ANALYSIS ON THE RESIDUALS IN GPS MEASUREMENT DUE TO TROPOSPHERIC EFFECT AT THE EQUATORIAL REGION

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ABSTRACT : Global Positioning System (GPS) has been widely used by professionals and practitioners to support diverse applications such as navigation, surveying, mapping and engineering purposes. However, for highly precise applications (i.e. landslide detection, petrology and high rise structural monitoring) the key limitations currently facing this satellite-based positioning system is the signal propagation delay caused by the effect of troposphere where most of world's weather takes place. The effect is much more pronounced in Malaysia as it is located at the equatorial region where the troposphere extends up to 16 km above the earth surface. High humidity climate within the nation exaggerates the effect even further. This paper leads to an understanding on residuals in GPS measurement due to tropospheric effect at the equatorial region. Based on series of GPS observation made within Johore RTK Network (which is located in the equatorial region), it is obvious that tropospheric effect leads to variations or uncertainties in GPS measurement. Result shows that by neglecting the use of a standard tropospheric model, maximum residuals in Easting, Northing and Height components due to tropospheric effect are 68.880 cm, 68.970 cm and 119.100 cm respectively. Similarly, reaching to the minimum and maximum RMS value of 16.8 and 29.2 respectively, GPS Height component is by far the most affected component compared to the Horizontal components (Easting and Northing). Based on comparative study between short (UTM-JHJY) baseline and long (UTM-MERS) baseline, result shows that the tropospheric effect is a distance-dependent error that increases when the baseline length between two GPS stations increases. Better result in the derived position is therefore can be expected from short GPS baseline compared to the long baseline

KEYWORDS : Equatorial region, GPS measurement, tropospheric effect

1. INTRODUCTION

Global Positioning System (GPS) is a satellite-based positioning system that nominally consists of 24 satellites, arranged in nearly circular orbital planes at altitudes of about 22,000 km above the ground. This all-weather 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. To date, GPS has been widely used by most professionals and practitioners around the globe to support various applications such as navigation, surveying, mapping and engineering. Due to its efficiency and practicality as a positioning tool, Department of Survey and Mapping Malaysia (DSMM) has established 27 RTK reference stations forming a network known as Malaysian Real Time Kinematic GPS Network (MyRTKnet) for the purpose of extending the use of services rendered by GPS in Malaysia.

However, for highly precise applications (i.e. landslide detection, petrology and high rise structural monitoring), the accuracy of the GPS measurement is often complicated by atmospheric effects, namely signal propagation delays in the ionosphere and troposphere. As far as ionosphere is concerned, it is possible to compensate the first order effect by forming an ionosphere-free (IF) linear combination. For the delay caused by the troposphere, no dispersion effect are present at GPS frequencies thus elimination process is impossible. According to Dodson et al. (1999), positioning error due to improper modeling of the tropospheric effect itself can range from 2 m at the zenith to over 20 m at lower elevation angles. The high and variable water vapour content, particularly within the troposphere above the equatorial region (i.e. Malaysia) may exacerbate the effect even further

(Mendes, 1999). To maintain the performance of GPS derived positions so as to enable to avoid disasterous consequences due to lack of accuracy and precision in the positioning data, substantial understanding on the troposphere and its effect are therefore important and highly demanded.

2. THE TROPOSPHERE

The first layer of the atmosphere is called the troposphere (see Figure 1). According to Mendes et al. (1998), this non dispersive medium is twice time thicker above the equatorial region (i.e. Malaysia) compared to the poles with an approximate of 16 km. The role of the troposphere is mainly as a medium for energy transfer. Apart from its unique characteristic of having an electrically neutral condition, troposphere is where most of the world's weather takes place. These include tropical storms, seasonal monsoons and the El-Nino and La Nina phenomena. Compared to only 75% in the mid latitude region, the troposphere in the tropics (or equator) contains nearly 90% of the atmospheric mass (Weisberg, 1976). The tropospheric temperatures decrease rapidly with altitude at a constant lapse rate of -5˚C to -7˚C per km toward the upper boundary of the troposphere (Shrestha, 2003) where the minimum temperature over the equator is about -62˚C and whereas over the poles is about -45˚C. Nevertheless, these temperatures do vary somewhat; the temperature above the island of Java once reached a record low level of -95˚C (Weisberg, 1976).

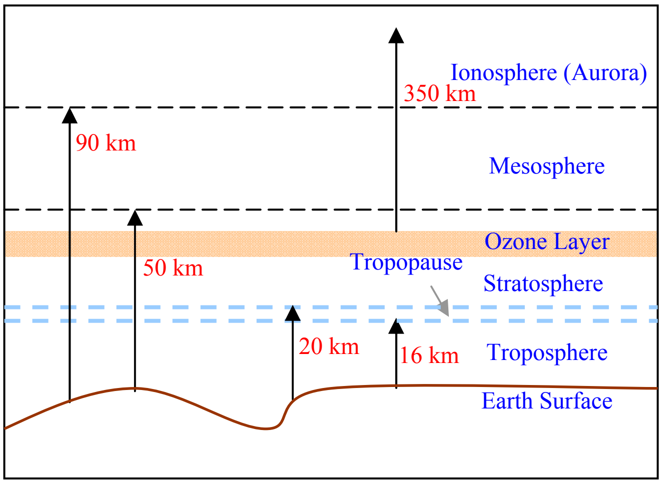

Figure 1. Atmospheric Layers of the Earth

3. TROPOSPHERIC MODELING

Due to the variability of refractive indices within the troposphere, the propagation speed of signals transmitted from GPS satellites are equally reduced with respect to free-space propagation. Often referred to as tropospheric effect, delay in time of GPS signals arrival induces variation in the accuracy of GPS positioning. In general, this so called tropospheric effect is also denoted as several other names which include tropospheric delay, tropospheric path delay and zenith path delay (ZPD). Tropospheric effect is usually being considered as a nuisance among GPS practitioners. As mentioned earlier, Dodson et al. (1999) asserts that positioning error due to improper modeling of the tropospheric delay itself can range from 2 m at the zenith to over 20 m at lower elevation angles. Careful modeling of the effect therefore should be carried out to achive high accuracy positioning especially in a condition where the relative height differences (between base and rover receivers) are excessively high (Bosy & Borkowski, 2005; Dai et al. 2006). It is noted that a large height difference can introduce a bias of the order of 2-5 mm per 100 m height difference (Gurtner et al. 1989). Nonetheless, based on simulation data, changes up to 1 cm in signal propagation delay can been seen if differences in station height range up to at least 50 m above the mean sea level (Yahya & Kamarudin 2007).

The troposphere is typically treated as the sum of two components. One is the hydrostatic component (dry part), whereas the other is the non hydrostatic component (wet part). Equation 3.1 shows the general modeling of the tropospheric effect.

$$d^{Trop} = d_d^z \cdot m_d(\varepsilon) + d_w^z \cdot m_w(\varepsilon) \tag{3.1}$$

where

d^{Trop}	is the tropospheric effect 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 to an approximate of 90% on the GPS signal refraction. This component results from the presence of gas contents of the troposphere which primarily composed of nitrogen and oxygen. Using the ideal gas law, this lowly varying part can be estimated at 1 mm accuracy based on additional pressure measurement (Hoeven et al., 2002). Equation 3.2 entails the mathematical model of the dry component.

$$d_d^z = (77.62).\frac{p}{T} \tag{3.2}$$

where

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

Wet part which composes atmospheric water vapour only accounts the remaining 10% of the effect. However, it is much more difficult to model as water vapour which comprises most of the wet part is a highly variable component spatially and temporally. Zhang & Lachapelle (2001) asserts that the daily variation of the wet delay usually exceeds that of the dry part by more than one order of magnitude, especially in temperate region. As mentioned earlier, the high and variable water vapour content, particularly in equatorial regions may exacerbate the effect even further (Mendes, 1999). Errors in wet component are the most significant factor of signal refraction. Unlike the dry part, according to Bevis et al. (1992) and Hoeven et al. (1998) the wet part can only be derived with an accuracy of about 6-10 mm in the zenith direction. Equation 3.3 expresses the mathematical model of the wet component.

$$d_w^z = -(12.96).\frac{e}{T} + (3.718 \times 10^5).\frac{e}{T^2} \tag{3.3}$$

where

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

4. THE EXPERIMENT

4.1 Data Acquisition

To study on the residuals in GPS measurement due to tropospheric effect at the equatorial region, three MyRTKnet stations in Johore RTK Network were integrated with three sets of GPS campaign in UTM; each set consist of three days of observation at three different monthly periods. Using static observation technique, well-calibrated dual-frequencies receiver known as Leica™ System 500 has been set at a GPS point in UTM for a total of nine hours per day. As it is located far from any obstructions, the multipath effect is therefore can be neglected during the observations. Scheduling of the data acquisition is as tabulated in Table 1.

Table 1. Data Acquisition Schedule

Observation Set	1	2	3
Observation Period	29–31 Aug 06	01-03 Dec 06	09–11 Jan 07

JHJY, KLUG and MERS permanent reference stations in Johore RTK network performed as base stations thus producing three difference baselines to be processed and analyzed. The shortest baseline is between JHJY-UTM with 17.9051 km followed by UTM-KLUG and UTM-MERS at 56.5244 km and 101.2633 km respectively. The location of these stations is as shown in Figure 2.

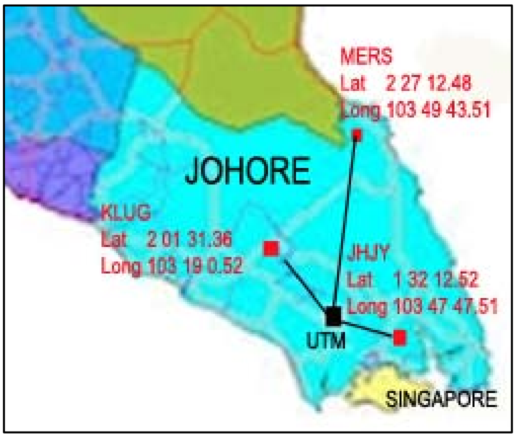

Figure 2. An Overview of Field Setup

4.2 GPS Satellites Availability

To establish the availability of the GPS satellites during the observation sessions, series of analyses have been made to check simultaneous satellites observation in term of its elevation and Dilution of Precision (DOP). It is noted that satellites at low elevation angle contribute to errors in propagating signals through the atmosphere. Therefore in this study, processing parameter of the satellite cut-off angle was set to above 10˚. Low value of Geometry Dilution of Precision (GDOP) indicates strong satellite geometry with a higher possibility of accuracy. Tables 2 presents the GDOP of satellites for the 3rd campaign in which almost similar to the two previous campaigns. Good GDOP were obtained between 1500 hours and 1800 hours in all cases. However, best GDOP of 1.67 is obtained on 11 January 2007. Here, assumption can be made that these observation data is in a satisfactory condition hence is sufficiently good to be further utilize to determine the residuals in GPS measurement due to the tropospheric effect.

Table 2. Multi Station Analysis for 3rd Campaign

Date	09/01/07		10/01/07		11/01/07	
Time	No GPS Satellites	GDOP	No GPS Satellites	GDOP	No GPS Satellites	GDOP
9:00	6	4.79	6	5.01	6	5.22
10:00	8	6.76	8	6.29	8	5.72
11:00	10	2.38	10	2.35	10	2.32
12:00	9	2.34	9	2.35	9	2.37
13:00	10	2.26	10	2.34	10	2.42
14:00	9	2.87	9	2.79	9	2.71
15:00	9	2.34	9	2.36	9	2.38

16:00	11	2.41	11	2.45	11	2.48
17:00	11	2.10	11	2.08	11	2.06
18:00	12	1.83	12	1.82	13	1.67

4.3 Analysis of Results

4.3.1 Tropospheric Effect on GPS Measurement

The tropospheric effect has been left uncompensated as no standard tropospheric model (i.e. Hopfield (1969), modified Hopfield (Goad & Goadman, 1974), Neill and Saastamoinen (1973) model) was applied during data processing. To eliminate the effect of ionosphere and both satellite and receiver clock bias, ionospheric free double difference solution has been applied. In addition to clear sky visibility, multipath effect was 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 is also been neglected. To investigate the performance of GPS measurement due to the tropospheric effect, residuals of GPS derived position (in cm) between computed and known value for each baseline during the 1st campaign have been tabulated against each hour of observation (see Tables 3-5). Based on these results, Root Mean Square (RMS) of each component was then calculated based on this mathematical equation:

$$RMS = \sqrt{\frac{\sum_{i=1}^{N}\left(x_i - \overline{x}\right)^2}{N-1}} \qquad (3.4)$$

where

N	is the amount of sampling data
x	is the residual of components Δ E, Δ N and Δ h
$\overline{x}$	is the residual mean value

Table 3. Residual of GPS Measurement of 1st Campaign of 29th August 2006

Time	UTM-JHJY			UTM-KLUG			UTM-MERS		
	Δ E	Δ N	Δ h	Δ E	Δ N	Δ h	Δ E	Δ N	Δ h
9:00	26.020	35.170	83.090	38.920	53.570	83.790	15.120	67.970	103.700
10:00	29.520	35.070	87.390	38.820	57.170	93.890	27.020	63.470	113.100
11:00	27.420	34.270	87.390	38.420	56.270	88.990	68.880	22.470	111.700
12:00	29.020	35.470	84.590	34.320	50.070	86.790	26.320	56.770	111.100
13:00	25.520	32.670	89.900	37.920	35.470	100.690	31.520	27.770	113.800
14:00	26.420	36.970	98.490	24.020	34.470	117.690	11.020	49.370	119.100
15:00	29.320	34.770	41.790	38.420	45.670	56.390	12.520	54.770	66.790
16:00	26.520	33.270	46.490	37.320	40.970	54.390	26.920	35.670	57.490
17:00	28.020	33.770	45.790	43.520	54.970	48.090	38.920	53.770	54.200
RMS	**1.509**	**1.286**	**22.349**	**5.361**	**8.874**	**23.456**	**17.668**	**15.847**	**26.789**

Max E: 68.880 cm N: 67.970 cm H: 119.100 cm

Table 4. Residual of GPS Measurement of 1st Campaign of 30th August 2006

Time	UTM-JHJY			UTM-KLUG			UTM-MERS		
	ΔE	ΔN	Δh	ΔE	ΔN	Δh	ΔE	ΔN	Δh
9:00	28.320	35.170	79.290	40.320	54.770	113.690	21.720	50.870	114.790
10:00	28.320	35.170	89.190	35.520	57.870	96.190	28.520	46.770	106.700

11:00	26.020	30.970	87.690	47.420	51.470	99.490	38.420	68.970	97.300
12:00	19.620	31.670	76.790	19.620	51.970	96.990	34.420	61.570	110.990
13:00	28.620	37.270	89.090	30.220	54.270	96.190	28.120	54.270	107.090
14:00	25.820	37.570	94.890	43.520	49.270	94.890	23.720	50.370	102.790
15:00	27.420	36.670	54.490	44.220	43.870	62.590	13.720	47.770	68.690
16:00	26.120	35.070	57.590	38.720	41.470	68.090	27.320	38.770	73.490
17:00	29.020	35.770	51.490	34.720	40.470	66.790	30.120	42.070	71.290
RMS	**2.881**	**2.305**	**16.775**	**8.459**	**6.208**	**17.838**	**7.183**	**9.372**	**18.415**

Max E: 47.420cm N: 68.970cm H: 114.790 cm

Table 5. Residual of GPS Measurement of 1st Campaign of 31st August 2006

Time	UTM-JHJY			UTM-KLUG			UTM-MERS		
	ΔE	ΔN	Δh	ΔE	ΔN	Δh	ΔE	ΔN	Δh
9:00	29.720	35.170	88.390	47.320	48.070	112.190	45.520	49.570	113.100
10:00	28.220	37.370	98.090	39.020	55.070	88.590	27.320	52.170	118.600
11:00	28.920	37.570	97.290	37.520	44.370	88.290	33.720	48.970	98.400
12:00	30.720	36.070	89.500	39.220	42.470	102.890	34.120	48.870	103.590
13:00	28.520	37.270	95.790	35.620	46.270	109.590	28.420	49.070	109.290
14:00	28.820	34.970	96.690	45.920	44.070	93.590	32.120	50.370	118.800
15:00	26.820	36.170	54.290	35.220	41.870	59.990	12.920	55.970	46.190
16:00	25.720	36.570	56.490	35.220	41.870	53.190	30.920	46.470	48.490
17:00	28.620	36.070	53.390	33.820	43.770	37.990	28.120	43.770	69.890
RMS	**1.471**	**0.929**	**20.080**	**4.818**	**4.188**	**26.387**	**8.521**	**3.403**	**29.209**

Max E: 47.320 cm N: 55.970 cm H: 118.800 cm

Based on the results, it is obvious that neglecting the use of a standard tropospheric model leads to variations in GPS measurement. Compared to the known value, maximum residuals of GPS Easting is at 68.880 cm in which can be referred to UTM-MERS baseline at 11 am 29/08/06. On the other hand, maximum residuals of 68.970 cm in GPS Northing can be referred to UTM-MERS baseline at 11 am 30/08/06. Maximum residuals of GPS Height component is at 119.100 cm in which can be referred to UTM-MERS baseline at 2 pm 29/08/06.

Theoretically, RMS values entails the degree to which the residuals tend to spread about its average values. From here, it is obvious that the RMS value for the Height component is the highest compared to both Easting and Northing. Reaching to the minimum and maximum value of 16.8 and 29.2 respectively, the Height component is by far the most highly variable positioning parameter due to the effect of the troposphere. Without appropriate compensation, it is believed that the performance of GPS Height component within the equatorial region is largely affected by the tropospheric effect compared to the Horizontal components.

4.3.2 Tropospheric Effect on Differences in Baseline Lengths

In order to investigate the influence of baseline length towards the amount of tropospheric effect, comparative study have been made on between short (UTM-JHJY) and long (UTM-MERS) baselines. Since the Height component is mostly affected by tropospheric effect, figures 3-5 show the differences of height value derived from both baselines of two sets of observation taken from the all three campaigns.

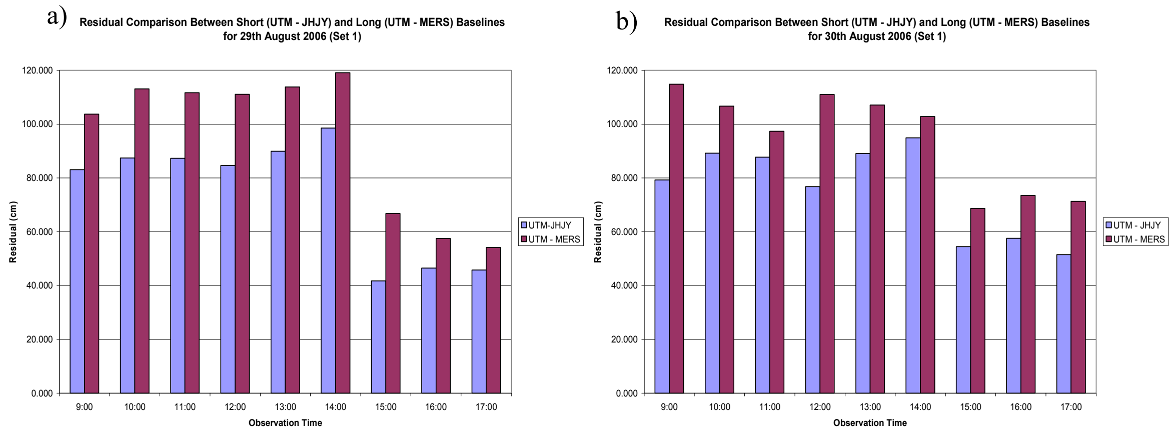

Figure 3(a,b). Residual Comparison Between Short (UTM - JHJY) and Long (UTM - MERS) Baselines of 1st campaign of 29-30 August 2006

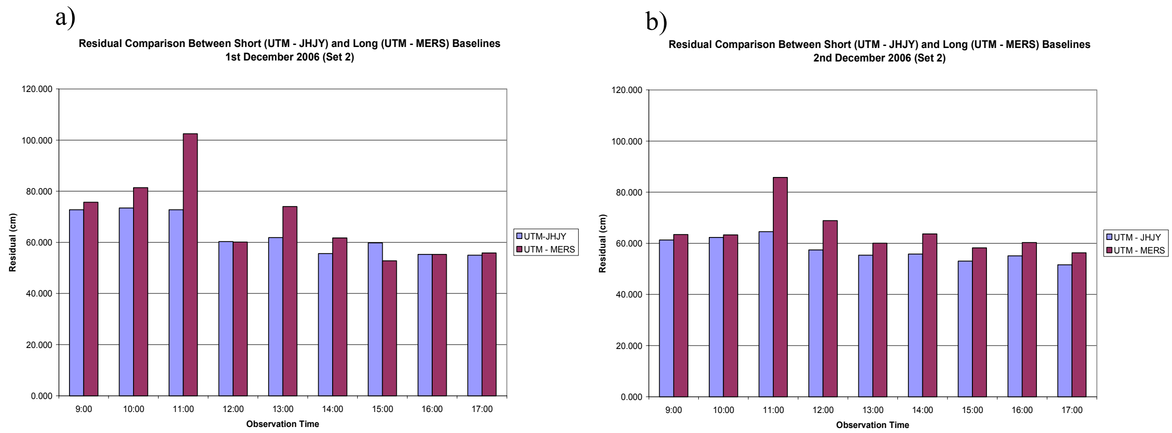

Figure 4(a,b). Residual Comparison Between Short (UTM - JHJY) and Long (UTM - MERS) Baselines of 2nd campaign of 1-2 December 2006

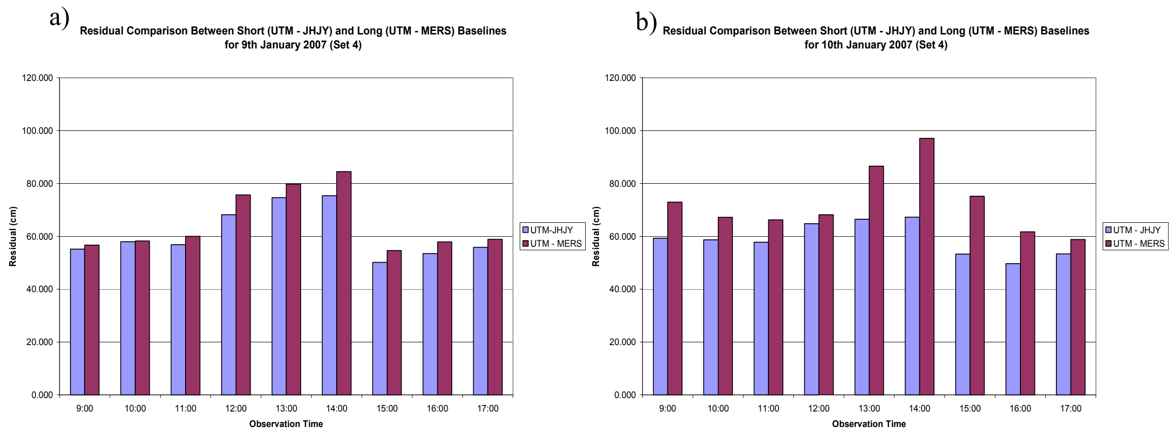

Figure 5(a,b). Residual Comparison Between Short (UTM - JHJY) and Long (UTM - MERS) Baselines of 3rd campaign of 9-10 January 2007

The result reveals that tropospheric error increases with the increases in the baseline length between two stations. For long baseline of 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 length before arriving to both receivers on the ground. However, for short baseline (UTM-JHJY), signal paths from satellite to both receivers are essentially identical. This is because the errors common to both stations tend to cancel during double differencing with the tropospheric correction decomposing into the common station parts and the satellite-dependent part. Better result in the derived position is therefore can be expected compared to long baseline.

5. CONCLUSION

Based on series of GPS observation made within Johore RTK Network, it is obvious that tropospheric effect leads to variations or uncertainties in GPS measurement within the equatorial region. Result shows that by neglecting the use of a standard tropospheric model, maximum residuals in Easting, Northing and Height components due to tropospheric effect are 68.880 cm, 68.970 cm and 119.100 cm respectively. Similarly, reaching to the minimum and maximum RMS value of 15.8 and 27.5 respectively, GPS height component is by far the most affected component compared to the Horizontal components (Easting and Northing). Based on comparative study between short (UTM-JHJY) baseline and long (UTM-MERS) baseline, result shows that the tropospheric effect is a distance-dependent error that increases when the baseline length between two GPS stations increases. Better result in the derived position is therefore can be expected from short GPS baseline compared to the long baseline.

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