Low Latitude Troposphere: A Preliminary Study Using GPS CORS Data in South East Asia

Tajul A. Musa, Samsung Lim & Chris Rizos
School of Surveying and Spatial Information Systems
The University of New South Wales, Sydney, NSW 2052, Australia

BIOGRAPHY

Tajul A. Musa is a PhD student in the School of Surveying and Spatial Information Systems, UNSW. His research interest is in network-based GPS positioning, network stochastic modeling and troposphere study.

Samsung Lim is a Senior Lecturer of the School of Surveying & Spatial Information Systems, UNSW. He obtained a Doctor of Philosophy in Aerospace Engineering & Engineering Mechanics from the University of Texas at Austin, a Master of Arts and a Bachelor of Arts in Mathematics both from Seoul National University. Samsung has been researching and lecturing on GPS theory and practical applications, GIS programming and project management since 1997.

Chris Rizos is a Professor and Head of the School of Surveying & Spatial Information Systems, UNSW. He obtained a Bachelor of Surveying and a Doctor of Philosophy both from the UNSW. Chris has been researching the technology and high precision applications of GPS since 1985. Chris is a Fellow of the Australian Institute of Navigation, a member of the Council of the Satellite Division of the U.S. ION, a Fellow of the International Association of Geodesy (IAG), a member of the Governing Board of the IGS, and is currently president of the IAG's Commission 4 "Positioning and Applications".

ABSTRACT

Hot and wet conditions in the equatorial or low latitude region degrade satellite positioning accuracy noticeably. The degradation is related to the strong tropospheric effect, especially the wet component which is approximately proportional to the content of water vapor in the troposphere and thus makes satellite positioning more challenging in this region. Despite the efforts to achieve better understanding of the signal delay in the low latitude troposphere, much more still remains to be improved. Knowing that the water vapor content is heavy in this region, it is of special interest for meteorologists to look into the tropospheric effect. Such knowledge is vital for understanding the global climate, whereas a short term variation of water vapor is very useful input to local weather forecasting. South-East Asia is selected in this study to investigate the effect of regional tropospheric delay, and broadly to understand the behavior of a low latitude troposphere. The study area covers Malaysia and Singapore where GPS CORS networks have already been established. Results from GPS data processing show that a wide variation of the tropospheric delay can be observed. As expected, the largest variation occurs during

the North-East monsoon (November to early March) and the South-West monsoon (early May to August). Coordinate repeatabilities of the sites in the network are calculated to show the impact of the tropospheric delay on the precision of GPS positioning activities. In addition, the variations of the tropospheric delay estimated from a local and a regional GPS network are compared to the results from the global network.

INTRODUCTION

The most dense, lowest layer of the earth's atmosphere is known as the troposphere. Extending from the ground to the stratosphere at approximately 13km altitude, it is the place where almost all weather occurs. The troposphere is composed of a mixture of several neutral dry gases, primarily nitrogen and oxygen, and possibly other traces of pollutants. The air in the troposphere also contains a variable amount of water vapor. The amount varies depending on the temperature and pressure of the air. The highest amount of water vapor can be observed in the equatorial region. Within this area, the elevation angle of sunlight remains relatively high and no distinctive season of the year can be defined. This natural phenomenon has a distinctive impact on the equatorial atmosphere i.e., it can hold more water vapor in the air. In addition, this is the region where short periodic variations of water vapor occur.

Satellite signals such as Global Positioning System (GPS) signals are affected by the troposphere. The signal which travels from space to earth changes its velocity due to the interaction with this layer, i.e., the signal is refracted. In GPS terminology, this effect is referred to as the tropospheric refraction or tropospheric delay (Hoffman-Wellenhoff *et. al*, 1994). The delay can be represented by a function of the satellite elevation angle and altitude of the GPS receiver, and is dependent on the atmospheric pressure, temperature, and water vapor pressure (Brunner and Welsch, 1993). The delay is wavelength-independent, and thus it cannot be canceled out by observing multi-frequency signals. The delay can be evaluated by integration of the tropospheric refractivity along the GPS signal path. For the modeling purpose, the refractivity is separated into hydrostatic (or 'dry') and wet components. The dry component contributes approximately 90% to the total tropospheric delay. The dry component can effectively be modeled to reduce its undesirable contribution down to 1% due to a small variation of the dry gases in the atmosphere (Spilker, 1996). However, the problem lies in modeling the wet component, i.e., the other 10% of the total delay. The wet delay is approximately proportional to the amount of water vapor in the atmosphere. Due to the strong variations on the distribution of water vapor in space and time, the wet delay is less predictable and therefore difficult to model. A relative tropospheric delay causes height errors in GPS positioning. The delay is amplified by the factor of cosec(?) e.g. 2.9 for ? =20° where ? is the satellite elevation angle (Beutler *et. al*, 1988). Meanwhile an absolute delay of 10cm will cause scale bias of 0.05ppm in the estimated baseline lengths (Rothacher and Mervart, 1996). Therefore, an improperly modeled wet component can cause a serious bias in high accuracy positioning.

Knowing that a large amount and strong variation of water vapor is found in the equatorial region, a better understanding of the tropospheric effect on the GPS positioning activities is needed. Furthermore, information about water vapor in this region is of special interest for meteorologists because its behavior is vital for understanding the global climate, whereas a short term variation of water vapor is a very useful input to local weather forecasting.

This paper investigates the effect of regional tropospheric delay on GPS positioning results, and thus contributes to an understanding of the behavior of a low latitude troposphere. A region of South-East Asia is selected in this study which covers the Malaysian peninsula and Singapore. GPS data from Continuous Operating Reference Stations (CORS) is used for the study. Results from the data processing show that a wide variation of the tropospheric delay can be observed. As expected, the largest variation occurs during the end of North-East monsoon and South-West monsoon. Coordinate repeatabilities of the sites in the network are calculated to show the impact of the tropospheric delay on the GPS positioning. In addition, the variations of the tropospheric delay estimated from a local and a regional GPS network are compared to the results from the global network.

STUDY AREA

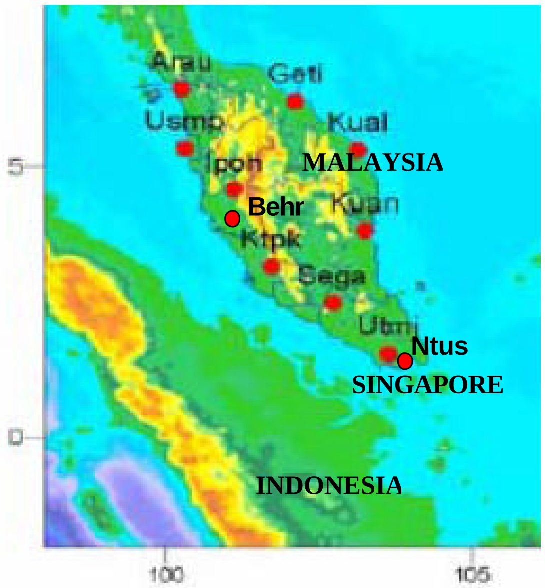

Figure 1: Study area and existing GPS stations

The study area (Figure 1) covers the Malaysian peninsula and Singapore (Latitudes from 1°N to 7°N and Longitudes from 100°E to 105°E) which is a part of South-East Asia. The atmosphere of the area is unique because it is located near the equator. Furthermore, the area is exposed to the ocean. Its climate is characterized by uniform temperature and pressure, high humidity and abundant rainfall. The area has two main seasons, the North-East monsoon (November to early March) and the South-West monsoon (early May to August). The two monsoons bring heavy rain, which sometimes leads to the monsoon flood in the east part of the Malaysian peninsula. There are no distinct wet or dry periods but the mean monthly rainfall shows drier weather conditions from May to early July and wetter conditions from November to January.

Besides its hot and wet conditions, the ionospheric activity of the area is strong when compared with other places around the world. A lot of ionosphere-related phenomena such as an equatorial anomaly and the fountain effect can be observed. Zain *et. al* (2002) have studied the ionospheric effect on GPS positioning during the geomagnetic storm in this area. The GPS CORS network of the area consists of Malaysia Active GPS System (MASS), Singapore Integrated Multiple Reference Station Network (SIMRSN) and a station known as NTUS which is part of the International GPS Service (IGS) global network. These stations are well equipped with dual-frequency GPS receivers, making it possible to calculate the ionospheric effect directly. The receivers record the GPS data at an interval of 30 seconds.

A PRIORI TROPOSPHERIC DELAY MODELING

For short relative GPS positioning e.g. a baseline of few tens of kilometers with small differences in altitude, the tropospheric delay at the rover is almost the same as the delay at the base station. In this case, the tropospheric delay and other correlated errors are effectively canceled out by the differencing process. In the case of medium length baselines (50-100km), the raw GPS data can be corrected by applying the a priori tropospheric delay. When differenced, the residual tropospheric delay should be at the minimum level. In fact, the residual is mainly from the wet component because of the difficulty of getting an accurate model for the wet part of the delay (Anna, 2000). For longer baselines, the residual is more significant and needs to be taken into account while processing the data.

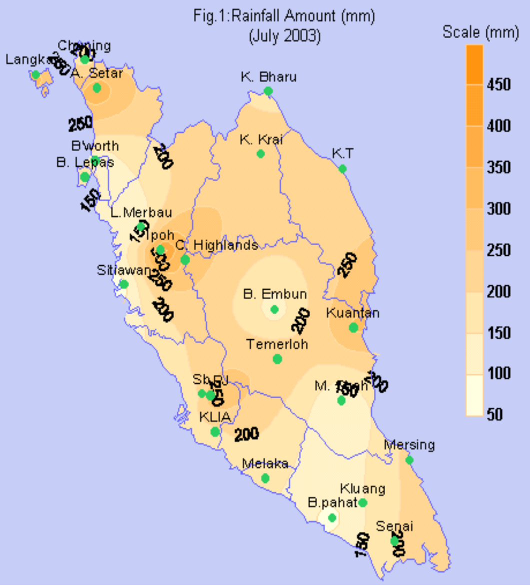

Figure 2. Rainfall over the Malaysian peninsula during the South-West monsoon in July 2003 (courtesy of MMS)

In the study area, the performance of the a priori model needs to be investigated even for a short baseline. For this purpose, three different sets of baselines are tested: a short baseline (UTMJ-NTUS, 25km), a medium-length baseline (UTMJ-SEGA, 143km) and two long baselines (UTMJ-BEHR, 339km and UTMJ-KUAN, 253km). Twenty four hour datasets for a month in each season are used: 1) the South-West monsoon in July 2003, 2) the inter-monsoon in September 2003 and 3) the North-East monsoon in December 2003. Figures 2, 3 and 4 show the average amount rainfall in each period as reported by the Malaysian Meteorological Service (MMS).

Two well known a priori tropospheric models were tested, i.e., the Saastamoinen model and the Modified Hopfield model. Both models use parameters derived from a standard atmosphere model. Three test schemes are used to isolate the wet component from the tropospheric effect.

- ✓ Test 1: No a priori model is applied.
- ✓ Test 2: Apply the dry model only.
- ✓ Test 3: Apply both the dry and the wet troposphere models.

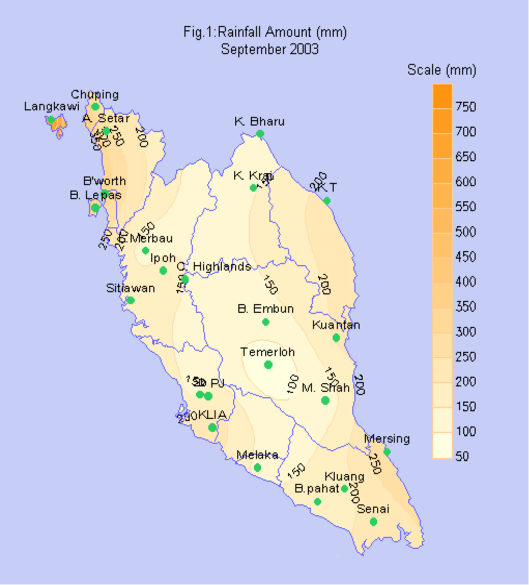

Figure 3. Rainfall over the Malaysian peninsula during the inter-monsoon in September 2003 (courtesy of MMS)

The GPS data processing incorporates Double-Differenced (DD) and Ionosphere-Free (IF) carrier phase measurements. The process resolves the "wide-lane ambiguity" and fixes the "narrow-lane ambiguity" subsequently, or uses the quasi-ionosphere free technique (Rothacher and Mervart, 1996). Assuming that higher order of the ionospheric delay is reasonably small and negligible, the tropospheric delay will dominate the DD-IF residual errors. Other geometric errors and the multipath effect can be minimized by using the precise GPS ephemeris data, and a proper modeling and calibration of the receiver antenna.

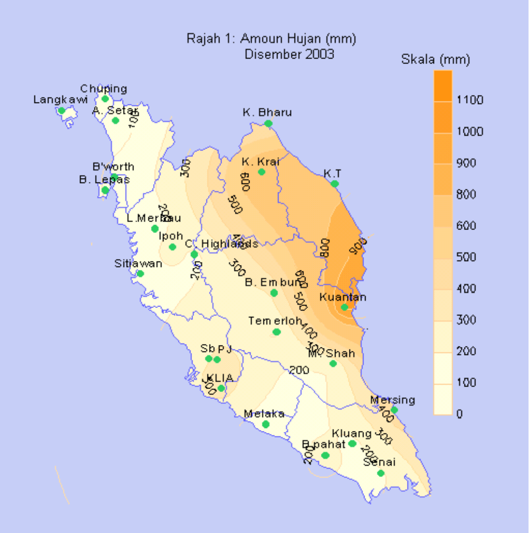

Figure 4. Rainfall over the Malaysian peninsula during the North-East monsoon in December 2003 (courtesy of MMS)

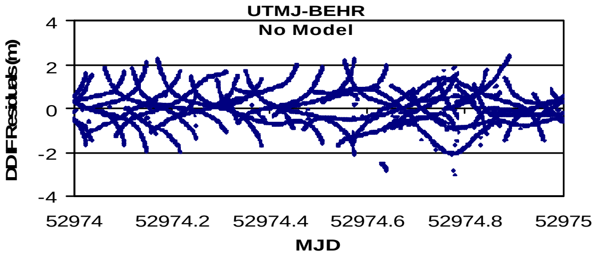

Figure 5. DD-IF residuals without applying a priori tropospheric model (Test 1)

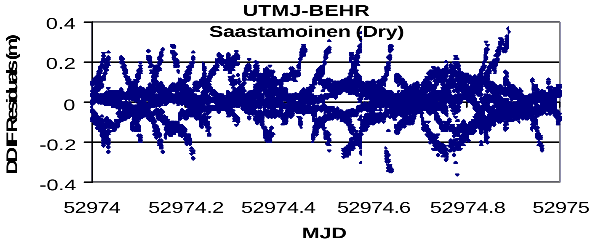

Figure 6. DD-IF residuals when the dry Saastamoinen model is applied (Test 2)

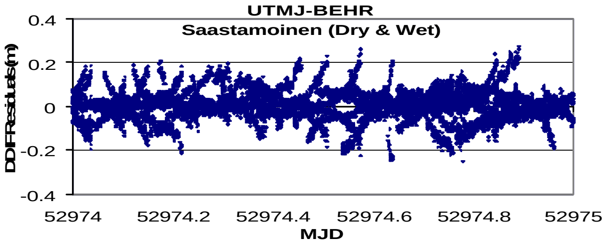

Figure 7. DD-IF residuals when both dry and wet Saastamoinen models are applied (Test 3)

For a selected baseline UTMJ-BEHR during the Day of Year (DoY) 335, DD-IF residuals for Tests 1, 2 and 3 are shown in Figures 5, 6 and 7, respectively. Figure 5 shows that the differential tropospheric delay can be observed up to 2m when no a priori tropospheric model is applied. The residuals are reduced to 0.3m if the dry Saastamoinen model is applied (Figure 6), however, no significant improvement is achieved if the wet component is added further (Figure 7).

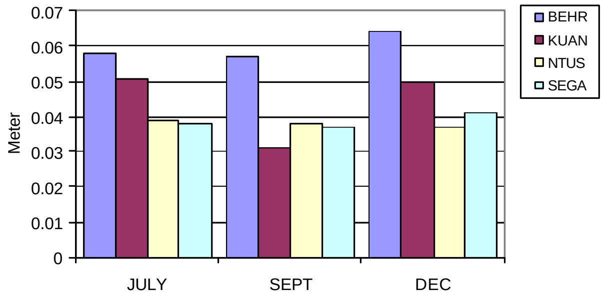

Figure 8. Average RMS errors of DD-IF residuals for base stations (relative to UTMJ) when the Hopfield model is applied

Figure 8 shows the average Root Mean Squares (RMS) errors of DD-IF residuals for Test 3 when the Hopfield model is applied. The figure indicates that the errors vary between 0.03m and 0.065m depending on the baseline length and the seasonal period. Maximum values are observed in July and December, i.e., during the two monsoon seasons.

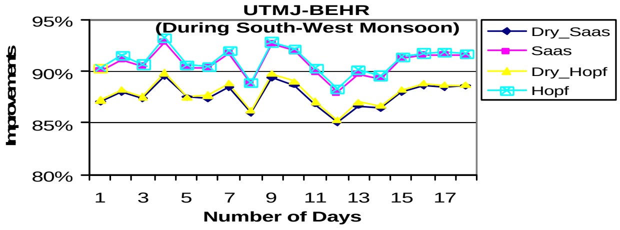

Figure 9. Percentile improvements of DD-IF residuals when the a priori models are applied to UTM-BEHR during the South-West monsoon

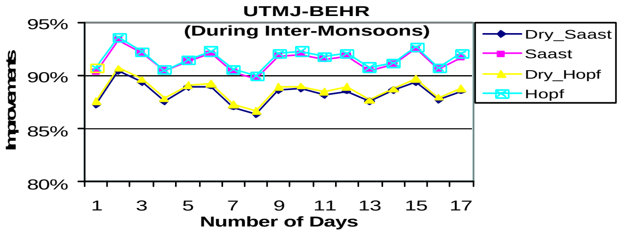

Figure 10. Percentile improvements of DD-IF residuals when the a priori models are applied to UTM-BEHR during the inter-monsoon period

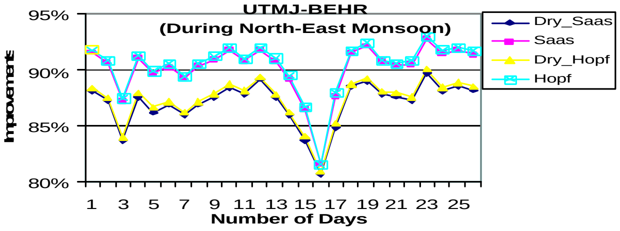

Figure 11. Percentile improvements of DD-IF residuals when the a priori models are applied to UTM-BEHR during the North-East monsoon

Percentile improvements are calculated in terms of RMS error for Tests 1, 2 and 3. Figures 9, 10 and 11 show the percentile improvements of the DD-IF residuals for UTMJ-BEHR when the a priori tropospheric models are applied to each season. The figures clearly show that there are no significant differences between the Saastamoinen model and the Hopfield model. Both the dry Saastamoinen model and the dry Hopfield model are able to remove 80% to 90% of the delay. However, it is certain that only small improvements (<5%) are achievable if the wet models are added further to the dry models. This is true for both a priori models regardless of the baselines tested.

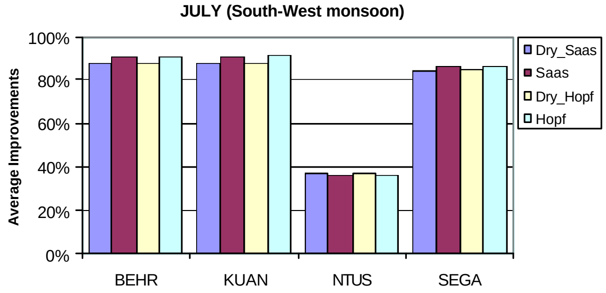

Figure 12. Average DD-IF improvements for each station (relative to UTMJ) during the South-West monsoon

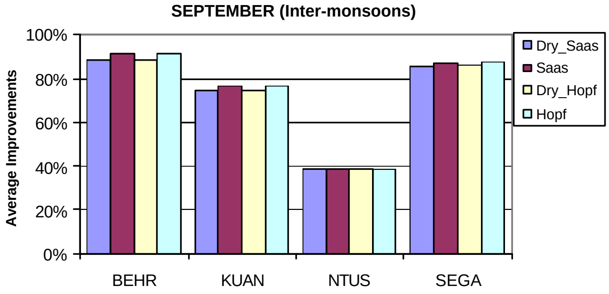

Figure 13. Average DD-IF improvements for each station (relative to UTMJ) during the inter-monsoon period

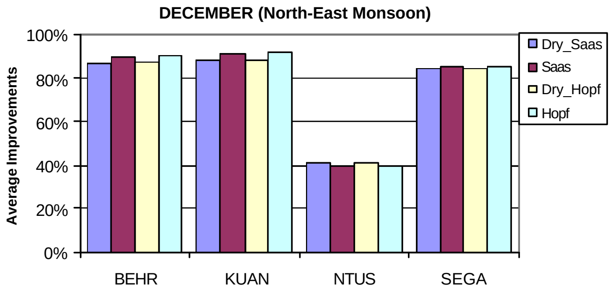

Figure 14. Average DD-IF improvements for each station (relative to UTMJ) during the North-East monsoon

Figures 12, 13 and 14 summarize the average improvements of the DD-IF residuals when the a priori models are applied. The a priori models show the average improvements of 70% to 90% for medium and long baselines. For a short baseline UTMJ-NTUS, the delay is not as significant as in the case of the long baselines. Nevertheless, improvements up to 45% can be achieved for NTUS during the North-East monsoon (Figure 12). During the inter-monsoon period (Figure 13), the result for KUAN shows less improvements if compared with the results during the two monsoon seasons. The result may be associated with the dry condition of the study area in July when the wet delay is not as significant.

ESTIMATION OF TROPOSPHERIC DELAY PARAMETERS

As seen in the previous section, it is clear that the a priori troposphere model cannot effectively remove the residual tropospheric delay. High accuracy GPS positioning still requires the residuals to be reduced by an appropriate modeling. The approach is usually to introduce additional unknown parameters in the least square estimation process, for example, a scale factor for every station per session can be solved. The estimation of the scale factor tends to average the residual tropospheric delay and thus improve the results. However, the scale factor is only a constant offset to the apriori model and does not reflect the time varying nature of the atmosphere. Alternatively, a time-varying polynomial scale factor can be introduced to estimate several troposphere parameters per session. Another viable approach is to use stochastic estimation to model using a first-order Gauss-Markov or random walk process (Dodson *et al*., 1996).

To study the effect of the residual tropospheric delay, the data is further processed by applying the estimation of troposphere scale factor. For this purpose, the troposphere parameters were estimated for every 2 hours per station and per session. The coordinate repeatabilities of the station in north, east and up directions are noted. Figures 15 and 16 show the coordinate repeatabilities for the station SEGA and Figures 17 and 18 do the same for BEHR. A very significant improvement, especially for the height component, is found after the estimation of the troposphere parameter.

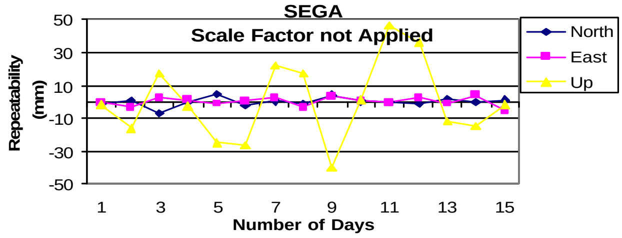

Figure 15. Coordinate repeatabilities for station SEGA during the South-West monsoon - no scale factor is applied

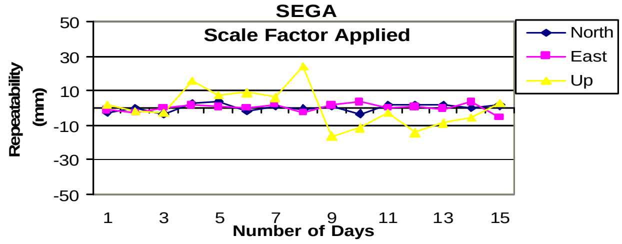

Figure 16. Coordinate repeatabilities for station SEGA during the South-West monsoon - scale factor is applied

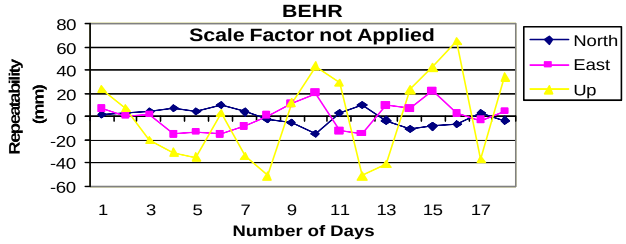

Figure 17. Coordinate repeatabilities for station BEHR during the North-East monsoon - no scale factor is applied

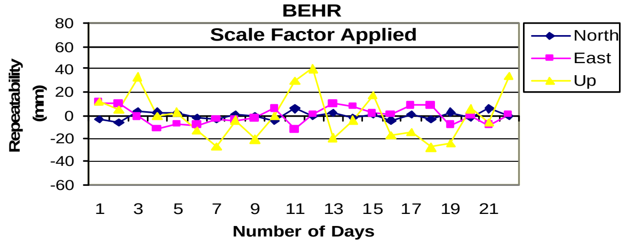

Figure 18. Coordinate repeatabilities for station BEHR during the North-East monsoon - scale factor is applied

Tables 1, 2 and 3 summarize the RMS of the coordinate repeatabilities. The results indicate that the scale factor can improve the precision of the coordinate. The coordinate repeatabilities are improved by a few millimeters in the North and East direction. The RMS of the height component is decreased by 12-36mm except for the station NTUS. The results during the two monsoons (Tables 1 and 3) are not so good if compared with the results during the inter-monsoon period (Table 2) in the case of no scale factor being applied. After applying the scale factor their differences are only a few millimeters.

Table 1. RMS of coordinate repeatability for July 2003 (South-West Monsoon)

	No Scale Factor			Scale Factor Applied		
STN	N (mm)	E (mm)	Up (mm)	N (mm)	E (mm)	Up (mm)
BEHR	5.0	5.1	44.5	2.9	3.9	18.2
KUAN	5.0	1.9	47.8	3.8	1.4	12.2
NTUS	4.6	3.6	17.1	4.4	3.5	17.3
SEGA	2.6	2.8	24.2	2.2	2.5	11.1

Table 2 RMS of coordinate repeatability for September 2003 (Inter-Monsoon)

	No Scale Factor			Scale Factor Applied		
STN	N (mm)	E (mm)	Up (mm)	N (mm)	E (mm)	Up (mm)
BEHR	4.8	5.7	30.6	2.8	4.5	18.7
KUAN	3.6	1.8	34	2.9	1.7	9.8
NTUS	4.2	3.7	15.8	3.8	2.5	14
SEGA	2.2	2.7	24.6	2.7	2.5	11.3

Table 3. RMS of coordinate repeatability for December 2003 (North-East Monsoon)

	No Scale Factor			Scale Factor Applied		
STN	N (mm)	E (mm)	Up (mm)	N (mm)	E (mm)	Up (mm)
BEHR	6.9	11.8	36.9	3.3	7.4	20.7
KUAN	7.8	4.2	27.2	3.7	1.1	5.6
NTUS	3.3	4.3	10.4	3.0	3.6	15.7
SEGA	3.9	3.2	46.5	2.8	2.5	13.1

ABSOLUTE VS RELATIVE TROPOSPHERIC DELAY

A relative tropospheric delay is more important than an absolute tropospheric delay for GPS positioning. However, an accurate absolute tropospheric Zenith Path Delay (ZPD) (i.e., the delay in the zenith direction) is crucial for meteorological applications. Typically the process of GPS ZPD estimation requires a large network of GPS reference stations to achieve a stable value for the absolute ZPD. Duan *et al.* (1996) have shown that for small sized GPS networks the total ZPD (that is the sum of dry and wet delay in the zenith direction) is sensitive to the relative ZPD but not to the absolute ZPD. This is due to the small elevation angle difference observed between any two GPS receivers in the network. On the other hand, a large network is needed in order to have large elevation angle variations so as to obtain a better estimation of the absolute ZPD. A good example is the global network of the International GPS Service (IGS) which is already in use, publishing 2 hour absolute ZPD values. This IGS estimate should be included at the time of processing regional/local GPS network data to benchmark the ZPD value derived from the regional/local solution.

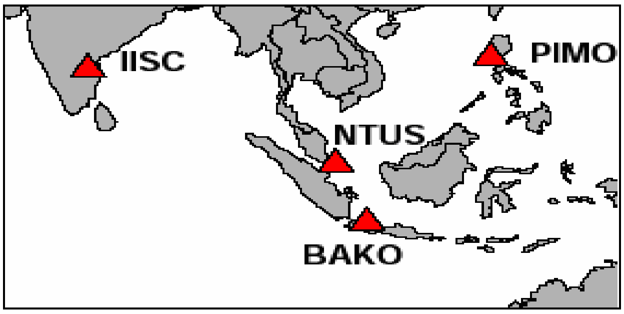

Figure 19. Regional GPS network

To analyze the relationship between the absolute/relative delay and the network size, a few regional IGS stations around the MASS network were used (Figure 19). For this test, KTPK is chosen as a reference station in the network (Figure 1). An IGS station NTUS, however, is treated as a local station because of the short distance to the MASS network (KTPK-NTUS is only 297km). This will give an advantage to the MASS network analysis in order to benchmark the absolute ZPD value to the IGS estimate using both local and regional networks.

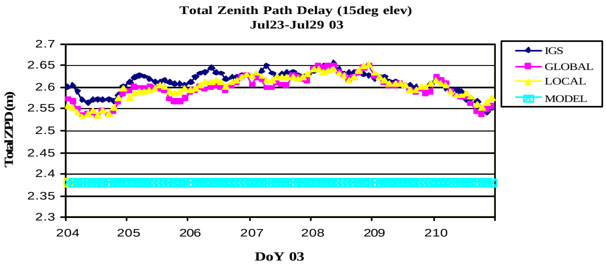

Figure 20. Total ZPD for station NTUS derived from different network size during the South-West monsoon

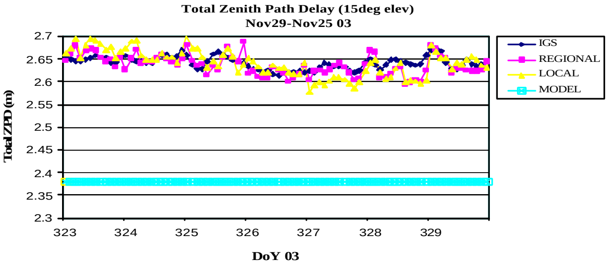

Figure 21. Total ZPD for station NTUS derived from different network size during the North-East monsoon

Two week data were selected for the test, DoY 204-210 (July 23-29 2003; i.e., during the South-West monsoon) and DoY 323-329 (November 19-25 2003; i.e., the first month of the North-East monsoon). For this analysis the satellite elevation cut-off angle was set to 10°, 15° and 20°, and a simple cosec mapping function was used. The tropospheric parameters were estimated at two hour intervals for each station. Only the results in the case of 15° for NTUS are shown in Figures 20-25. Tables 4 and 5 give the statistics of the test results.

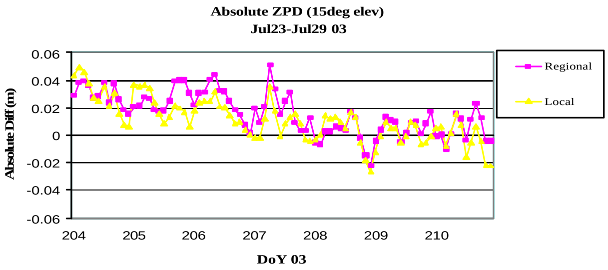

Figure 22. Absolute total ZPD difference for station NTUS wrt absolute IGS value using different network size during the South-West monsoon

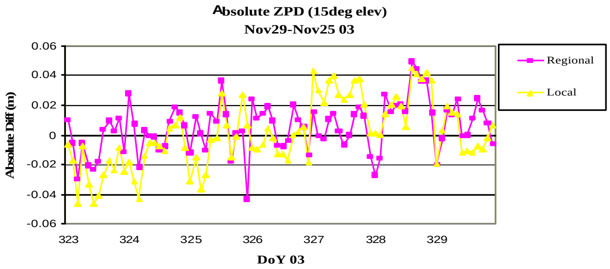

Figure 23. Absolute total ZPD difference for station NTUS wrt absolute IGS value using different network size during the North-East monsoon

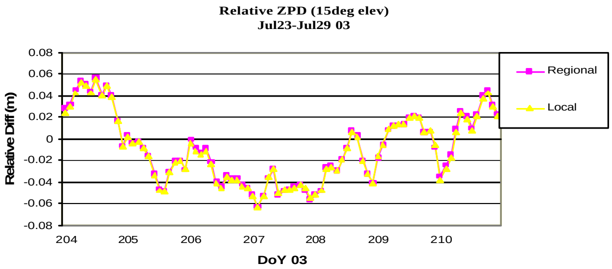

Figure 24. Relative total ZPD difference (regional and local) for station NTUS during South-West monsoon

Absolute ZPDs in Figures 20 and 21 show a large mean value of 2.60m and 2.65m. Inspecting Figures 20, 21 and Table 4, it can be found that the absolute ZPD value (compared to the IGS value) for NTUS derived from the regional network is accurate to 3-5mm, in terms of RMS values when compared to the local network. Figures 22 and 23 show the extracted values of the absolute ZPD for both networks. All tests (for 20°, 15°, 10° cut-off elevation angles) show that the differences between the regional and the local absolute ZPD are within 1-3mm (during the South-West monsoon) and 5-8mm (during the North-East monsoon). Both local and the regional absolute ZPD estimates differ by 18-32mm in their RMS wrt the IGS values, where the maximum difference occurs during the North-East monsoon for the 10° cut-off elevation angle.

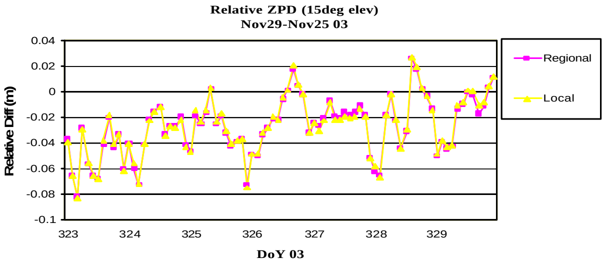

Figure 25. Relative total ZPD difference (regional and local) for station NTUS during North-East monsoon

Table 4. Statistic of absolute ZPD difference (to value published by IGS) for station NTUS

		South-West Monsoon		North-East Monsoon	
Elevation	Network	Mean (m)	RMS (m)	Mean (m)	RMS (m)
20°	Regional	0.005	0.024	-0.013	0.023
	Local	-0.001	0.024	-0.016	0.028
15°	Regional	0.016	0.019	0.006	0.018
	Local	0.011	0.022	0.001	0.023
10°	Regional	0.014	0.021	0.019	0.024
	Local	0.017	0.022	0.027	0.032

Table 5. Statistic of relative ZPD difference for station NTUS, KTPK as reference station

		South-West Monsoon		North-East Monsoon	
Elevation	Network	Mean (m)	RMS (m)	Mean (m)	RMS (m)
20°	Regional	-0.004	0.041	-0.024	0.033
	Local	-0.006	0.041	-0.026	0.035
15°	Regional	-0.009	0.033	-0.027	0.035
	Local	-0.010	0.033	-0.027	0.035
10°	Regional	-0.007	0.029	-0.021	0.029
	Local	-0.007	0.028	-0.021	0.028

Comparing Figures 24 and 25, there is no significant difference for the relative ZPD value estimation between the two networks. Table 5 also indicates the same conclusion.

CONCLUDING REMARKS

Hot and wet conditions in the equatorial or low latitude region degrade satellite positioning accuracy noticeably. The degradation is related to the strong tropospheric effect, especially the wet component which is approximately proportional to the amount of water vapor in the atmosphere. This preliminary study demonstrated the effect of the tropospheric delay on GPS positioning in the low latitude region. The tropospheric effect on the region becomes large during the two monsoon seasons, i.e, the North-East and the South-West monsoon. The performance of the existing a priori tropospheric models is not satisfactory when modeling the wet delay. Thus, the residual tropospheric delay still affects the coordinate precision. Improvements on the coordinate repatabilities were achieved by applying the scale factor. The study also shows that a better estimation of the absolute tropospheric delay is obtained by using the regional network instead of the local network. However, no significant difference is found for the estimation of the relative delay by using either the regional or the local network.

ACKNOWLEDGMENTS

We gratefully thank Department of Survey and Mapping Malaysia (DSMM) for providing us with the data used in this study.

REFERENCES

Anna B.O.J (2000) ***Real Time Modeling of the Troposphere for Network RTK***, NKG Satellite Geodesy WG Meeting at Onsala Space Observatory.

Brunner, F.K., Welsch, W.M. (1993) *Effect of the troposphere on GPS measurements*, GPS World, 4(1), 42-51.

Beutler, G., Bauersima, I., Gurtner, W., Rothacher, M., Schildknecht, T., Geiger, A. (1988) ***Atmospheric refraction and other important biases in GPS carrier phase observation***, in Atmospheric Effects on Geodetic Space Measurements, Monograph 12, School of Surveying, UNSW, Australia, 15-43.

Dodson, A.H., Shardlow, P.J., Hubbard, L.C.M., Elegered, G., Jarlemark, P.O.J. (1996) ***Wet tropospheric effects on precise relative GPS height determination***, Journal of Geodesy, 70(4), 188-202.

Duan, J., Bevis, M., Fang, P., Bock, Y., Chiswell, S., Businger, S., Rocken, C., Solheim, F., Hove, T.V., Ware, R., McClusky, S., Herring, T.A., King, R.W. (1996) ***GPS meteorology: direct estimation of the absolute value of precipitbale water***, Journal of Applied Meterology, 35(6), 830-838.

Hoffmann-Wellenhof, B., Licthenegger, H., Collins, J. (1994).***Global Positioning System: Theory and Practice***, 4h edition, Springer, Berlin, Germany, 98-106.

Malaysian Meteorological Service (2002) Ministry of Science, Technology and Innovation. http://www.kjc.gov.my.

Spilker Jr., J.J. (1996) ***Global Positioning System: Theory and Applications***, Volume I, American Institute of Aeronautics and Astronautics, Inc., 517-546.

Rothacher, M., Mervart, L. (1996) ***Manual of Bernese GPS Software***, Version 4.0, Astronomical Institute, University of Berne, 159-188.

Zain, A.F.M., Ho, Y.H., Abdullah, M. (2002) ***Enabling GPS technology on Equatorial Ionosphere monitoring during geomagnetic storm of July 15-17, 2000***, Proceedings of 15th Int. Tech. Meeting of the Satellite Division of the Insitute of Navigation, Portland, Oregon, USA 24-27 September, 1341-1344.