Discrepancies in GPS Positioning during Varying Monsoon Periods in Malaysia

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ABSTRACT

The broad field of engineering presents vast opportunities among local practitioners to benefit from Global Positioning System (GPS) as an ingenious yet practical space-based technology in providing the critical positioning data needed for projects including large buildings, roads, bridges, sewers and tunnels. Offering a competitive advantage by increasing productivity when coordinating to existing topography or staking out design features on the ground, one of the key limitations of this multi-satellites system however is the latency in time of satellite-to-receiver signal arrival caused by the variablity of refractive indices within the Earth's troposphere where all of weather changes and most climatic variations take place. As the weather condition in Malaysia is mainly characterized by two monsoon regimes: the Southwest Monsoon (from late May to September) and the Northeast Monsoon (from November to March) with two transition periods (from April to early May and September to October) that contributes spatial and temporal variations of the tropospheric refractive indices each year, 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 the derived positions. This paper aims to investigate the impact of varying monsoon periods on the performance of three dimensional vectors of GPS derived positions. Series of comprehensive analyses were conducted based on GPS data retrieved from five continuously operating reference stations forming parts of the Malaysian Real-Time Kinematic GPS Network (MyRTKnet). The result reveals that the latency in the satellite-to-receiver signal propagation caused by the varying refractivity of the local troposphere during varying monsoon periods in Malaysia leads to significant variations of about 64 percent accuracy degradation in GPS positioning performance. Without appropriate compensation, the performance of GPS positioning is a matter of concern for high precision applications where the utmost possible accuracy is highly demanded.

1. INTRODUCTION

The weather condition in Malaysia is mainly characterized by two monsoon regimes: the Southwest Monsoon and the Northeast Monsoon. Relatively signifies drier weather with most states experience minimum monthly rainfall with high temperature and high Mean Sea Level (MSL) pressure, the Southwest Monsoon normally occurs from late May to September each year. Bringing heavy rainfall particularly to the east coast states of Peninsular Malaysia and western Sarawak with high amount of relative humidity, the Northeast Monsoon on the other hand occurs from November to March each year. Associated with large-scale seasonal reversals of pressure, temperature and winds, the monsoon weather is one of the major features of the tropical atmosphere that caused by the larger amplitude of the land temperature compared to that of the nearby oceans. During the seasonal monsoon periods, variability of refractive indices due to the presence of dry gases and water vapour triggered by varying prevailing winds within the Earth's troposphere induces latency with respect to free-space radio wave propagation. Usually denoted as a nuisance among high precision satellite-based positioning practitioners i.e. Global Positioning System (GPS), the resulting decrease in signal's 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 the derived positions. Discrepancies in GPS derived positions due to the satellite-to-receiver signal interference are a matter of concern for highly precise applications where the utmost possible accuracy is merely important and highly demanded. Without appropriate compensation, positioning deficiency due to the tropospheric effect can range from about 2 m at the zenith to over 20 m at lower elevation angles (Dodson et al. 1999).

Much research has gone into the designing and testing of tropospheric models to compute the refractivity along the path of satellite-to-receiver signal propagation for atmospheric and signal propagation studies. Mostly derived from the radiosonde data, observed mostly on the European and North American continents, these models include Hopfield (1969), Saastamoinen (1973), 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. Divided into the hydrostatic and the wet components, Saastamoinen (1973) model has a good reputation in which is widely used for high accuracy GPS positioning (Jensen 2002). The accuracy of the Saastamoinen model was estimated to be about 3 cm in zenith (Mendes 1999). Given that ground meteorological data is available, Saastamoinen (1973) model is considerably sufficient to compute zenith tropospheric delay (Katsougiannopoulos et al. 2006).

This paper concentrates on examining the performance of GPS positioning under the influence of the varying monsoon weather periods associated with tropospheric-related error in Malaysia. In this research, 1 second interval of GPS data retrieved from continuously operating reference stations: Johor Jaya (JHJY), Kluang (KLUG), Mersing (MERS), Malacca (JUML) and Klang (MERU) were used. Each reference station is equipped with a high precision dual frequency receiver connected continuously through leased line with ISDN backup in IPVPN communication network to a Control Centre in Kuala Lumpur. Producing results at high confidence level with each station experiencing excellent views of satellites and considerable satellite-to-receiver geometry throughout the observation periods, the quality of the data retrieved from these stations is expectedly high. 3 sets of observation campaigns with each set represents the varying monsoon periods of Southwest Monsoon, Northeast Monsoon and Inter Monsoon periods were used. Several analyses were conducted in this study. Amongst other analyses include: analysis on three-dimensional vectors of GPS baseline solution and analysis on discrepancies of both horizontal and vertical positioning components.

2. GPS POSITIONING PERFORMANCE

2.1 GPS Baseline Solution

The fundamental issue in GPS positioning is the ability to mitigate all potential errors and biases in the system. The atmosphere related error associated with weather condition and varying meteorological parameters within the troposphere constitutes one of these potential errors. To study the performance of GPS positioning on the basis of relative baseline solution during Southwest Monsoon, Inter Monsoon and Northeast Monsoon periods, the quality of each GPS data is estimated in term of ratio, reference variance and Root Mean Square (RMS). Ratio is a measure of how well the processing software is able to determine fixed-integer solutions. Fixed-integer solution is obtained when the processor is able to find a set of integer values for the ambiguity. Reference variance on the other hand is a measure as to how well the baseline processor estimates the expected error. RMS values entails the degree to which the baseline residuals tend to spread about its average values. As higher number of ratio is considered better, smaller values for the reference variance and the RMS in the baseline solution tend to produce better results in GPS positioning.

JHJY and JUML stations were used to indicate the influence of seasonal monsoon towards the estimated three-dimensional vectors of GPS baseline solution. As ionosphere free-double difference solution was applied to mitigate the effect of the ionosphere, the tropospheric effect on the other hand were left uncompensated (no tropospheric models were applied) throughout the process. In place of the broadcast orbits, International GNSS Service (IGS) final orbits were used to improve measurement caused by the orbital error. 20 degrees of elevation cut-off angle were set during data processing. For the purpose of the study, IGS final Earth rotation parameters were employed. Figure 1 illustrates the computed ratio, reference variance and RMS of 10 consecutive days of observation campaigns over year 2006 during Southwest Monsoon, Inter Monsoon and Northeast Monsoon.

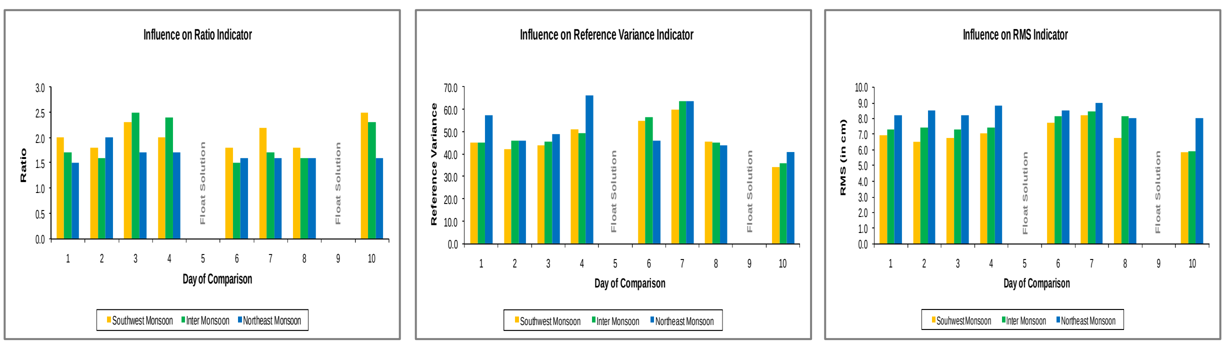

Figure 1: The influence of Malaysian Monsoons on GPS baseline indicator

On the basis of three-dimensional vectors of GPS baseline solution, the ratio indicator for the Northeast Monsoon is lower compared to during the Southwest Monsoon and the Inter Monsoon seasons. Similarly, the baseline solution for the Northeast Monsoon tends to produce larger amount of reference variance and RMS. With an approximate of 9 cm, the highest RMS is detected on Day 4 during Northeast Monsoon. Based on the results, it is apparent that the GPS baseline solution tends to produce poor estimated three-dimensional vectors during the Northeast Monsoon compared to the Southwest Monsoon and Inter Monsoon season. This might be due to the signal bending and refraction caused by the variability of atmospheric refractive indices during heavy rainfalls that induces higher amount of relative humidity and MSL pressure throughout the Northeast Monsoon period.

Furthermore, it is also noted that on Day 5 and Day 9; only float solution can be produced throughout all Malaysian monsoon periods. Float solutions in general are weaker than fixed-integer solutions. In contrast to the fixed-integer solution, a float solution is obtained when the baseline processor cannot compute a definitive integer value for the ambiguity terms.

Hypotheses can be made that this condition might be due to the relative distance factor between JHJY and JUML stations (187 km) that contribute much on the complexity of the observables ambiguity resolution at certain observation period. Moreover, signals transmitted from a satellite need to propagate through different amount of atmospheric content (e.g. dry gases and water vapour) within the troposphere due to large difference in baseline length before arriving to both receivers on the ground. To evaluate the significant of GPS baseline length selection on the quality of GPS positioning performance, 4 baselines in reference to JHJY station were used. The distances between KLUG, MERS, JUML and MERU stations in relative to JHJY are respectively sufficient to signify short baseline (76 km), medium baseline (101 km), long baseline (187 km), and very long baseline (319 km). Again by using similar processing parameters used during the earlier analysis, Figure 2 illustrates the computed ratio, the reference variance and the RMS over 10 consecutive days during Northeast Monsoon of 2006 at varying baseline length.

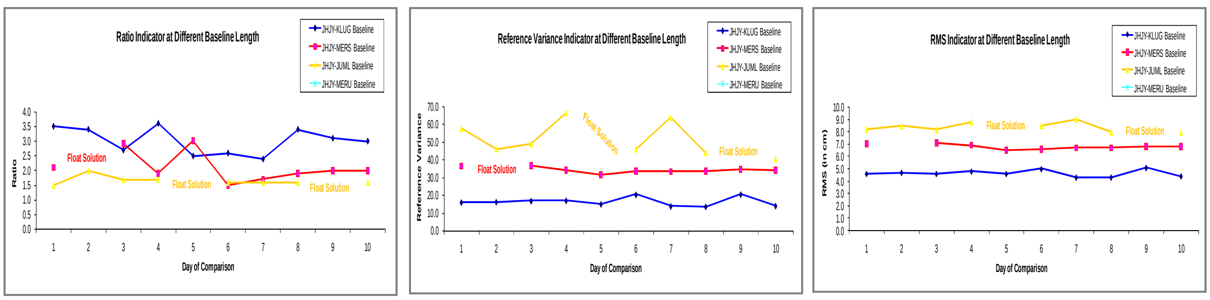

Figure 2: The influence of different baseline length on GPS baseline indicator

The result reveals that tropospheric error caused by the variability of weather conditions and meteorological parameters is a distance dependant error that increases with the increases in the baseline length. Poor results in the GPS baseline solution especially in term of the estimated three dimensional vectors can be expected at very long baseline. Consistently providing fixed baselines solutions throughout the GPS 10 days' observation campaigns, it is clear that JHJY-KLUG baseline (short baseline) produces better result in all estimated three dimensional vectors followed by the JHJY-MERS baseline (medium baseline) and the JHJY-JUML baseline (long baseline). As far as the JHJY-MERU baseline (very long baseline) is concerned, it is apparent that only float baseline solution can be produced. For high accuracy GPS applications, the use of long baseline during data processing should be avoided. To evaluate the influence of commonly used tropospheric model towards variations on the estimated three dimensional vectors of the GPS baseline solution, another analysis was made based on the two in-build tropospheric models: the Saastamoinen model and the Hopfield model. To envisage the dispersion caused by the use of the Saastamoinen model and the Hopfield model towards the quality of GPS baseline solution, no tropospheric models on the other hand were applied on the other set of GPS data. Based on GPS data retrieved from JHJY and JUML stations over 10 consecutive days during Inter Monsoon of 2006, Figure 3 illustrates the result of the study.

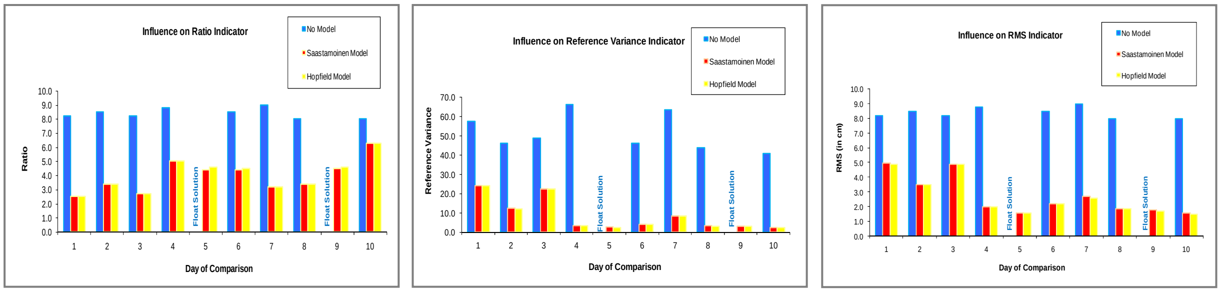

Figure 3: The influence of tropospheric model on GPS baseline indicator

Based on the result, it is obvious that global tropospheric models tend to improve the performance of ratio, reference variance and RMS of GPS baseline solutions. Moreover, it is apparent that neglecting the use of tropospheric models leads to variations in GPS baseline solution. As seen on Day 5 and Day 9, float solution can also be avoided by applying global tropospheric models in data processing. The GPS baseline ratio indicator tends to improve up to 294 percent after applying the tropospheric models. The GPS baseline reference variance value on the other hand tends to improve up to 94 percent after applying the tropospheric models. Similarly, as far as the GPS baseline reference RMS indicator is concerned, the improvement ranges from 3.2 cm to 6.4 cm; that is around 39 percent to 80 percent respectively.

2.2 GPS Positioning Error Analysis

To investigate the performance of GPS Easting, Northing and Height positioning components under the influence of the Malaysian monsoon period, further analyses using 8 consecutive days of JHJY and KLUG observation data were conducted. Again using similar processing parameters used during the earlier analysis (only in this case, no tropospheric models were applied), Figure 4 illustrates the residual in GPS positioning components during Southwest Monsoon, Inter Monsoon and Northeast Monsoon period of 2006.

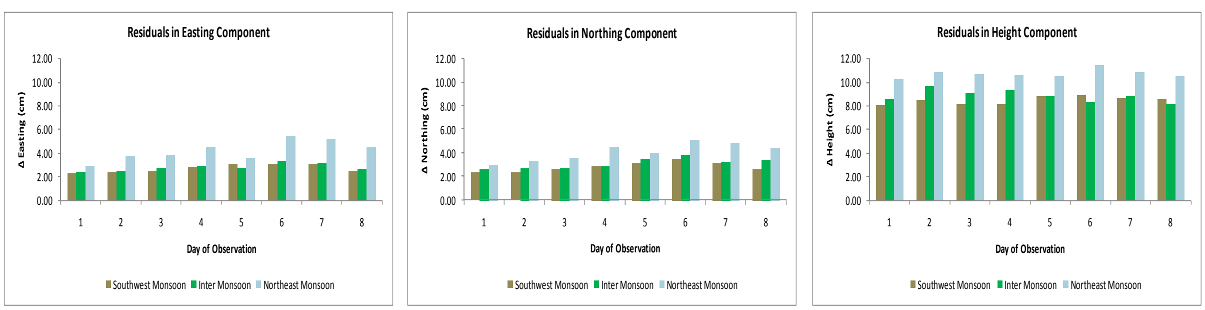

Figure 4: Residuals in GPS positioning component

Based on the result, it is obvious that neglecting the use of tropospheric a priori models leads to variations in GPS derived positions. Though most of today's manufacturers claimed that GPS receiver have the capability to retrieve positioning information at about 1 cm to 2 cm Horizontal accuracy and about 3 cm to 5 cm Vertical accuracy, it was found that without appropriate compensation, the effect induces discrepancies from about 2.31 cm to 5.50 cm in the GPS Easting component; that is almost 64 percent variation compared to the expected reference value. As far as the Northing component is concerned, the residuals range from about 2.34 cm to 5.10

cm; that is almost 61 percent variation compared to the reference value. Reaching to about 8.00 cm to 11.40 cm; that is almost 52 percent and 55 percent variation compared to the Easting and Northing components respectively, the Height component is by far the most variable positioning parameter resulting from the satellite-to-receiver signal propagation delay.

On the basis of the influence of monsoon weather towards expected residuals on the performance of GPS positioning, it is noted that the Northeast Monsoon tends to influence much on the derived positions compared to the Southwest Monsoon and the Inter Monsoon periods. The average value of residuals in Easting, Northing and Height components during Northeast Monsoon are 4.24 cm, 4.08 cm and 10.67 cm respectively. As far as the Inter Monsoon is concerned, the average value of residuals in Easting, Northing and Height components are 2.79 cm, 3.11 cm and 8.80 cm respectively. The average value of residuals in Easting, Northing and Height components during Southwest Monsoon on the other hand are 2.73 cm, 2.81 cm and 8.43 cm respectively. In most cases, Southwest Monsoon and Inter Monsoon period tends to produce small residuals variations (on average) especially on the Easting (0.17 cm) and Northing (0.30 cm) components with Inter Monsoon tends to produce higher amount of residuals compared to the Southwest Monsoon. As far as the Height component is concerned, residuals variations (on average) of about 0.63 cm can be expected. As Northeast Monsoon tends to influence much on the GPS derived positions, the maximum residuals of Easting, Northing and Height components during this monsoon period are 5.50 cm, 5.10 cm and 11.40 cm respectively.

In order to gauge the contribution of monsoon weather to variation in discrepancies of the GPS derived positions, three-dimensional error analyses were conducted. A three-dimensional error analysis is a precursor of total deviations and discrepancies in GPS Easting, Northing and Height components. It can be expressed as:

$$3DError = \left((\Delta E)^2 + (\Delta N)^2 + (\Delta H)^2 \right)^{\frac{1}{2}} \quad (1)$$

where:

ΔE is the error in Easting component

ΔN is the error in Northing component

ΔH is the error in Height component

Based on the results obtained from Figure 4, the following figure illustrates the result of the three-dimensional error analyses conducted during Southwest Monsoon, Inter Monsoon and Northeast Monsoon periods.

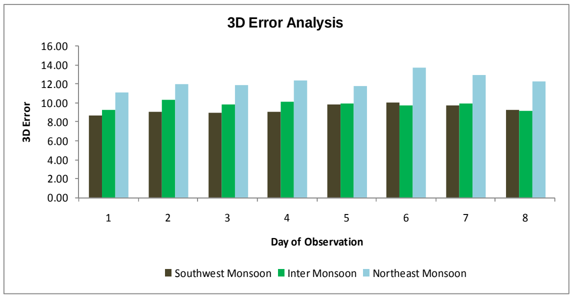

Figure 5: 3D Error analysis during Malaysian Monsoon period

The result reveals that greater amount of total deviations and discrepancies in GPS Easting, Northing and Height components can be expected during Northeast Monsoon period. The average amount of three-dimensional errors during Northeast Monsoon is 12.21 cm. Similarly, the average amount of three-dimensional errors during Inter Monsoon and Southwest Monsoon periods are 9.76 cm and 9.30 cm respectively. Without appropriate compensation, it is suggested that the accuracy of GPS positioning is a matter of concern especially during the Northeast Monsoon and therefore should not be taken lightly when dealing with applications where the accuracy is of paramount important and highly demanded.

3. CONCLUDING REMARKS

In this research, certain variations and discrepancies can be expected on the basis of three dimensional vectors i.e. ratio, reference variance and RMS towards the performance of the GPS baseline solutions and the derived positioning components during varying monsoon periods. As it was found that the effect is distance dependent errors that will increases when the baseline length between two stations is increased, the results reveal that the Northeast Monsoon tends to contribute the greatest impact on the accuracy of GPS three-dimensional positions in comparison to the Southwest Monsoon and the Inter Monsoon periods. Providing that the GPS Height is the most affected positioning components caused by the variability of refractive indices at varying monsoon periods, greater attention during data processing is therefore recommended especially when dealing with high precision applications where the utmost possible accuracy is highly demanded. The use of tropospheric models, for example Saastamoinen and Hopfield model was found to be substantial in improving the Height determination performance and hence suggested to be employed during data processing.

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