



THE INFLUENCE OF TROPOSPHERIC DELAY ON GPS HEIGHT VARIATION IN PENINSULAR MALAYSIA

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ABSTRACT

Triggered by innovative field operation and system interoperability brought by the state-of-the-art satellite-based positioning and navigation technology, Global Positioning System (GPS) has been widely used by professionals and practitioners to address diverse applications covering from the low cost and recreational uses to highly accurate and scientific purposes. As proper functioning of the receiver requires uninterrupted signal reception from at least four available satellites, the key limitations currently facing this fully-operational multi-satellites system is the latency of satellite-to-receiver signal arrival caused by the variability of tropospheric refractive indices, which in turn affects the accuracy of GPS measurements. This paper highlights the integration of GPS and ground meteorological campaigns performed within the Universiti Teknologi Malaysia (UTM) campus and the Johor RTK network with the ultimate aim of better understanding on the subtleties of tropospheric delay and its impact on GPS height variation in Peninsular Malaysia. It was found that the tropospheric delay induces significant variations of about 42.2 cm to 119.5 cm in the accuracy of the GPS height determination. Greater attention during data processing is therefore recommended especially when dealing with high precision applications where the utmost possible accuracy is merely important and highly demanded.

Keywords: GPS; height variation; tropospheric delay.

1.0 INTRODUCTION

Global Positioning System (GPS) is one of the fully-operational all-weather satellites technologies currently available to all-inclusive users at no direct charge. In addition to its distinct and valuable applications in engineering, surveying and scientific research expeditions, GPS technology has proven to be instrumental in revolutionizing the fast growing modern positioning and navigation approaches and has been responsible much in planning a great variety of human endeavours. As proper functioning of a GPS receiver requires uninterrupted signal reception from at least four available satellites, the key limitations currently facing this fully-operational multi-satellites system is the latency of the phase and group velocities associated with the satellite-to-receiver carrier and signal information (PRN code and navigation data) caused by the variability of tropospheric refractive indices with respect to free-space radio wave propagation (Spilker, 1996). Usually considered as a nuisance among high precision practitioners, the resulting decrease in velocity increases the time taken for the signal to reach a receiver's antenna, thereby increasing the equivalent path length, which in turn affects the accuracy of GPS measurements.

The tropospheric effect is much more pronounced at the equatorial region due to its hot and wet conditions. As Peninsular Malaysia is located within the equatorial region and geographically surrounded by seas, the high and variable water vapour content, resulting from myriad hydrological process within the local troposphere may exacerbate the effect even further.

This research focuses on examining the performance of GPS height determination on the basis of satellite-to-receiver signal delay caused by the troposphere in Peninsular Malaysia. In this research, five GPS reference stations forming part of the Malaysian real-time kinematic GPS network (MyRTKnet) in Johor were used. For the purpose of the study, RINEX data retrieved from these stations were integrated with GPS and ground meteorological data observed from a GPS station located at the UTM campus. Conducted at varying antenna heights for each session of observation in four campaigns with each campaign lasting for three days, series of extensive analyses were performed in addition to the satellite-to-receiver signal simulation tests, for better understanding on the performance of the tropospheric delay, on the basis of varying temperature, Mean Sea Level (MSL) pressure and relative humidity.

2.0 THE TROPOSPHERE

The troposphere is the first layer of the Earth's atmosphere where all of weather changes and most climatic variations takes place. Resulting from its continued contact with the ground and the energy bombardment from space, the term troposphere defines as the turning sphere due to the turbulent characteristics of this medium. The troposphere is non-dispersive medium for radio frequencies as high as about 15 GHz. The troposphere in the tropics (i.e. equator) contains nearly 90 percent of the atmospheric mass. In addition to many other gases that exist in small but important amounts, Nitrogen, Oxygen and water vapour constitute most of the troposphere.

2.1 Tropospheric Effect

Spatial and temporal variability of the tropospheric refractive indices due to the presence of dry gases and water vapour induces latency in the propagation of the radio wave signal. Considered to be the effect of the atmospheric below the ionosphere, the delay induces a code range and carrier-phase error; that is the measured satellite to receiver distance will be longer than the actual geometric range.

There are two main components of tropospheric biases that affect GPS positioning accuracy: the hydrostatic component and the wet component. The hydrostatic component characterizes the effect of the induced dipole moment of the dry constituent. The wet component on the other hand characterizes the dipole moment of water vapour, along with the orientation effects of the permanent dipole moment of water molecules. The daily variation of the wet delay usually exceeds that of the dry component by more than one order of magnitude, especially in temperate region (Zhang and Lachapelle, 2001). According to Gurtner et al. (1989), large relative height difference can introduce bias of the order of 2 mm - 5 mm per 100 m height difference. Positioning error due to improper modelling of the tropospheric effect can range from about 2 m at the zenith to over 20 m at lower elevation angles (Dodson et al., 1999).

2.2 Tropospheric Modelling

Much research has gone into the creation and testing of tropospheric interference models to compute the refractivity along the path of signal propagation for atmospheric and signal propagation studies. In addition to the Saastamoinen (1973) model, amongst others include Hopfield (1969), Davis et al. (1985), Ifadis (1986) and Mendes (1999).

The various tropospheric models differ primarily with respect to the assumptions made regarding the vertical refractivity profiles and the mapping of the vertical delay with elevation angles. Based on the ideal laws of gas, Saastamoinen (1973) model has a good reputation in which is widely used for high accuracy GPS positioning (Jensen, 2002). Producing the most reliable baseline results compared to the Hopfield (1969) and the simplified Hopfield (1969) model (Satirapod and Chalermwattanachai, 2004), the Saastamoinen model was estimated to be about 3 cm accuracy (Mendes, 1999).

3.0 THE EXPERIMENT - Field Data Collection

Leica™ System 500 dual frequency receiver and Davis GroWeather™ ground meteorological sensor were set up next to one another at one GPS station in UTM. A series of field observations were carried out for a total of 9 hours per day which was divided into three sessions of 3 hours each. For each session, the antenna height was increased systematically. In addition to one second interval of GPS data, ground meteorological parameters of temperature, Mean Sea Level (MSL) pressure and relative humidity were measured at ten minute intervals in each session. Forming four sets of observations, the procedures were repeated in all campaigns with each set consists of three consecutive days of data collection. **Table 1** shows the time scheduling of the field data collection.

Table 1: Field observation schedule

Campaign		1	2	3	4
Observation Period		Aug 29-31, 2006	Dec 1-3, 2006	Jan 6-8, 2007	Jan 9-11, 2007
9 hr	Session 1	Antenna Height : 0.5 m (9a.m. - 12p.m.)			
	Session 2	Antenna Height : 1.0 m (12p.m. - 3p.m.)			
	Session 3	Antenna Height : 1.5 m (3p.m. - 6p.m.)			

Five GPS reference stations: Johor Jaya (JHJY), Kukup (KUKP), Kluang (KLUG), Pengerang (TGPG) and Mersing (MERS) forming Johor RTK network were used as the base stations, thus producing five different baselines. In relative to UTM station, these baselines range at about 17.9 km (UTM-JHJY), 32.2 km (UTM-KUKP), 56.5 km (UTM-TGPG), 62.8 km (UTM-KLUG) and 101.3 km (UTM-MERS) respectively.

3.1 Multi-Station Analysis

A multi-station analysis was performed to determine the availability of the satellites and the satellite-to-receiver geometry during the GPS observation campaigns. Different amount of satellites and satellite-to-receiver geometries can magnify or lessen the errors in the GPS derived positions. As the satellite availability and the Geometry Dilution of Precision (GDOP) at

a location repeats each day because the constellation is unchanged from day-to-day (except it rises about four minutes earlier each day), **Figures 1-3** present the multi-station analysis conducted during the fourth campaign from January 9-11, 2007. In addition, **Figure 4** presents the satellite elevation detected on January 9, 2007.

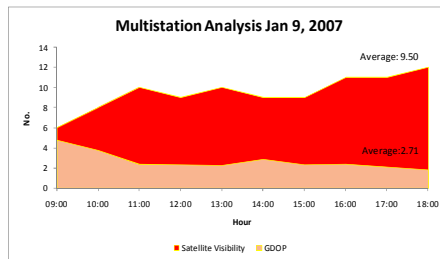


Figure 1: Multi-Station analysis for January 9, 2007

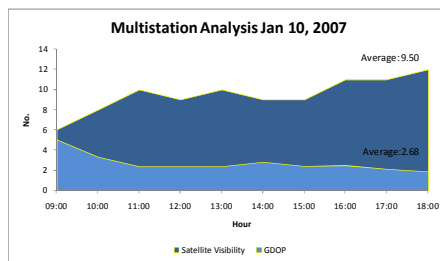


Figure 2: Multi-Station analysis for January 10, 2007

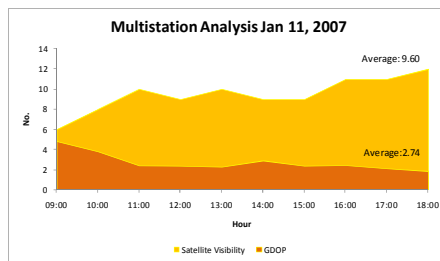


Figure 3: Multi-Station analysis for January 11, 2007

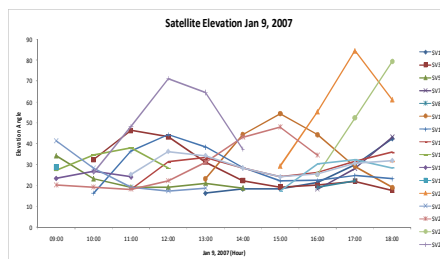


Figure 4: Satellite elevation for January 9, 2007

Good GDOP is obtained when the simultaneously tracked satellites are considerably visible within receiver's observational quadrants. In this study, 10 visible satellites with GDOP of 2.71 in

average were detected during the observation campaign. As each station experiencing excellent views of satellites and considerable satellite-to-receiver geometry, the quality of the data retrieved from these stations is expectedly high. Producing results at high confidence level, these data were suitable to cater most of the GPS applications, where the highest possible position accuracy is sought.

3.2 Data Processing

In order to mitigate the effect of the ionosphere, Ionosphere free (IF) double difference solution was applied during GPS data processing. In addition, International GNSS Service (IGS) final Earth rotation parameters (ERP) were used to mitigate radial displacement caused by the polar motion. To improve measurement caused by the orbital error, IGS final orbits were used in place of the broadcast orbits

4.0 ANALYSIS OF RESULT

Discrepancies in the computed ellipsoidal height at UTM of four GPS campaigns compared to the known value were firstly calculated. As the tropospheric effect been left uncompensated with no tropospheric model was applied during data processing, discrepancies of the ellipsoidal height between the computed and the known values for each baseline during the four field campaigns were firstly plotted per hour of observation. To visualize the variation on the GPS height positioning component due to the tropospheric delay, **Figures 5-8** present the results obtained from all campaigns in 3D. Using similar data retrieved from **Figures 5-8; Figures 9-12** present results after applying Saastamoinen model in data processing.

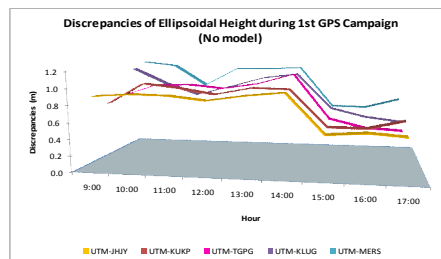


Figure 5: GPS height variation for 1st campaign (without model)

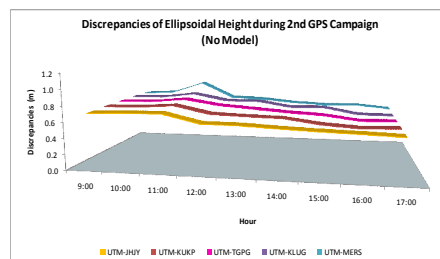


Figure 6: GPS height variation for 2nd campaign (without model)

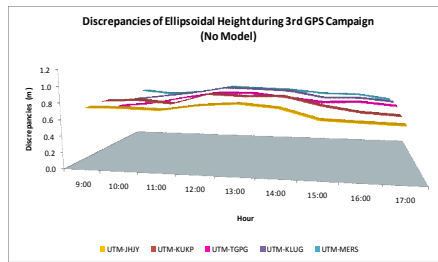


Figure 7: GPS height variation for 3rd campaign (without model)

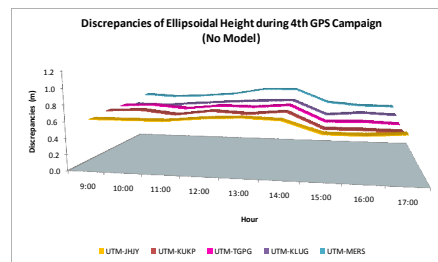


Figure 8: GPS height variation for 4th campaign (without model)

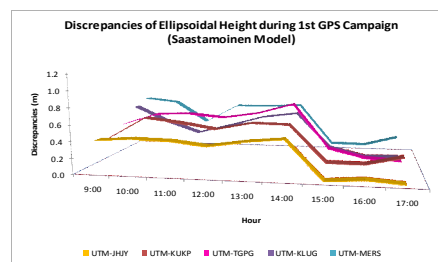


Figure 9: GPS height variation for 1st campaign (with Saastamoinen model)

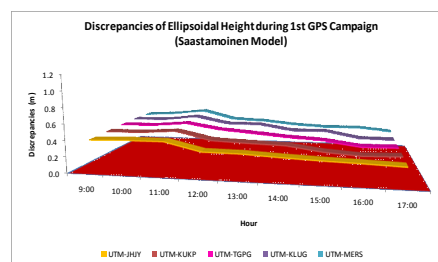


Figure 10: GPS height variation for 2nd campaign (with Saastamoinen model)

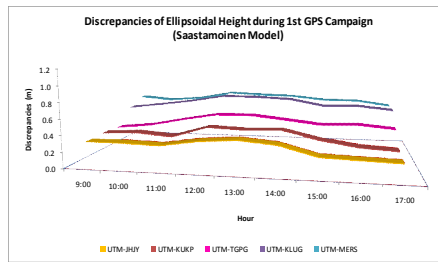


Figure 11: GPS height variation for 3rd campaign (with Saastamoinen model)

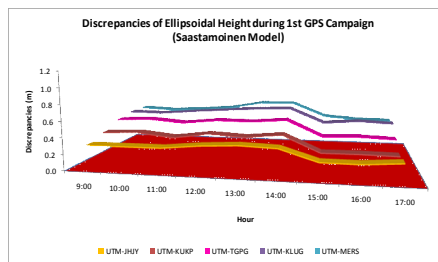


Figure 12: GPS height variation for 4th campaign (with Saastamoinen model)

From the results obtained in this study, it is obvious that the latency in the satellite-to-receiver signal caused by the local troposphere in Peninsular Malaysia induces variations in the accuracy of the height determination using GPS. Neglecting the use of a tropospheric model leads to significant amount of variations in the height components. In the 1st campaign (**Figure 5**), discrepancies of about 42.2 cm – 119.5 cm in the height component were obtained followed by 51.7 cm - 89.7 cm height variation during the 2nd campaign (**Figure 6**). The 3rd campaign (**Figure 7**) and the 4th campaign (**Figure 8**) produced 60.7 cm - 85.9 cm and 48.0 cm - 80.6 cm height variation respectively.

Certain improvement on the other hand can be detected after applying the Saastamoinen tropospheric model in data processing. Mitigating most of the effects induced by the varying refractivity of the local troposphere, improvement of about 44.9 cm (54 percent) and 30.3 cm (47 percent) in the height component were obtained during the 1st campaign (**Figure 9**) and the 2nd campaign (**Figure 10**) correspondingly. The 3rd campaign (**Figure 11**) and the 4th campaign (**Figure 12**) on the other hand produced 27.2 cm (37 percent) and 21.8 cm (35 percent) improvement in the height positioning component.

As far as the effects of different set of antenna heights, the results obtained show that the 0.5 m increment of the antenna height per session has no significant effects towards the accuracy of computed height obtained from each baseline. This might be due to the fact that a 0.5 m increment is very small compared to the range of coverage of the troposphere medium above the Earth's surface (16 km above the equator). Further study however can be conducted at larger scale (say 100 m height increment or differences) to visualize the so called altitude dependency of the error towards the accuracy of GPS height determination.

The results obtained also reveal that the tropospheric delay is also a distance dependent error that will increase when the baseline length between two stations is increased. GPS height variations of about 0.1 cm – 0.5 cm per km can be expected at different baseline length. The height variations might be due to the different amount of tropospheric content experienced by

the satellite-to-receiver signal prior arriving to both receivers on the ground caused by the large difference in baseline length. Similarly, the best height determination performance was detected over the shortest UTM-JHJY baseline. In relative to the UTM-JHJY baseline, height variations of about 1.6 cm (2 percent), 1.7 cm (3 percent), 3.4 cm (5 percent) and 8.3 cm (12 percent) can be detected over the UTM-KUKP, UTM-TGPG, UTM-KLUG and UTM-MERS baseline respectively.

The utmost variation of about 84.2 cm (in average) in the height component can be detected between 12 noon and 1 p.m. each day. Providing the lowest amount of height variations of about 62.9 cm (in average) on daily basis, better results in the computed height were detected around 4 p.m. to 5 p.m.. The height variations might be due to the inter-dependent relationship between the time of occurrences and the variability of the local temperature, MSL pressure and relative humidity, resulting dissimilar amount of associated tropospheric biases that affect GPS measurement per day. Positive correlation can be expected between the temperature and the MSL pressure with both sets tend to increase and to decrease together; that is usually low at midnight, decreasing in the early hours of the morning, before increasing rapidly until just after midday. The relative humidity on the other hand is usually high at midnight and in the early morning before drops dramatically after the sun rises, until to its lowest just after midday.

To further comprehend the inter-dependent relationship of the associated tropospheric delay and the varying meteorological parameters, simulation tests were conducted using satellite-to-receiver signal propagation delay computation prototype. Known as TROPO_v2.exe, it is the improved version of TROPO.exe developed by Dodo et al. (2008). Whilst satellite elevation angle, station height and station latitude were remained constant, the satellite-to-receiver signal propagation delay on the other hand were simulated based on the Saastamoinen tropospheric model at different temperatures, MSL pressures and relative humidities. **Figures 13-15** shows the results of the study.

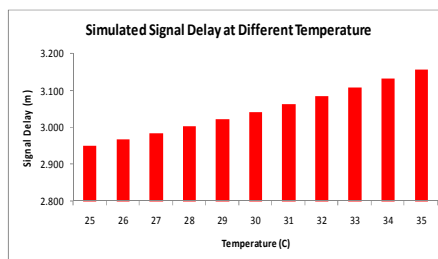


Figure 13: Simulated signal delay at different temperature

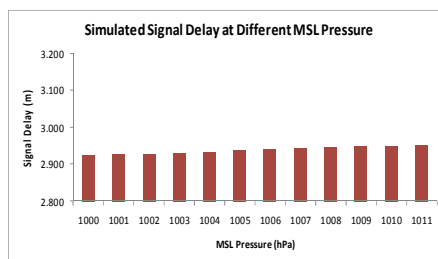


Figure 14: Simulated signal delay at different MSL pressure

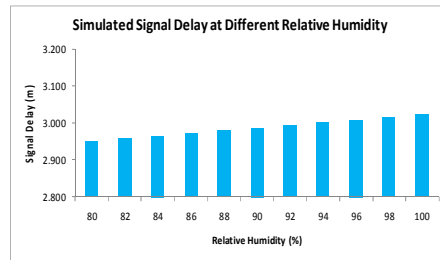


Figure 15: Simulated signal delay at different relative humidity

Apparently, the satellite-to-receiver signal propagation delay will increase when the temperature, MSL pressure and relative humidity are increased. Changes from about 1.8 cm to 2.5 cm can be obtained on the simulated delay with temperature increment of about 1 degree Celsius. Signal delay variations of about 0.3 cm on the other hand were obtained with increases of about 1 hPa of MSL pressure. As far as the relative humidity is concerned, increases of about 1 percent induce 0.7 cm variations on the simulated satellite-to-receiver signal propagation delay.

5.0 CONCLUSIONS

This paper reports the impact of local troposphere towards the variation of GPS height determination in Peninsular Malaysia. Based on the results, it is obvious that the latency in the satellite-to-receiver signal caused by the varying refractivity of the local troposphere, induces significant variations of about 42.2 cm to 119.5 cm in the accuracy of the GPS height determination and therefore is a matter of concern among local high precision applications where the utmost possible accuracy is highly demanded. As the results reveal that the tropospheric delay is a distance dependent error that will increase when the baseline length between two stations is increased, inter-dependent relationship of the associated tropospheric delay with the time of occurrences and the varying meteorological parameters were also detected based on simulation tests conducted using satellite-to-receiver signal propagation delay computation prototype called TROPO_v2.exe. The use of tropospheric models, for example Saastamoinen model however was found to be substantial in improving the height determination performance and hence suggested to be employed during data processing.

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REFERENCES

- Boudouris, G. 1963. On the Index of Refraction of Air, the Absorption and Dispersion of Centimetre Waves by Gases, *Journal of Research of the National Bureau of Standards - D. Radio Propagation*, 67D(6), 631-684.
- ?Davis, J. L., et al. 1985. Geodesy by Radio Interferometry: Effects of Atmospheric Modelling Errors on Estimates of Baseline Length, *Radio Science*, 20(6), 1593-1607.

?Dodo, J. D., et al. 2008. The Effect of Tropospheric Delay on GPS Height Differences along the Equator. *Journal of Surveying and Land Information Science* 68(3):145-154.

?Gurtner, W., et al. 1989. The Use of the Global Positioning System in Mountainous Areas, *Manuscripta Geodetica*, 14, 53-60.

Hopfield, H. S. 1969. Two-quadratic Tropospheric Refractivity Profile for Correcting Satellite Data, *Journal of Geophysical Research*, 74, 4487-4499.

Ifadis, I. 1986. The Atmospheric Delay of Radio Waves: Modelling the Elevation Dependence on a Global Scale, Technical Report no.38L thesis, Chalmers University of Technology, Goteborg, Sweden.

Jensen, A. B. O., et al. 2002. Integrating Numerical Weather Predictions in GPS Positioning, paper presented at ENC GNSS-2002, Copenhagen.

Mendes, V. B. 1999. Modelling the Neutral-Atmosphere Propagation Delay in Radiometric Space Techniques, 353 pp, University of New Brunswick, Canada.

Saastamoinen, I. 1973. Contribution to the Theory of Atmospheric Refraction, *Bulletin Geodesique*, 107, 13-34.

Satirapod, C., and P. Chalermwattanachai 2004. Impact of Different Tropospheric Models on GPS Baseline Accuracy: Case Study in Thailand, paper presented at GNSS 2004: The 2004 International Symposium on GNSS/GPS, Sydney, Australia, 6-8 December 2004.

Spilker, J. J. 1996. Tropospheric Effects on GPS, in *Global Positioning System: Theory and Applications*, edited by J. J. Spilker and Parkinson, pp. 517-546, American Institute of Aeronautics and Astronautics Inc.

Zhang, J., and G. Lachapelle 2001. Precise Estimation of Residual Tropospheric Delays Using a Regional GPS Network for Real-time Kinematic Applications, *Journal of Geodesy*, 75, 255-266.