THE IMPACT OF TROPOSPHERIC DELAY TOWARDS THE ACCURACY OF GPS HEIGHT DETERMINATION

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Abstract

When Global Positioning System (GPS) satellite signals propagates through the earth's neutral atmosphere, the radio signals are affected significantly by the variability of its refractive index, which causes primarily in the delay of the arrival, usually referred to as the tropospheric delay. Without proper compensation, the delay affects significantly to the accuracy of GPS derived position especially in height component therefore is a matter of concern for geodetic and other high accuracy applications.With a view to visualize any discrepancies on height component of GPS measurement due to the tropospheric delay, RINEX data of MyRTKnet from five GPS reference stations in Johor have been integrated with GPS and ground local meteorological observations. Being held at one of GPS point in UTM, changes made on the antenna height at each observation session. In order to determine the amount of GPS signal propagation delay, a computer program namely TROPO.exe has also been developed based on a refined Saastamoinen tropospheric model. Results show that the tropospheric delay is a distance-dependent error that will increase when the baseline lenght between two stations increases. Furthermore, it also varies with changes in meteorological condition of daily observation. Based on another test using simulated data, it is proved that the amount of tropospheric delay will decrease when the antenna height increases.

Keywords : *Ground local meteorological observation, MyRTKnet data, refined Saastamoinen model, tropospheric delay*

1.0 INTRODUCTION

1.1 Global Positioning System (GPS)

Global Positioning System (GPS) is an all-weather satellite-based positioning system operated by the U.S. Department of Defense (DoD). This multi-satellites system provides real time three-dimensional positioning (X, Y, Z or latitude, longitude and height), velocity information and time in common reference system 24 hours a day.

GPS is capable of quickly collecting vast amounts of position information. However, as in any positioning techniques or devices, GPS derived position is polluted by many sources of error. Error can be defined as any deviation in measured position from the true position. In brief, GPS measurement errors can be classified into three major groups, which are satellite, receiver and signal propagation dependent. Satellite error dependent consists of clock bias and orbital error. Receiver error dependent refers to antenna phase center variation, clock bias and multipath while the signal propagation dependent refers to ionospheric and tropospheric delay.

1.2 Tropospheric Delay

Troposphere is the lower part of atmosphere where most of the world's weather takes place. Bounded above by the tropopause, it is situated at difference layer thickness above the earth surface which as according to Mendes (1998), extends up to about 16 km in the equator where Malaysia is located. Due to the variability of refractive index within the troposphere, the propagation speed of signals transmitted from GPS satellites are equally reduced with respect to free-space popagation, usually referred to as tropospheric delay. Delay in time of GPS signals arrival induces variation in which a matter of concern for geodetic and other high accuracy applications.

The tropospheric delay is typically treated as the sum of two components. One is the hydrostatic component or also known as dry part, whereas the other is the nonhydrostatic component or also known as wet part. Equation 1.1 shows the general mathematical expression of the delay.

$$d^{Trop} = d_d^z \cdot m_d(\varepsilon) + d_w^z \cdot m_w(\varepsilon) \quad \text{.................................} \quad (1.1)$$

where

d^{Trop}	is the tropospheric delay at a given elevation angle ε
d_d^z, d_w^z ·	are the dry and wet zenith delays
m_d, m_w	are the corresponding mapping functions for mapping the zenith delay to the slant signal direction

Janes et. al. (1989) asserts that the dry part contributes amount of delay the most whereby approximately 90% on the GPS signal refraction. This component results from the gas contents of the troposphere. Nevertheless, the dry part can be computed accurately from pressure measured at the receiver antenna. Equation 1.2 shows general mathematical model of the dry component.

$$d_d^z = (77.62).\frac{p}{T} \quad \text{.................................} \quad (1.2)$$

where

p	is the atmospheric pressure in milibars (mbar)
T	is the temperature in degrees Kelvin

Wet component only accounts the remaining 10% of the delay. However, it is much difficult to model due to the diversity of water vapor distribution. As a result, errors in wet component are the most significant factor of signal refraction. Equation 1.3 shows general mathematical model of the wet component.

$$d_w^z = -(12.96).\frac{e}{T} + (3.718 \times 10^5).\frac{e}{T^2} \quad \text{.................................} \quad (1.3)$$

where

e	is the partial pressure of water vapour in milibars (mbar)

According to Remondi (1984), there are two ways in correcting for the wet propagation delay. The first technique is to measure the sky brightness temperature via radiometric microwave observations along the signal path using a water vapor radiometer. However, apart from being expensive, Kaplan, E. (1996) asserts that water vapor radiometer does not provide accurate data for satellites at low elevation angles. Furthermore, it is also impractical for most applications.

The second technique in correcting for the wet propagation delay is to depend on several tropospheric algorithms developed by geophysicists. Denoted as the most practical approach yet available, these models were experimentally derived with correspond to radiosonde data, observed mostly on the European and North American continents. Examples of proposed tropospheric models are Hopfield (1969), Chao (1972), Saastamoinen (1973), Lanyi (1984) and Neill (1996).

1.3 Refined Saastamoinen Model

Refined Saastamoinen model is one of the available standard tropospheric model for the determination of tropospheric path delay. Apart from other tropospheric models, refined Saastamoinen model has a good reputation in which is widely used for high accuracy GPS positioning (Jensen, 2002). The accuracy of the model was estimated to be about 3cm in zenith (Mendes, 1998). According to Hofmann-Wellenhof (1994), refined Saastamoinen model which includes both dry and wet parts as well as its mapping function can be expressed as:

$$\Delta^{Trop} = \frac{0.002277}{\cos z}\left[P + \left(\frac{1255}{T} + 0.05\right)e - B\tan^2 z\right] + \delta R \qquad (1.4)$$

where

Δ^{Trop}	is propagation delay in terms of range (m)
z	is zenith angle of the satellite
P	is atmospheric pressure at the site in milibar (mbar)
T	is temperature at the station in Kelvin (K)
e	is partial pressure of water vapor in milibar (mbar)
B, δR	are the correction terms for height and zenith angle

Based on Equation 1.4, e is calculated as a fractional of 1 from the relative degree of moisture. According to Murakami (1989), e can be outlined as:

$$e = 6.108RH \text{ x } \exp\left[\frac{17.15T - 4684}{T - 38.45}\right] \qquad \text{.................................} \; (1.5)$$

where

RH	is site relative humidity (in percentage)

The pressure P at height above sea level h (in kilometers) is given in terms of the surface pressure Ps and temperature T. Again, as according to Murakami (1989), P can be defined as:

$$P = Ps\left[\left(\frac{T - 4.5h}{T}\right)\right]^{7.58} \qquad \text{.................................} \; (1.6)$$

2.0 GPS AND GROUND LOCAL METEOROLOGICAL OBSERVATION

To acquire GPS derived position, static observation technique using well-calibrated dual-frequencies receiver, known as Leica™ System 500 have been used at one of GPS points (G11) in UTM. Ground meteorological sensor namely Davis GroWeather™ System weather station have been set next to the GPS instrument. Ten minutes interval of ground local meteorological data (temperature, pressure and relative humidity) were measured throughout the process. Overview of the GPS observation is as shown in Figure 2.1.

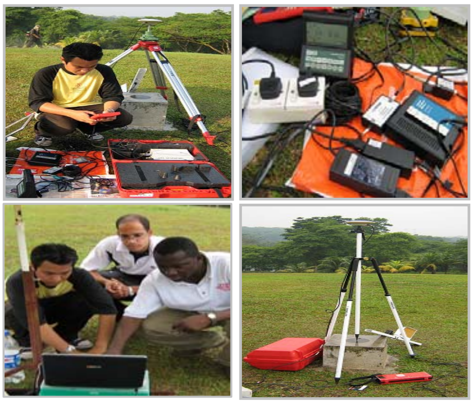


Figure 2.1: GPS Observation

Series of field observations were carried out for a total of nine hours per day and divided into three sessions (three hours per session). For each session, the antenna height had been increased systematically. These procedures were repeated for a total of four sets of observations where each set consists of three consecutive days of data collections. Scheduling of the field observation is as tabulated in Table 2.1.

Table 2.1: Time Scheduling of Field Observation

Observation Set		1	2	3	4
Observation Period		29–31 Aug 06	01-03 Dec 06	06–08 Jan 07	09–11 Jan 07
9 hours	1st Session (9am - 12pm)	Antenna Height : 0.5 m			
	2nd Session (12pm – 3pm)	Antenna Height : 1.0 m			
	3rd Session (3pm – 6pm)	Antenna Height : 1.5 m			

Five GPS reference stations in Johor RTK network performed as base stations thus producing five difference baselines to be processed and analyzed. Figure 2.2 depicts the overview of baselines while Table 2.2 shows the descriptions of selected MyRTKnet stations as well as distance relative to the rover station (GPS point) in UTM.

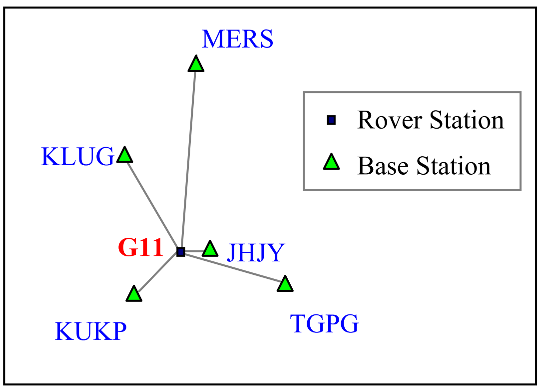


Figure 2.2: Baselines Overview of GPS Observation

Table 2.2: Descriptions of MyRTKnet Stations in Johor

ID	JHJY	KUKP	TGPG	KLUG	MERS
Station	Johor Bahru	Pontian	Pengerang	Mersing	Mersing
Location	SMK Taman JohorJaya(1)	JPS Bandar Permas	SK Tanjung Pengelih	Pejabat Daerah Kluang	SMK Mersing
Latitude	01º 32' 12.517586"	01º19' 59.790303"	01º 22' 2.678994"	02º 01' 31.361182"	02º 27' 12.482131"
Longitude	103º 47' 47.510364"	103º 27' 12.355342"	104º 06' 29.730485"	103º 19' 0.520982"	103º 49' 43.505376"
Elipsoidal Height (m)	39.1959	15.4282	18.0874	73.5879	18.0812
Distance Relative to G11 (km)	17.9051	32.1902	56.5244	62.7530	101.2633

3.0 PROCESSING METHODOLOGY

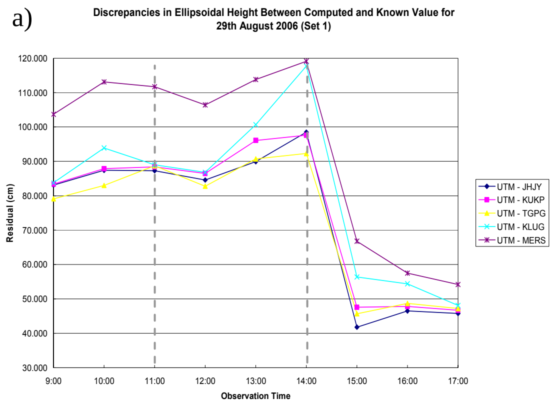
In order to study the impact of troposphere on the height determination, the tropospheric effect have been left uncompensated as no standard tropospheric model applied during processing. To eliminate the effect of ionosphere and both satellite and receiver clock bias, ionospheric free double difference solution has been applied. Multipath effect were assumed entirely eliminated by the long hours of observations in which case is 3 hours per session. As the GPS receiver is well-calibrated and in excellent condition, antenna phase center variation in this study have also been neglected. According to Waypoint Consulting Inc., (2005), there is no clear benefit to using the precise ephemeris for orbital correction for baselines of 200 km or less. Therefore, as baselines range from only 17 to 100 km in this research, the broadcast ephemeris has been used.

4.0 RESULTS AND ANALYSIS

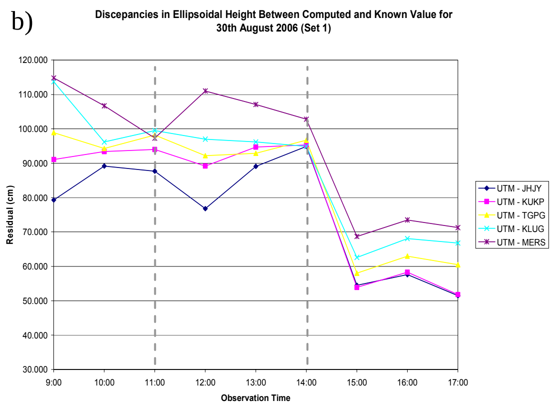
4.1 Tropospheric Effect on the Amount of Discrepancies of Ellipsoidal Height

Residuals in the computed ellipsoidal height at G11 of four sets of field observation compared to the known value were firstly calculated. As mentioned earlier, in this process, tropospheric effect have been left uncompensated. To visualize the variation on the height component of GPS measurement due to the tropospheric delay, discrepancies of ellipsoidal height between computed and known value for each baseline have been plotted against each hour of observation (see Figure 4.1, 4.2, 4.3 and 4.4)

a)



b)



c)

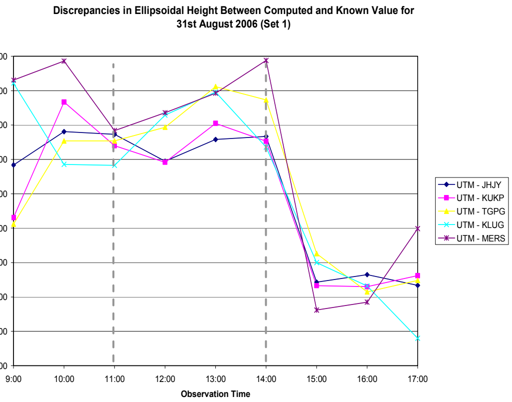
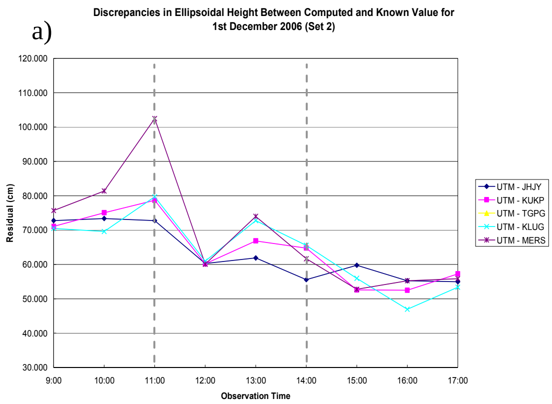
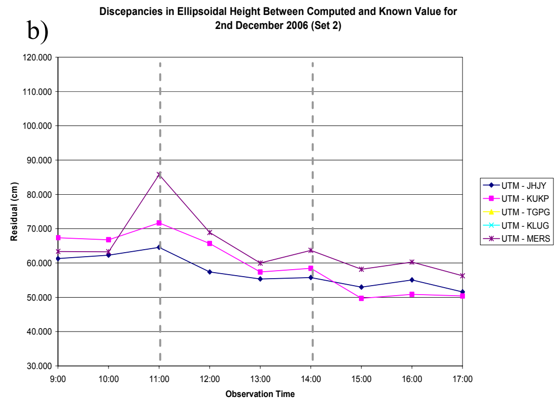


Figure 4.1 (a,b,c): Discrepancies of Ellipsoidal Height Between Computed and Known Value of Set 1 Observation (29–31 August 06)

a)



b)



c)

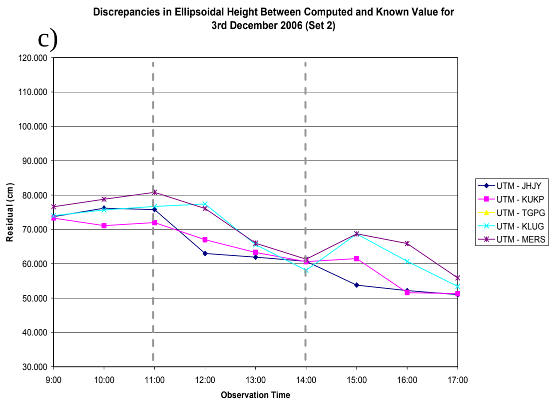
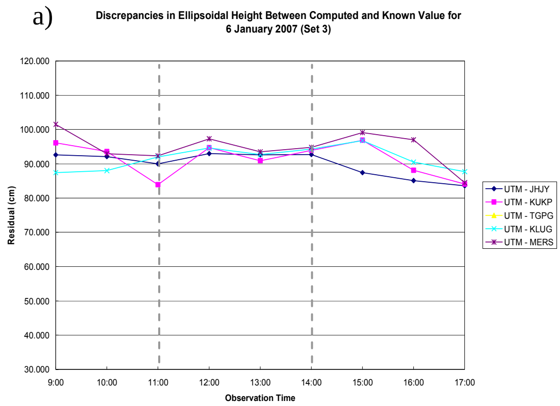
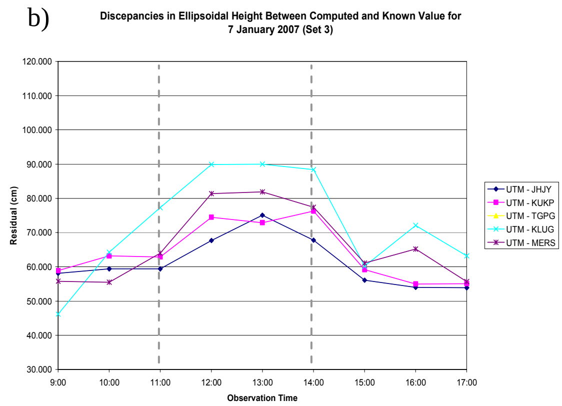


Figure 4.2 (a,b,c): Discrepancies of Ellipsoidal Height Between Computed and Known Value of Set 2 Observation (01 – 03 December 06)

a)



b)



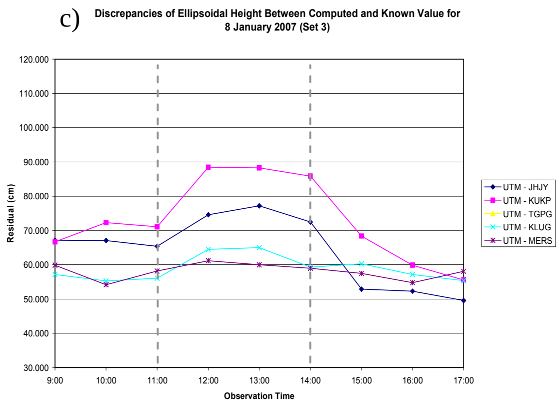


Figure 4.3 (a,b,c): Discrepancies of Ellipsoidal Height Between Computed and Known Value of Set 3 Observation (06 – 08 January 07)

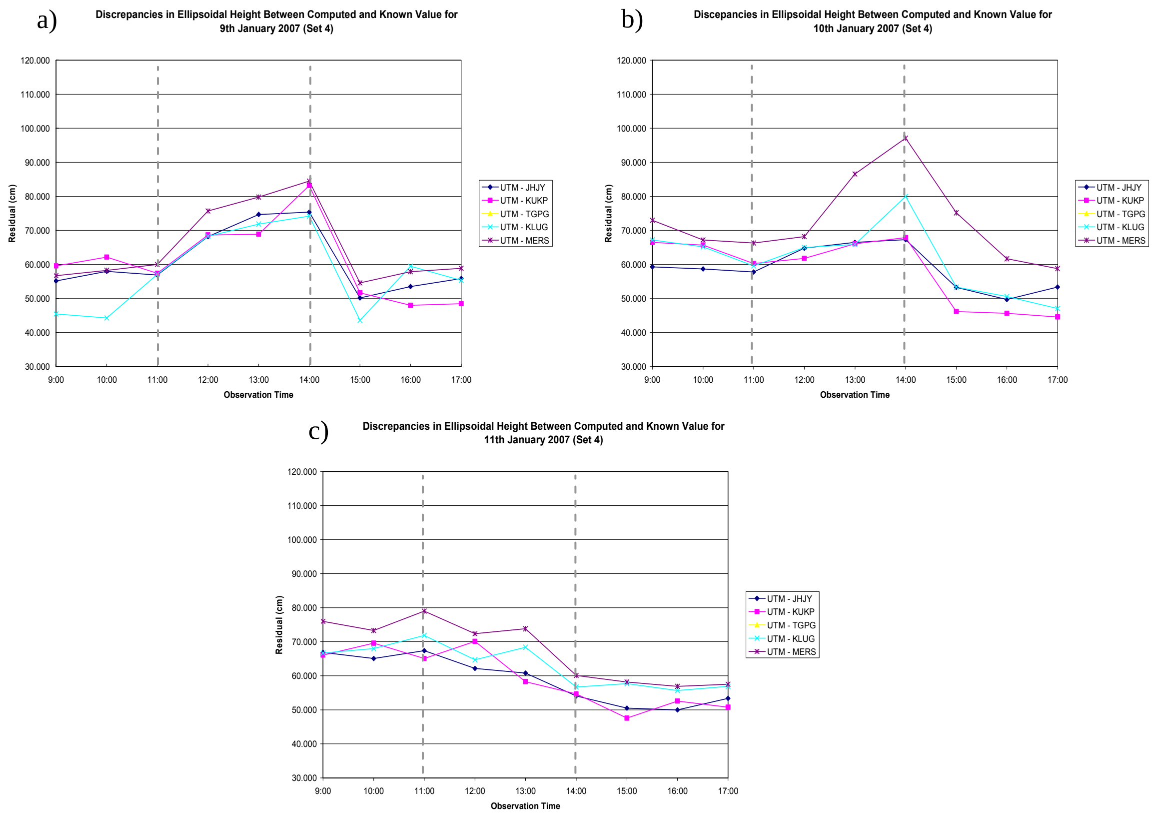


Figure 4.4 (a,b,c): Discrepancies of Ellipsoidal Height Between Computed and Known Value of Set 4 Observation (09 – 11 January 07)

Based on the results, it is obvious that neglecting the use of a standard tropospheric model leads to variations or uncertainties in height component of GPS measurement. Compared to the known value, maximum discrepancies of computed ellipsoidal height is at 119.100cm in which can be referred to UTM-MERS baseline at 2pm 29/08/06. On the other hand, minimum discrepancies is at 37.990cm in which can be referred to UTM-KLUG baseline at 5pm 31/08/06.

There is a susceptible of having maximum differences between the computed and known value at 10 to 12pm followed by another occurance period at 2 to 3pm. On the other hand, better result in computed height component is generally confined around 5 to 6pm.To analyze the correlation between this scenario to the effect of troposphere on GPS heighting, as extracted from Set 4 observation (see

Figure 4.4(a,b,c)), Table 4.1 shows the differences in term of meteorological condition at occurance time of maximum and minimum residuals for UTM-MERS baseline.

Table 4.1: Meteorological Condition at Maximum and Minimum Residuals of Computed Ellipsoidal Height for UTM-MERS Baseline of Set 4 Observation

UTM-MERS Baseline				
SET 4	9/1/2007	Max Residual(cm)		84.500
		Min Residual(cm)		54.600
		Met Value@ Max Residual	Temperature(C)	24.6
			Pressure(Hpa)	1009.4
			R.Humidity(%)	37
		Met Value@ Min Residual	Temperature(C)	23.7
			Pressure(Hpa)	1009.0
			R.Humidity(%)	37
	10/1/2007	Max Residual(cm)		97.090
		Min Residual(cm)		58.000
		Met Value@ Max Residual	Temperature(C)	31.9
			Pressure(Hpa)	1010.4
			R.Humidity(%)	38
		Met Value@ Min Residual	Temperature(C)	29.0
			Pressure(Hpa)	1008.0
			R.Humidity(%)	35
	11/1/2007	Max Residual(cm)		79.000
		Min Residual(cm)		56.900
		Met Value@ Max Residual	Temperature(C)	23.8
			Pressure(Hpa)	1012.9
			R.Humidity(%)	43
		Met Value@ Min Residual	Temperature(C)	24.1
			Pressure(Hpa)	1010.0
			R.Humidity(%)	41

It is clear that slight changes in meteorological condition can affect the amount of computed discrepancies. Differences up to 29.9cm between maximum and minimum residuals (9/1/2007) can be detected when changes in temperature and pressure were at 0.9C and 0.4Hpa respectively. However for observation on 10/1/2007, differences up to 39cm between maximum and minimum residuals can be detected when changes in temperature, pressure and relative humidity were at 2.9C, 2.4Hpa and 3% respectively. For observation on 11/1/2007, differences up to 22.1cm between maximum and minimum residuals can be detected when changes in temperature, pressure and relative humidity were at -0.3C, 2.9Hpa and 2% respectively. Based on these results, conclusion can be made that there is a direct correlation between the meteorological condition and the amount of discrepancies due to tropospheric delay.

4.2 Tropospheric Delay Analysis on Differences in Baselines Lenghts

In order to investigate whether tropospheric delay is also a distance-dependent error, comparison have been made on the residuals between short (UTM-JHJY) and long (UTM-MERS) baselines. Figure 4.5, 4.6, 4.7 and 4.8 illustrate the differences of height value derived from both baselines of all sets of observation.

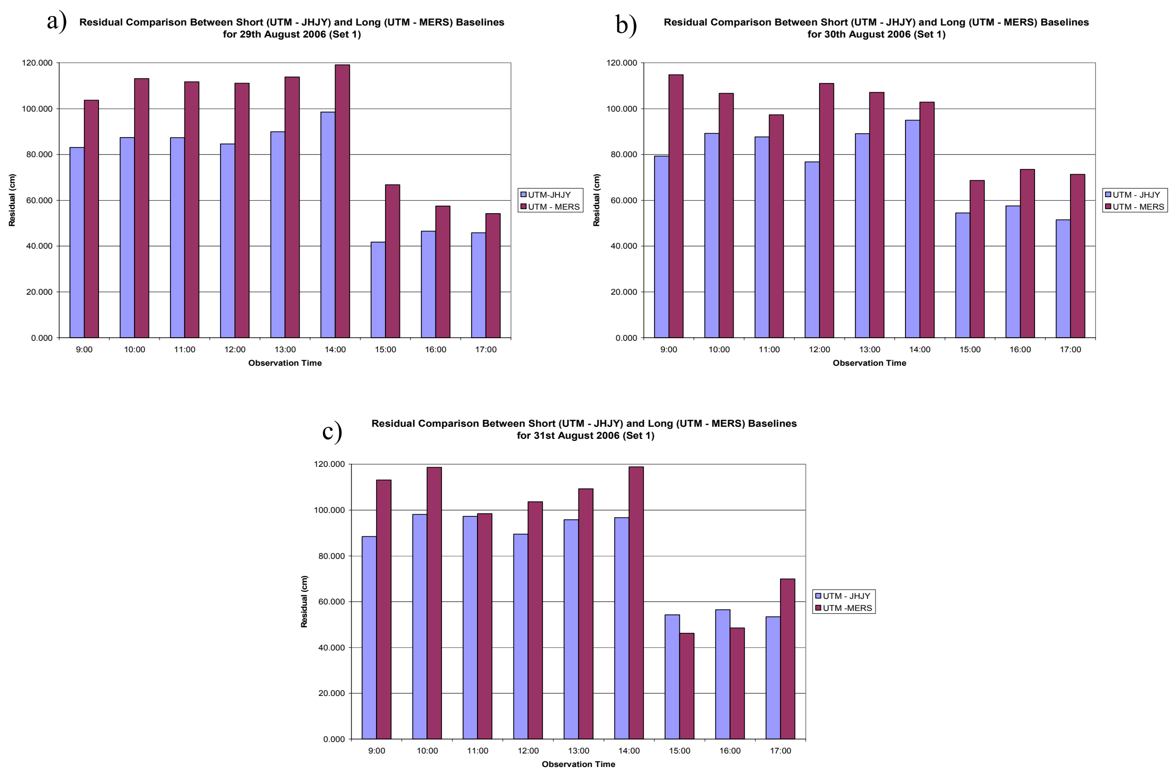


Figure 4.5(a,b,c): Residual Comparison Between Short (UTM - JHJY) and Long (UTM - MERS) Baselines of Set 1 Observation

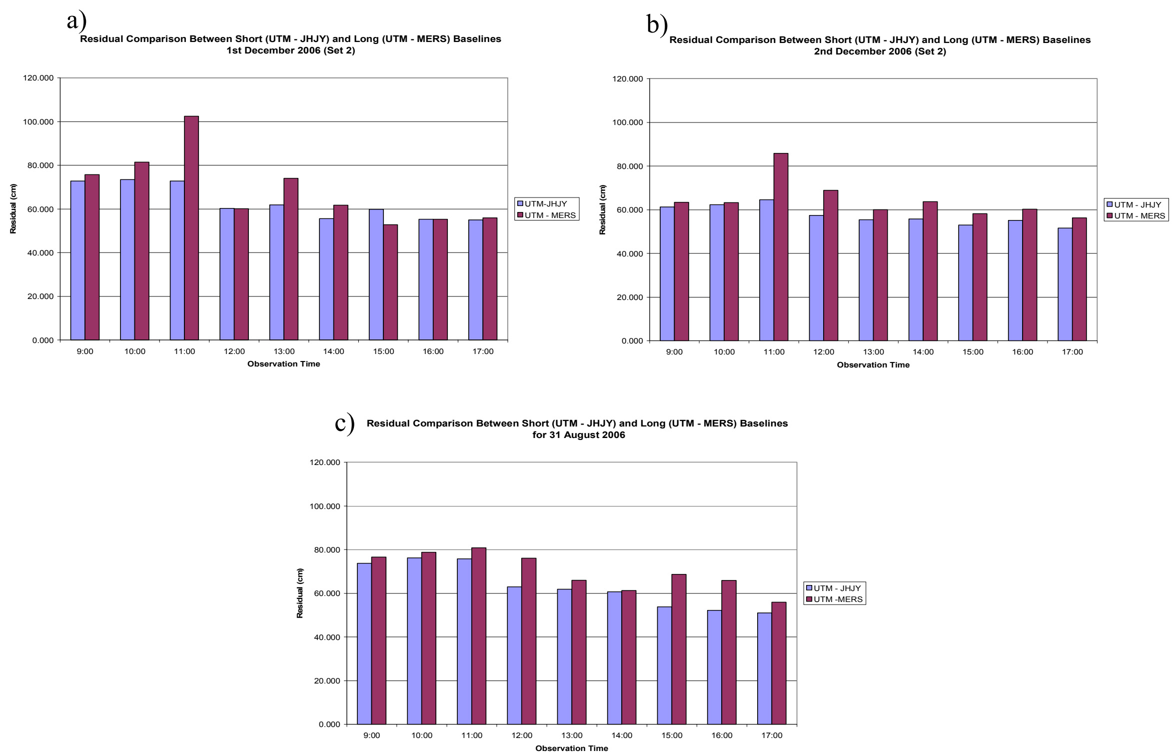
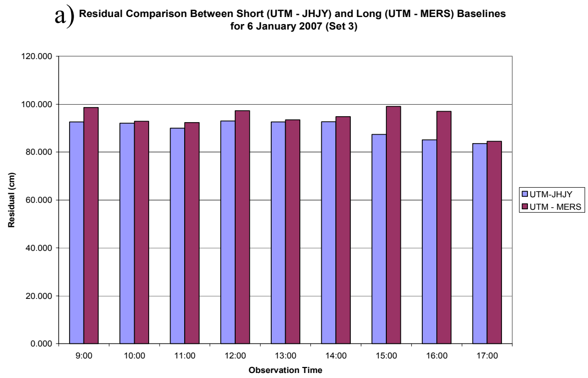
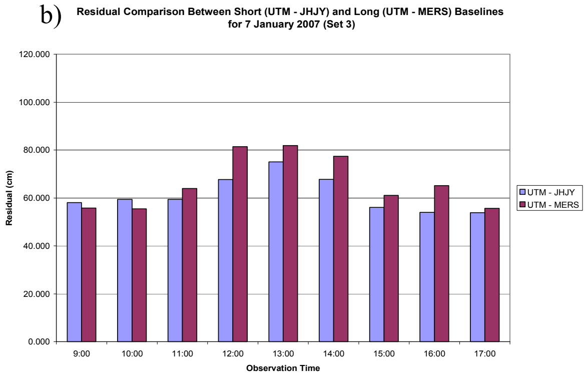


Figure 4.6(a,b,c): Residual Comparison Between Short (UTM - JHJY) and Long (UTM - MERS) Baselines of Set 2 Observation

a)


b)


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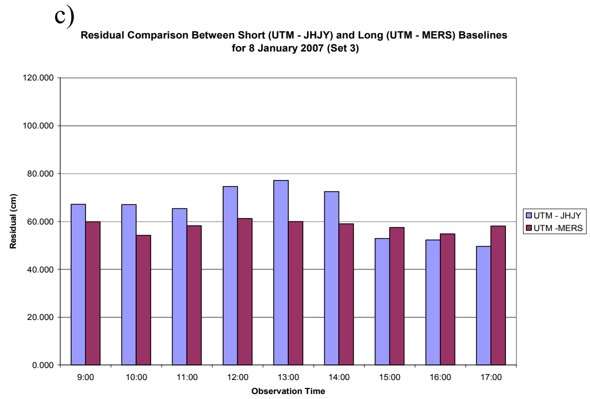
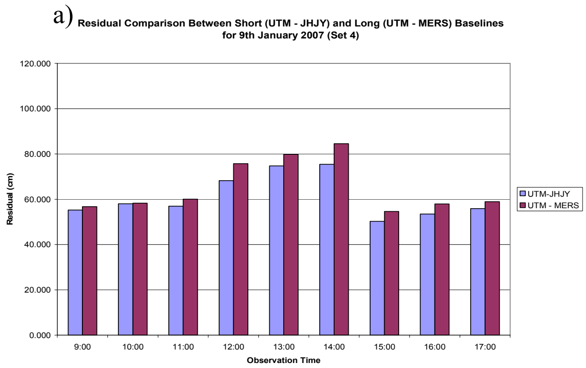
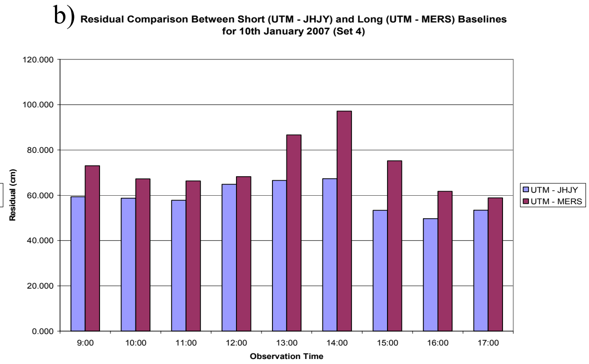


Figure 4.7(a,b,c): Residual Comparison Between Short (UTM - JHJY) and Long (UTM - MERS) Baselines of Set 3 Observation

a)


b)


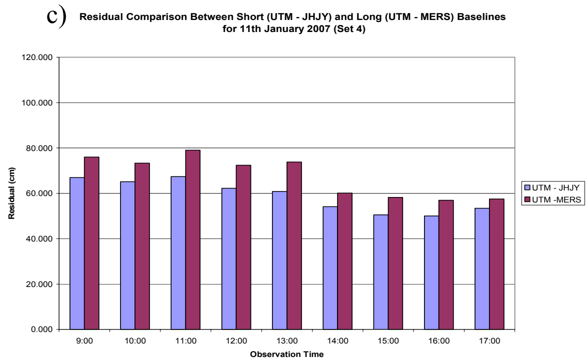
c)


Figure 4.8(a,b,c): Residual Comparison Between Short (UTM - JHJY) and Long (UTM - MERS) Baselines of Set 4 Observation

It is obvious that tropospheric error will increase when the baseline lenght between two stations increases. For long baseline such as UTM-MERS, the difference in tropospheric refraction will primarily be a function of the difference in the weather condition. This is due to the fact that signals transmitted from a satellite need to propagate through different amount of atmospheric content such as gases and water vapour within the troposphere due to large difference in baseline lenght before arriving to both receivers on the ground. However, for short baseline, signal paths from satellite to both receivers are essentially identical. Therefore, better result in the derived position is expected compared to long baseline.

4.3 Estimation of GPS Signal Propagation Delay

Within the troposphere, the propagation speed of signals transmitted from GPS satellites are equally reduced with respect to free-space popagation. To determine signals propagation delay of each available satellite, a computer program namely TROPO.exe have been developed based on refined Saastamoinen model. A total of four available satellites have been used in this study. These satelites namely SV 1, 7, 22 and 27 have been observed from UTM-JHJY baseline at 29 August 2006. The estimated delay recorded in UTM-JHJY baseline at 29 August 2006 for each satellite is then plotted and shown in Figure 4.9.

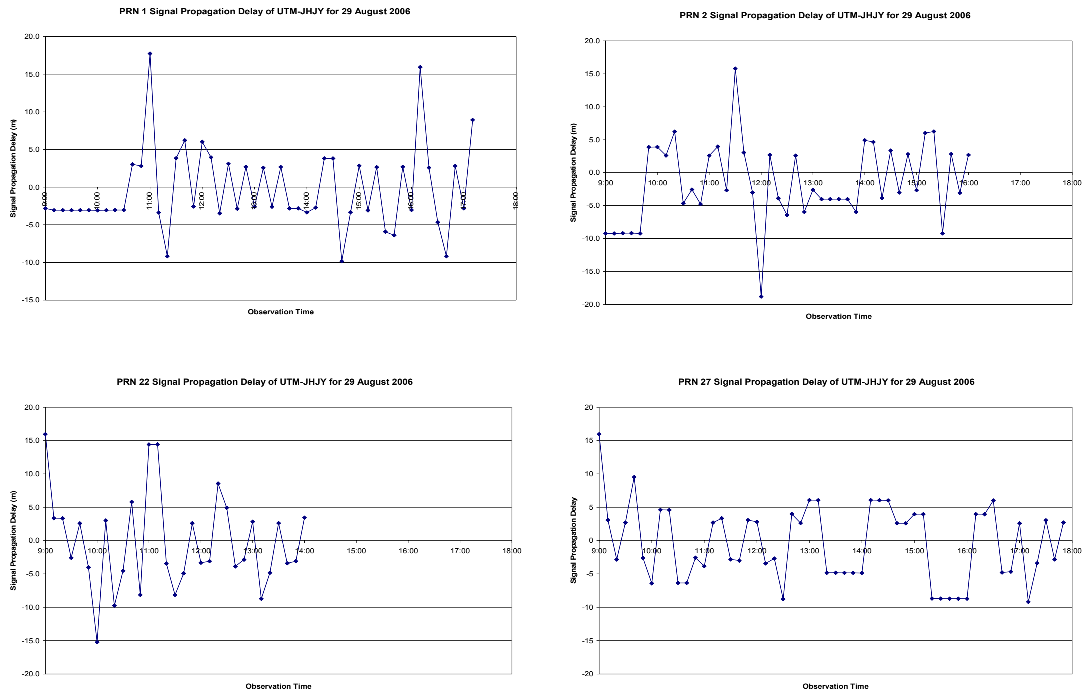


Figure 4.9: Signal Propagation Delay of a) SV 1 b) SV 7, c) SV 22, d) SV 27 in UTM-JHJY Baseline for 29 August 2006

Figure 4.9 shows inconsistency in the delay variation. Reaching maximum delay up to 18 meters in pseudo range, the peak of the delay was detected at 11 am for SV 1. For SV 7, the occurrence time is at 12 pm. Maximum latency of signal propagation for SV 22 was detected at 10 am followed by 9 am for SV 27.

4.4 Tropospheric Delay Analysis on Differences in Antenna Height

Based on results obtained from Figure 4.1 - 4.4, increment on the antenna height at 0.5 meter per session shows no significant effects or improvement towards the accuracy of computed ellipsoidal height obtained from each baseline. This might be due to the fact that 0.5 meter increment is very small compared to the range of coverage of the troposphere medium above the earth surface (16km above equator).

To study in which way the delay are influenced by differences in station height above mean sea level, a test has been conducted using seven sets of simulated data. While both ground local meteorological condition (temperature, pressure and relative humidity) and satellite elevation angle being kept constant, signal propagation delay at each condition has been computed using different value of station heights. List of simulated data used in this study is as shown in Table 4.2.

Table 4.2: Simulated Computation Data

Set	Temp. (C)	Pressure (Hpa)	R.Humidity (%)	Sat. Elev. (deg)	Stn Height (m)
1	32.3	1010.2	56	60.00	0.00*
2					5.00
3					50.00
4					100.00
5					1000.00
6					10000.00
7					50000.00

* at mean sea level (MSL)

Based on these simulated data, Table 4.3 shows the amount of signal propagation delay computed using TROPO.exe for each set of data.

Table 4.3: Amount of Signal Propagation Delay

Set	Signal Propagation Delay (m)	Differences (m)
1	2.6863	CONSTANT
2	2.6850	0.0013
3	2.6729	0.0134
4	2.6595	0.0268
5	2.4294	0.2569
6	0.9929	1.6934
7	0.2714	2.4149

Theoretically, the lesser the amount of signal propagation delay, the better derived position results can be obtained using GPS. From here, it is obvious that the higher station is, the smaller amount of signal propagation delay can be detected. The amount of signal propagation delay for station at MSL is 2.6863 m whereas at 5 m above MSL is 2.6850 m. This shows 5 m of differences in height can only give an effect or improvement around 0.0013 m or 1.3 mm in signal propagation delay. Changes up to 1 cm can only been seen if differences in station height range up to at least 50 m above the mean sea level.

5.0 CONCLUSION

Result obtained in this study shows that it is obvious that neglecting the use of a standard tropospheric model leads to variations in computed height component. Furthermore, the tropospheric refraction varies with changes on meteorological condition such as atmospheric pressure, temperature and relative humidity. Tropospheric delay is distance-dependent error that will increase when the baseline lenght between two stations increases. To study in which way the delay are influenced by differences in station height above mean sea level, a test has been conducted using seven sets of simulated data. Based on the result, it is proved that the amount of tropospheric delay will decrease when the antenna height increases.

6.0 ACKNOWLEDGEMENT

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7.0 REFERENCES

Ali H. (2005), "Garis Panduan mengenai Penggunaan Perkhidmatan *Malaysian RTK GPS Network* (MyRTKnet)", Department of Survey and Mapping Malaysia, KPUP Circular, vol 9.

Ali H., Nordin A.F., Abu S. and Chang. L.H. (2006), "MyRTKnet: Get set and go!", MyCoordinates, June 2006.

Diggle, D. (1994), "An Investigation Into the Use of Satellite-Based Positioning System for Flight Reference / Autoland Operations," Ph.D. Dissertation, Department of Electrical and Computer Engineering, Ohio University, Athens, Ohio.

Hay, C. and Jeffrey Wong (2000), "Enhancing GPS Tropospheric Delay Prediction at Master Control Station", GPS World, Jan 2000.

Hofmann-Wellenhof, B., Lichtenegger, H. and Collins, J. (1994), "GPS Theory and Practice", Fourth revised edition, Springer Wien, New York.

Janes H.W., Langley R.B., Newby S.P. (1989), "A comparison of several modes for the prediction of tropospheric propagation delay", Proceeding of the Fifth International Geodetic Symposium on Satellite Positioning, Las Cruces, New Mexico

Jensen, A.B.O., Tscherning, C.C., Madsen, F. (2002), "Integrating Numerical Weather Predictions in GPS Positioning", ENC GNSS-2002, Copenhagen.

Kamarudin M.N. and Mohd Zaki M.Z.(2005), "Tropospheric Delay Effects On Relative GPS Height Determination", Proceeding of the 2005 International Symposium and Exhibition on Geoinformation. Penang, Malaysia.

Kaplan, E.D. (1996),"Understanding GPS: Principles and Applications", First edition, Artech House Boston, London.

Mendes, V.B. and Langley, R.B. (1998),"Optimization of Tropospheric Delay Mapping Function Performance for High-Precision Geodetic Applications", Proceeding of DORIS Days, Toulouse, France.

Murakami (1989), "The Orbit Determination of Global Positioning System Satellites for Geodetic Applications: Development and Result at the Geographical Survey Institute", Bulletin of Geographical Survey Insitute, vol.34.

Remondi, B.W. (1984),"Using the Global Positioning System (GPS) Phase Observable for Relative Geodesy: Modeling Processing and Results", Ph.D. Dissertation, The University of Texas, Austin,Texas.

Waypoint Consulting Inc. (2005), "Static Baseline Accuracies as a Function of Baseline Length, Observation Time and the Effect of using the Precise Ephemeris" www.novatel.com/products/waypoint_techreports.htm