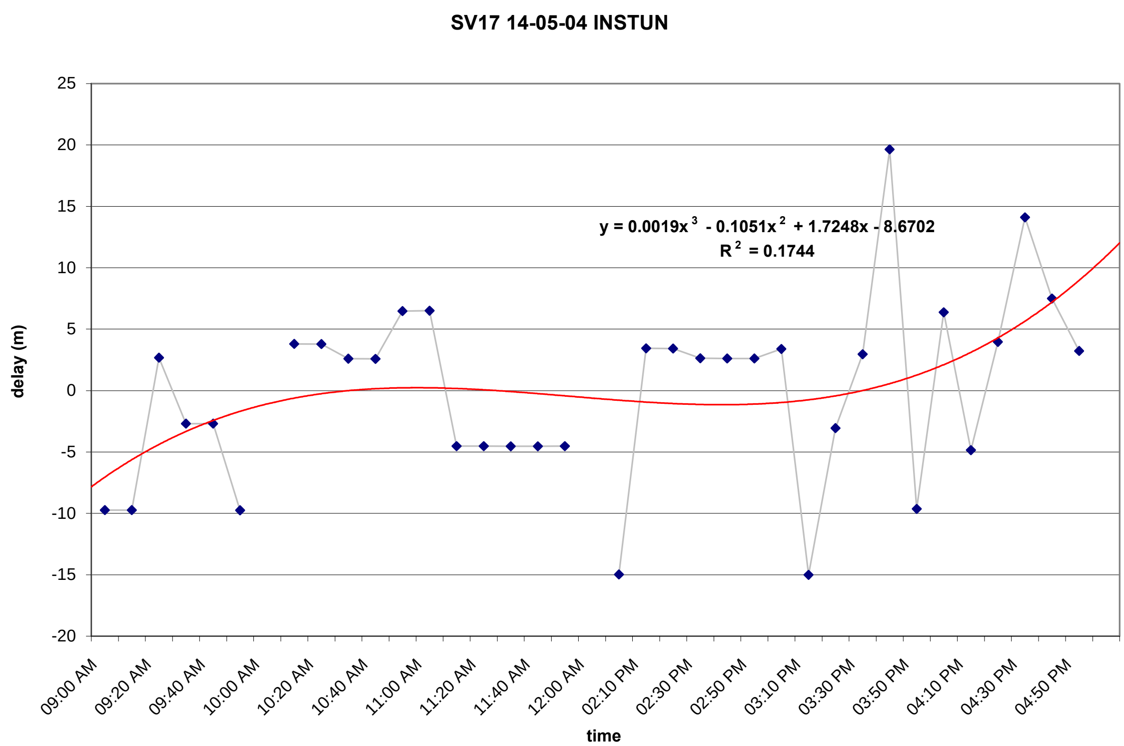
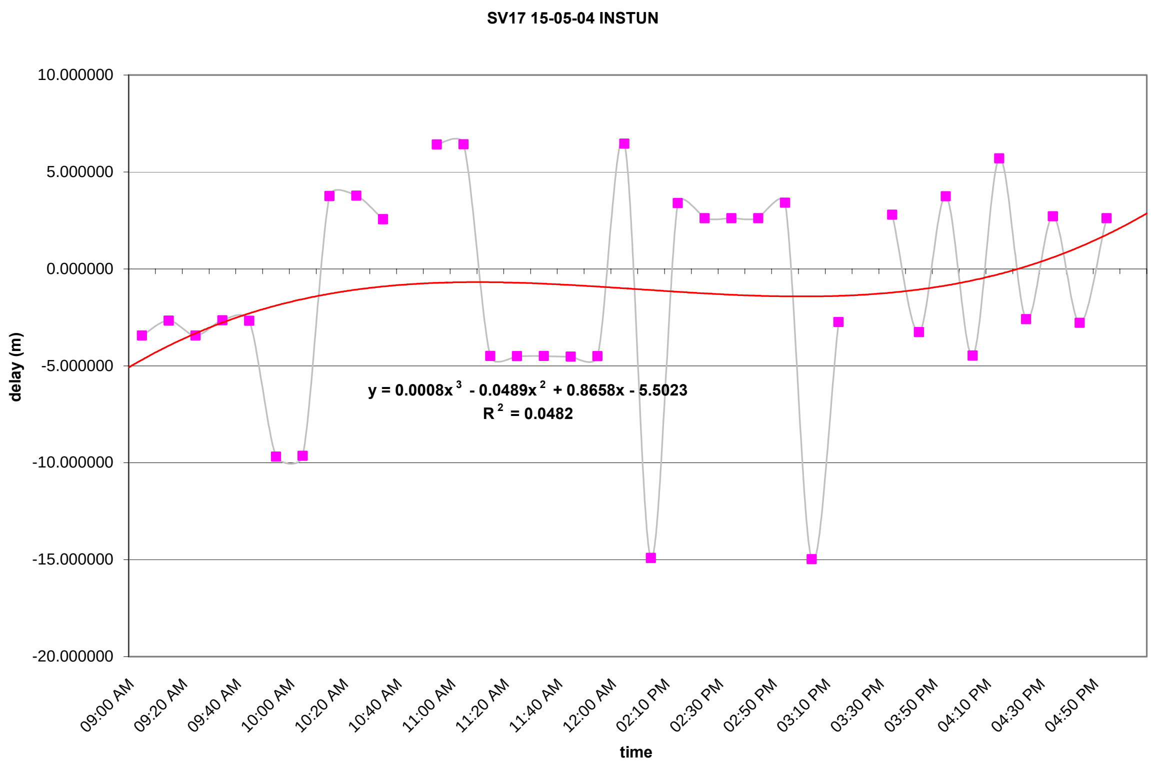
04:30 PM
04:40 PM
04:50 PM
05:00 PM

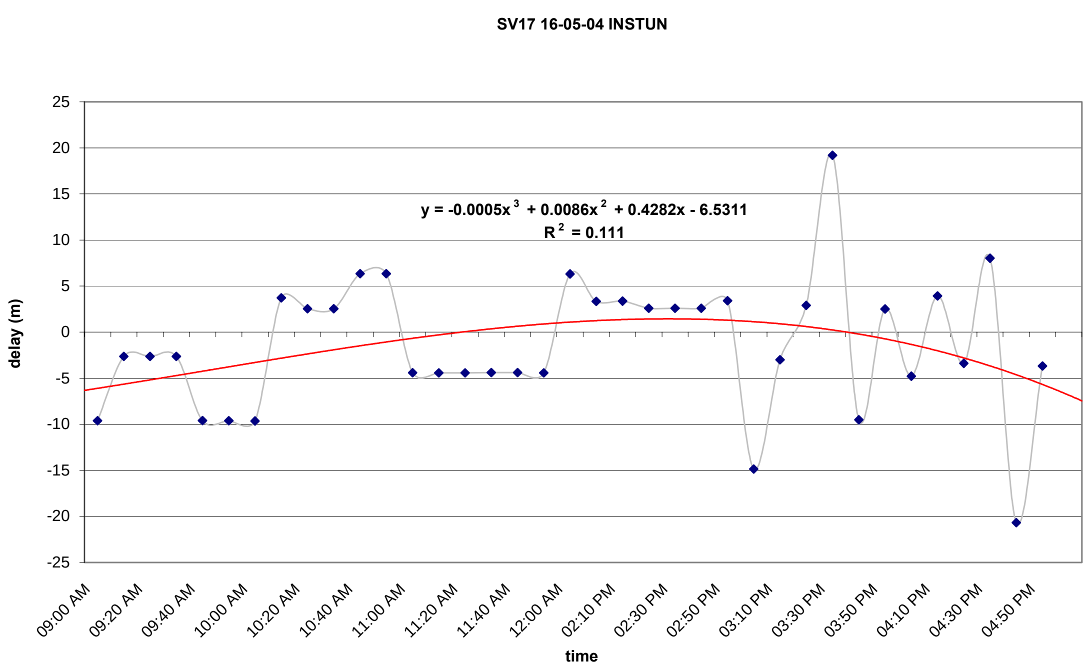
(a)


SV17 14-05-04 INSTUN
y = 0.0019x^3 - 0.1051x^2 + 1.7248x - 8.6702
R^2 = 0.1744
delay (m)
time
25
20
15
10
5
0
-5
-10
-15
-20
09:00 AM
09:20 AM
09:40 AM
10:00 AM
10:20 AM
10:40 AM
11:00 AM
11:20 AM
11:40 AM
12:00 AM
02:10 PM
02:30 PM
02:50 PM
03:10 PM
03:30 PM
03:50 PM
04:10 PM
04:30 PM
04:50 PM

(b)

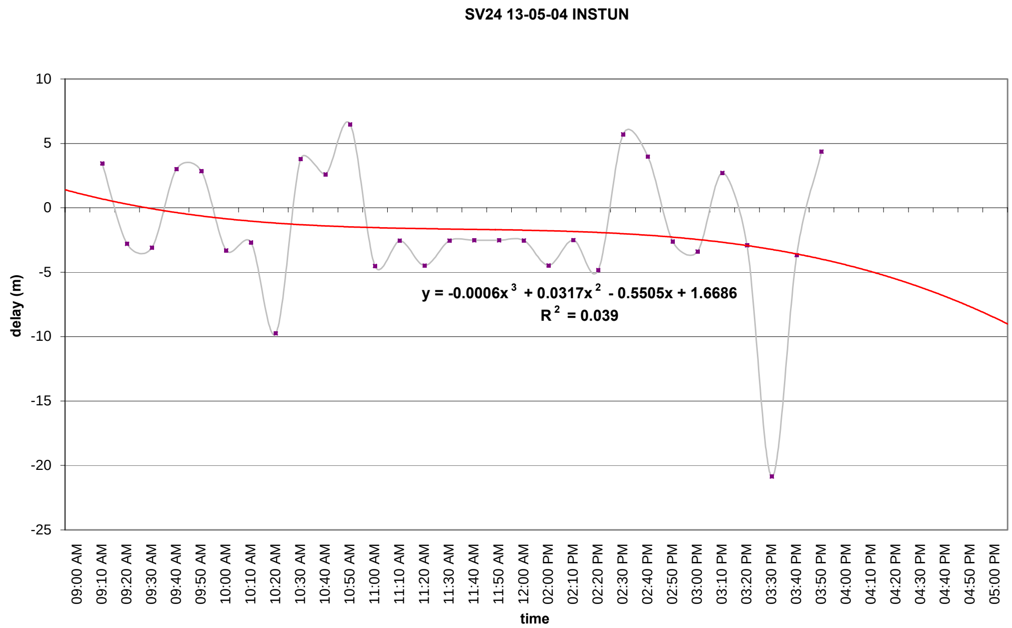


(c)

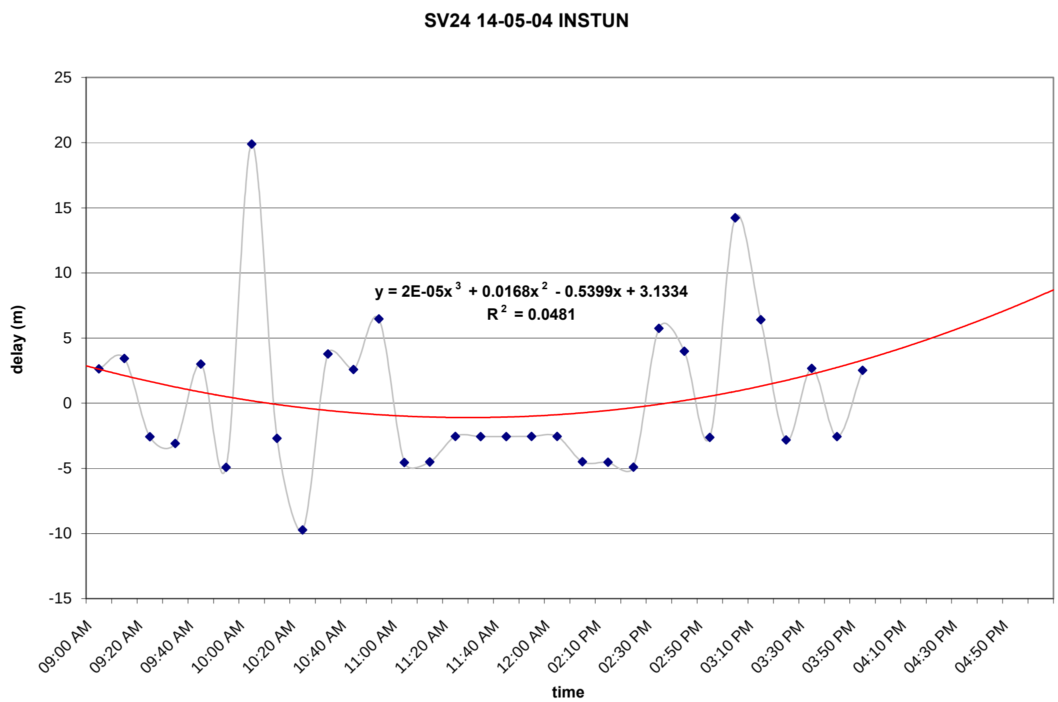


(d)

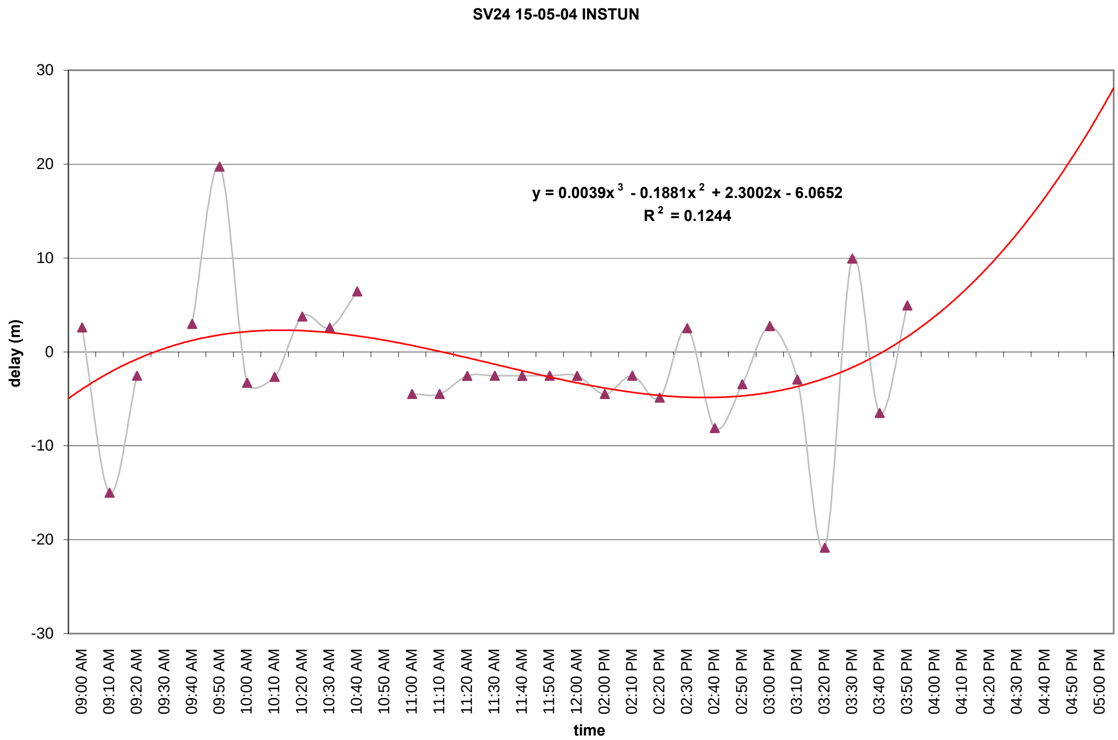
Figure 5-5: Signal refraction delay of PRN17 on day 1 day 2 day 3 and day 4


SV24 13-05-04 INSTUN
delay (m)
time
y = -0.0006x³ + 0.0317x² - 0.5505x + 1.6686
R² = 0.039

(a)


SV24 14-05-04 INSTUN
delay (m)
time
y = 2E-05x³ + 0.0168x² - 0.5399x + 3.1334
R² = 0.0481

(b)



(c)

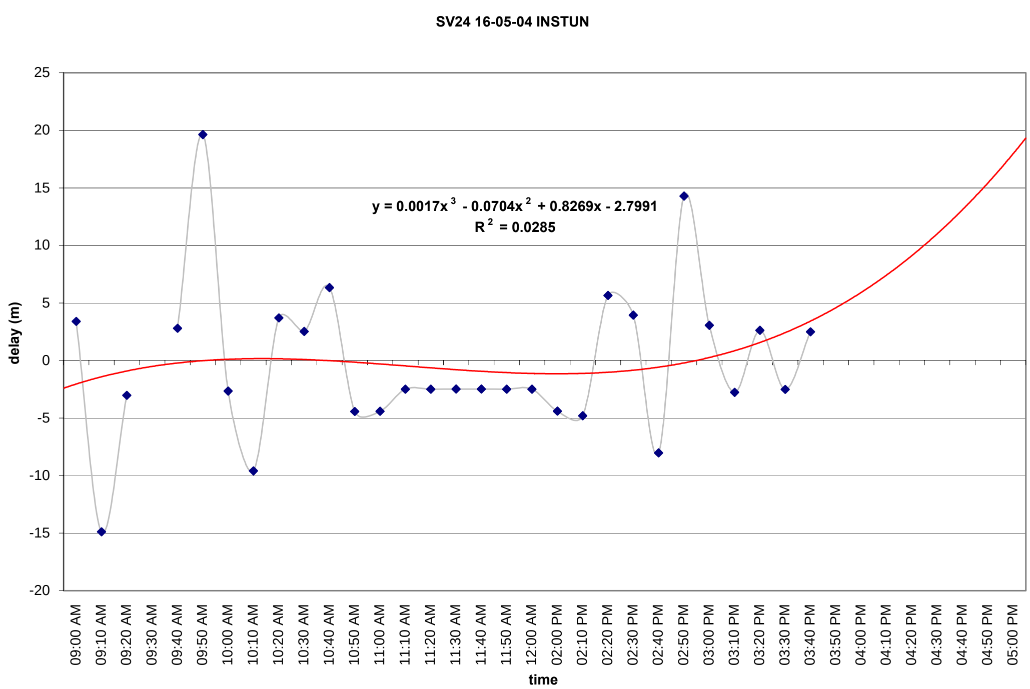


Figure 5-6: Signal refraction delay of PRN24 on day 1 day 2 day 3 and day 4

The result shows inconsistency in the delay variation but reach a maximum delay up to 20 meters in pseudorange. The sinusoidal red line in the plot shows the 3rd degree polynomial for the modeling purposes. The difference between the observe data and the control value of the point is represented in figure 5-7:-

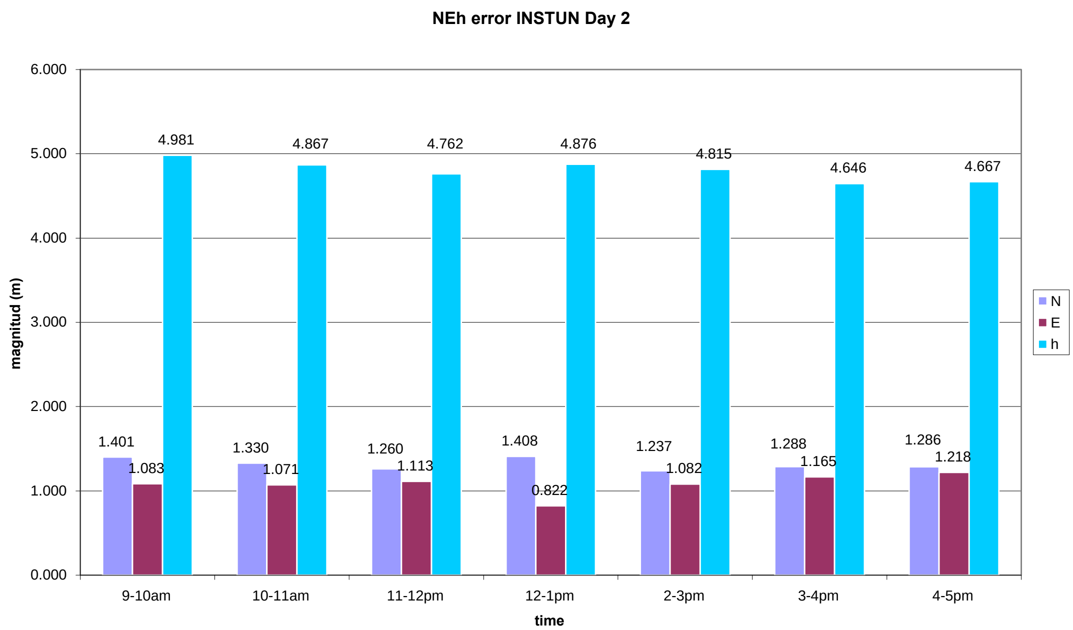


Figure 5-7: Position value differences to the control value of the point

The result as shown in figure 5-7 is base on a single long baseline processing and shows an error magnitude nearly 5 meters for the height components. This is what we believe to be the result of the 20-meter range delay experience by the signal estimated using the Saastamoinen model earlier.

5.10 Conclusions and Recommendation

The result of introducing a Saastamoinen model into the data shows a delay variation for up to 20 meter in pseudorange, which causes an error up to 5 meter to the height component which may came from the tropospheric delay of the signal since all the major error source has been virtually eliminated during the processing. This paper verify that the integration of ground meteorological observations and GPS lead to a better understanding of the tropospheric delay to the GPS signal and improve the GPS height accuracy.

5.11 ACKNOWLEDGEMENTS

We acknowledge the geodesy section of Institut Tanah dan Ukur Negara (INSTUN), and Department of Survey and Mapping Malaysia (DSMM) for their coorporation in this study. This study is funded by vote 74158 Research Management Centre (RMC)-UTM.

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CHAPTER 6

SUMMARY AND CONCLUSIONS

6.0 Summary

Tropospheric water vapor plays an important role in the global climate system and is a key variable for short-range numerical weather prediction. Despite significant progress in remote sensing of wind and temperature, cost-effective monitoring of atmospheric water vapor is still lacking. Data from the Global Positioning System (GPS) have recently been suggested to improve this situation.

The highest amount of water vapour can be observed is in the Equatorial region like Malaysia. Knowing that a large amount and strong variation of water vapour is found in the Equator region, a better understanding of the effect on the Global Positioning System (GPS) positioning activities is needed. Furthermore, the information about of water vapour in this region is of special interest for meteorologists because the behaviour is vital for understanding the global climate, whereas a short term variation of water vapour is a very useful input to local weather forecasting.

As the GPS signals propagate from the GPS satellites to the receivers located on the ground, they are also delayed by the troposphere. The delay can be represented by a function of satellite elevation and altitude of the GPS receiver, and is dependent on the atmospheric pressure, temperature and water vapour pressure. For modeling purpose the refractivity is separated into two components, hydrostatic (dry) and wet components. The hydrostatic component is dependent on the dry air gasses in the atmosphere and it accounts for approximately 90% of the delay.

The delay can be evaluated by the integration of the tropospheric refractivity along the GPS signal path, moisture content of the atmosphere and it accounts for the remaining effect of the delay.

High accuracy GPS software estimates the total tropospheric delay in the zenith direction at regular time intervals. Wet delay is caused by atmospheric water vapor, and dry or hydrostatic delay by all other atmospheric constituents.

The Global Positioning System can improved all-weather estimates of the atmospheric refractivity at very low cost compare with conventional upper-air observing systems. The applications of GPS has led to a new and potentially significant upper-air observing system for meteorological agencies. It is proposed in the estimation of integrated precipitable water vapour for the use in objective and subjective weather forecasting. This technique can be useful for Malaysia.

6.1 Conclusions

Continuous GPS satellite data incorporated with meteorological parameters can be use to study the effect of the lower part of the atmosphere. The main objective of this project is to demonstrate the feasibility of using (GPS) and that of ground based meteorological data to provide information for tropospheric model development. The development of a model and mapping of precipitable water vapours useful for climate studies.

In this study an investigation on the existing techniques has been executed in order to provide additional information. The extensive testing of simulated data with various surface modeling are carried out and data are collected from MASS GPS permanent stations in Malaysia maintained by JUPEM. The data collected by these stations are identified, evaluated and transferred for further processing. The meteorological data from several sites were identified and collected and processed for the quality of data. Then data analysis was carried out using a processing algorithm and was conducted at UTM. The modeling and testing of the model are carried out to determine the suitable tropospheric model to be used and the capabilities of the model to be developed. Then the field verification of the tropospheric model which is obtained by integrated GPS data and that of the ground based meteorological data several points was tested.

The applications of GPS has led to a new and potentially significant upper-air observing system for meteorological agencies and proposed in the prediction of weather forecasting. This technique can be useful for Malaysia since the continuous GPS satellite data obtained from Jabatan Ukur & Pemetaan Malaysia (JUPEM) can be incorporated with meteorological parameters used to study the effect of the lower part of the atmosphere. This study can provide benefits to government agencies, scientific researchers and even public who are interested in current information of weather forecast. The project is beneficial to researcher at UTM, JUPEM and Malaysian Meteorological Services since the real time data collected for surveying and navigation for future references and model developments can be acquired especially valuable information for short term weather broadcast and improved weather prediction in Malaysia. The Malaysian public especially the Navigation community can used this data for navigation purposes.

The result of introducing a Saastamoinen model into the data shows a delay variation for up to 20 meter in pseudorange, which causes an error up to 5 meter to the height component which effected from the tropospheric delay of the signal since all the major error sources have been virtually eliminated during the processing. The tropospheric delay can be estimated by using real time meteorological data and GPS observations.

A revision of the existing model has been carried out base on local meteorological parameters to satisfy the humid tropical climate such as Malaysia before it can be applied for high accuracy GPS purposes. An appropriate mapping function need to be identified and introduce into the calculation to get a more reliable result.

Finally, the study had verified that the integration of ground meteorological observations and GPS lead to a better understanding of the tropospheric delay to the GPS signal and improve the GPS height accuracy.

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APPENDIXES

APPENDIX A

A1: Observation of GPS and Ground based meteorological data

GPS antenna used for data collection

Ground based Meteorological instrument

Ground-based Meteorological instrument collecting data

Map showing the location of GPS MASS station at UTM

GPS Antenna at MASS station in UTM

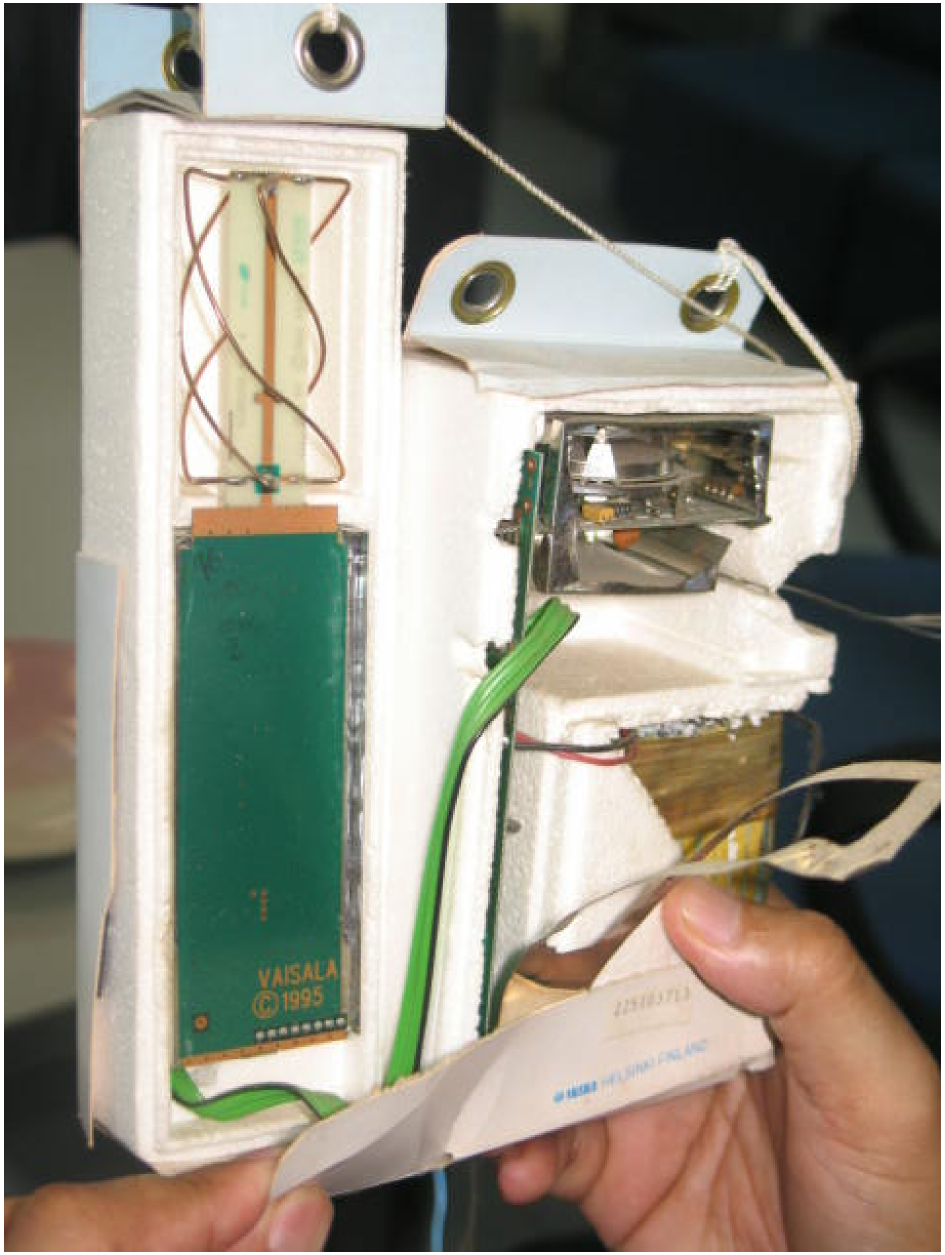
APPENDIX B

Acknowledgement:

Special thanks to Meteorological department for the opportunity to visit the KLIA meteorological department in Sepang, Selangor

B1. Meteorological data obtained by releasing balloon

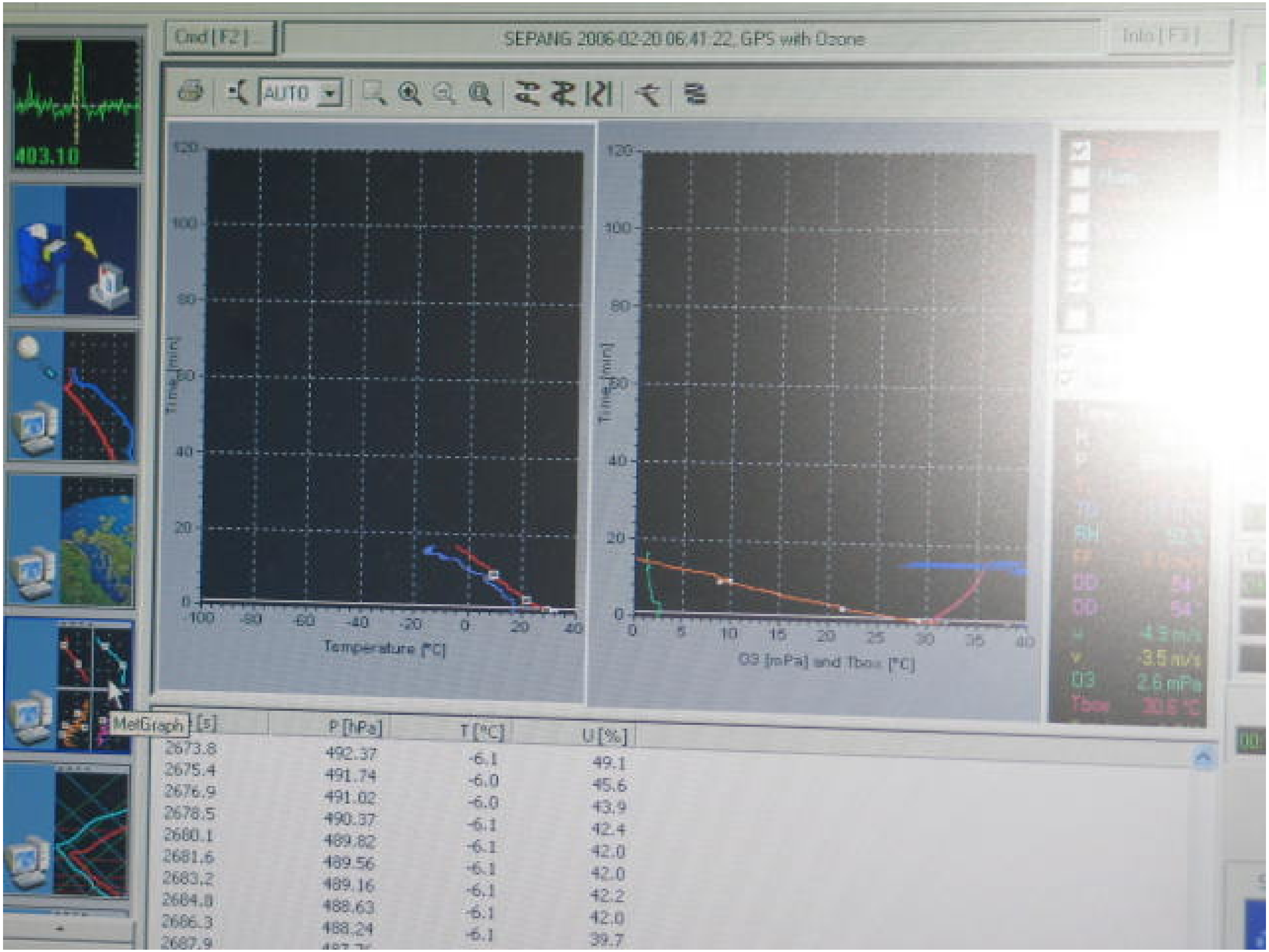
B2. Meteorological data obtained by releasing balloon



B3. Radiosonde with GPS receiver

B4. Balloon with radiosone and GPS receivers

B5. Balloon with radiosone and GPS receivers



B6. Data collection download from computer