GPS Zenith Path Delay Estimation for Meteorological Applications: From Low Latitude to the Mid Latitude Regions

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Abstract

The estimation of ZPD from GPS data was realized can provide useful quantity for meteorological information. Recent development in GPS data processing has allowed the estimation of ZPD from a network of CORS. Comparisons with other ZPD product processed by other processing centre must be performed to evaluate the quality of the estimated ZPD. In this paper, details of the network of ground stations, the processing strategy, a wide variation of estimated ZPD in low latitude and mid latitude region and the quality of the estimated ZPD are presented. The estimated ZPD are expected to be valuable for a wide variety of climate and weather applications.

1.0 INTRODUCTION

Water vapour is highly variable both in space and time across the Earth’s atmosphere. First it plays a fundamental role in the hydrological cycle. It can be produced through the evaporation of liquid water (oceans, seas, lakes and rivers) or sublimation from a solid (ice or snow) to a gas. Once in the air, water vapour gets cold and as a result, the excess water vapour condenses (changes from a gas to a liquid) to form clouds and produce precipitation in terms of rain, snow, sleet, freezing rain and hail. Second it is the dominant greenhouse gas in the atmosphere, which it plays an important role in the greenhouse effect, i.e., the effect which makes the Earth’s surface become warmer. Moreover, many global meteorological phenomena
such as tropical storms, El Niño and La Niña require information on the regional and global spatial (in 3-dimensions) and temporal variability of the atmospheric water vapour.

The Global Positioning System (GPS) is a useful tool for the remote sensing of atmospheric water vapour. The GPS signals traveling from satellite to receiver propagate through the atmosphere. The signals are delayed due to the amount of dry gases and water vapour in the troposphere layer. This increase the time taken for the signal when it travels through the troposphere. The effects are called tropospheric refraction, tropospheric path delay or simply tropospheric delay (Hofmann-Wellenhof et al., 2001). The tropospheric delay can be divided into dry and wet components. The dry component is caused by the dry air gases in the atmosphere such as nitrogen (78%) and oxygen (21%) with only small concentrations of other trace gases. The wet component however depends on the humidity content of the troposphere and contains significant levels of water vapor (Buchdahl, J. and Hare, S., 2000). The total delay in the GPS signal is known as the slant path delay, or in zenith direction known as Zenith Total Delay (ZPD) or Zenith Path Delay (ZPD). The ZPD also consist of the hydrostatic and wet component which are known as the zenith hydrostatic delay (ZHD) and the zenith wet delay (ZWD), respectively. The ZWD can be expressed in terms of Integrated Water Vapor (IWV) and the IWV was realized as a useful quantity for meteorological applications (Bevis et al., 1992).

In this paper, the ZPD estimation has been conducted from two CORS networks – the Australian Regional GPS Network (ARGN) and the Malaysian Real-Time Kinematic network (MyRTKnet), which stretches from the low latitude to the mid latitude region. Moreover, the IGS (International GNSS Service) stations were included in the ZPD estimation process so as to provide an opportunity to assess the estimated ZPD against the IGS derived troposphere products. The estimated ZPD are expected to be valuable for a wide variety of climate and weather applications.
2.0 LITERATURE REVIEW

2.1 Tropospheric Path Delay

The tropospheric delay can be computed through the integration along the signal path through the troposphere using following expression (Hofmann-Wellenhof et al., 2001):

\[ d^{\text{trop}} = \int (n - 1) ds \]  \hspace{1cm} (2.1)

where \( n \) is the refractive index and \( ds \) is the path length. The equation can be expressed in terms of the refractivity of the troposphere \( N^{\text{trop}} = 10^6(n - 1)\):

\[ d^{\text{trop}} = 10^{-6} \int N^{\text{trop}} ds \]  \hspace{1cm} (2.2)

The tropospheric delay can be separated into two main components: the “hydrostatic” or dry and the “wet” component.

\[ N^{\text{trop}} = N^{\text{trop}}_h + N^{\text{trop}}_w \]  \hspace{1cm} (2.3)

where the hydrostatic and wet components are caused by the dry gases (primarily nitrogen and oxygen) and the water vapour respectively. About 90\% of the magnitude of the tropospheric delay arises from the dry component, and the remaining 10\% from the wet component (Hofmann-Wellenhof et al., 2001). Using the previous equation we may write

\[ d^{\text{trop}} = 10^{-6} \int N^{\text{trop}}_h ds + 10^{-6} \int N^{\text{trop}}_w ds \]  \hspace{1cm} (2.4)

or

\[ d^{\text{trop}} = d^{\text{trop}}_h + d^{\text{trop}}_w \]  \hspace{1cm} (2.5)
The total tropospheric delay in slant path delay can be mapped to the zenith direction, yield the ZPD. Using the mapping function, equation (2.5) is modified as:

\[
d_{\text{trop}} = ZHD_m_h(E) + ZWD_m_w(E) \tag{2.6}
\]

where consist of the zenith hydrostatic delay (ZHD) and zenith wet delay (ZWD) components. The term of E is the satellite elevation angle, \(m_h(E)\) is the hydrostatic mapping function and \(m_w(E)\) is the wet mapping function.

3.0 GPS ZPD ESTIMATION

3.1 Study Area and Climate Condition

The studies were conducted at two difference regions, in Peninsula Malaysia and in Australia. The two regions have distinct climate characteristic. Peninsula Malaysia is located in a low latitude region, the area which is experiencing high variation and large amount of water vapour. The area is exposed to intense sunlight all year round, with the temperature ranging from 27°C to 32°C Celsius. The annual average rainfall in Peninsula Malaysia is 2,000 – 3,000 mm and the relative humidity is about 80% all year round. The Peninsula Malaysia has two distinct seasons; a) Southwest Monsoon - from late May to September and, b) Northeast Monsoon - from November to March. The Northeast Monsoon brings heavy rainfall to area on the east coast states of Peninsula Malaysia, such as Pahang, Terengganu and Kelantan whereas the Southwest Monsoon brings rainfall to the western side of Peninsula Malaysia such as Kuala Lumpur, Pulau Pinang and Kedah. In addition, Pahang, Terengganu, Kelantan and Johor always been prone to flash flood.

Australia is located in the southern hemisphere so the seasons are opposite to the northern hemisphere. Late November is the beginning of summer, which lasts through February. March through May is fall, June to August is winter, and spring occurs from September until November.
The climate of Australia varies greatly from one part of the country to another. The largest portion of the land in Australia is desert or semi arid land. Most of the deserts lie in the central, western and south-central part of the country. It is windy and extremely dry, with temperatures high during the day and low at night. Central Australia receives less than 250mm of rain per year. In summer daytime, temperatures range from 32 to 40 °C and in winter, this falls to 18 to 23 °C.

Southern regions, especially on the east and west sides of Australia, are classified as a temperate climate. These areas have more seasonal changes, with hot summers and moderately cold winters, with temperatures averaging close to 20°C. Rainfall is evenly spread between summer and winter though is generally heavier in the first half of the year. The northern part of the country has tropical climate due to its proximity to the equator. The tropical region has distinct wet and dry seasons. The wet season corresponds with summer and lasts from November through April. The dry season corresponds with winter and lasts from May through October.

3.1 Data Acquisition

The establishment of MyRTKnet, ARGN and IGS stations open an opportunity to use of these stations in a GPS network for meteorology application. In this research, five MyRTKnet stations in Peninsula Malaysia operated by Department of Survey and Mapping Malaysia (DSMM) were selected. These stations were:

1) GETI in Geting, Kelantan
2) PEKN in Pekan, Pahang
3) USMP in Kampus Universiti Sains Malaysia, Pulau Pinang
4) BANT in Banting, Selangor
5) JHJY in Johor Jaya, Johor Bharu.
Selected GPS stations from the ARGN consist of 9 stations which is maintained by Geoscience Australia. These GPS stations were:

1) COCO in Coco Island
2) KARR in Karratha
3) DARW in Darwin
4) TOW2 in Townsville
5) SYDN in Sydney
6) MOBS in Melbourne
7) CEDU in Ceduna
8) HIL1 in Hillarys
9) ALIC in Alice Springs.

Furthermore, about four IGS stations were used:

1) BAKO in Indonesia
2) NTUS in Singapore
3) IISC in India
4) PIMO in the Philippines

These stations are processed in a single network in order to achieve better results when using an enlarged station network. Moreover, absolute ZPD can be estimated only when the network is covering a reasonable region, because the same satellite is seen from different elevation angles at each station. In other words, long baselines may contribute to a better separation of correlated parameters of ZPD. The observation data were selected from 1st June to 31st August 2008. Dual frequency GPS data (L1 and L2) were used with sampling rate at 30 seconds for 24 hour period. Figure 1 shows the locations of the MyRTKnet, ARGN and IGS stations.
Figure 1: Location of the IGS, MyRTKnet and ARGN stations.
3.2 Processing Strategy for Estimating ZPD

The GPS data are processed as a single network in post-processing mode by using the Bernese GPS software version 5.0. In order to obtain high quality of ZPD estimates, the GPS data processing parameters and model are carefully configured, as listed in Table 1.

**Table 1:** Parameters setting and models for data processing

<table>
<thead>
<tr>
<th>Processing parameters</th>
<th>Processing strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input data</td>
<td>Daily</td>
</tr>
<tr>
<td>Network design</td>
<td>OBS-MAX</td>
</tr>
<tr>
<td>Elevation cut off angle</td>
<td>3°</td>
</tr>
<tr>
<td>Weighting of the observables</td>
<td>With cos²(z), z = zenith angle</td>
</tr>
<tr>
<td>Sampling rate</td>
<td>30 - 180 s</td>
</tr>
<tr>
<td>Orbits / EOP</td>
<td>IGS final orbits (SP3) and EOP (Earth Orientation Parameters).</td>
</tr>
<tr>
<td>Station coordinates</td>
<td>Tightly constrained to the ITRF2005 reference frame.</td>
</tr>
<tr>
<td>Absolute antenna phase center corrections</td>
<td>PHAS COD.I05, SATELLIT.I05</td>
</tr>
<tr>
<td>Ocean loading model</td>
<td>FES2004</td>
</tr>
<tr>
<td>Ionosphere</td>
<td>Double difference ionospheric free (IF) linear combination (L3).</td>
</tr>
<tr>
<td>Ambiguities solution</td>
<td>Fixed, resolved using QIF strategy</td>
</tr>
<tr>
<td>Ionosphere model for ambiguity fixing</td>
<td>Global ionosphere model from CODE</td>
</tr>
<tr>
<td>Gradient Estimation</td>
<td>Horizontal gradient parameters: tilting (24 h interval).</td>
</tr>
<tr>
<td>A-priori model</td>
<td>A-priori Saastamoinen model (hydrostatic part) with dry Niell mapping function.</td>
</tr>
<tr>
<td>Mapping Function</td>
<td>Wet-Niell mapping function (1h interval)</td>
</tr>
</tbody>
</table>
3.3 The Analysis

a) The Estimated ZPD Value for MyRTKnet stations.

From Figure 2, the time series of estimated ZPD for five MyRTKnet stations (BANT, GETI, JHJY, PEKN and USMP) are shown. Table 2 shows the statistics of the time series.

![Figure 2: The time series of estimated ZPD for MyRTKnet stations.](image)

<table>
<thead>
<tr>
<th>Station</th>
<th>Latitude</th>
<th>Climate</th>
<th>Min</th>
<th>Max</th>
<th>Mean</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>GETI</td>
<td>6.226</td>
<td>Tropical</td>
<td>2507.1</td>
<td>2709.5</td>
<td>2626</td>
<td>26.064</td>
</tr>
<tr>
<td>USMP</td>
<td>5.358</td>
<td>Tropical</td>
<td>2492.3</td>
<td>2694.1</td>
<td>2617.968</td>
<td>30.381</td>
</tr>
<tr>
<td>PEKN</td>
<td>3.493</td>
<td>Tropical</td>
<td>2507.4</td>
<td>2690.7</td>
<td>2622.154</td>
<td>26.502</td>
</tr>
<tr>
<td>BANT</td>
<td>2.826</td>
<td>Tropical</td>
<td>2484.6</td>
<td>2721.9</td>
<td>2623.839</td>
<td>33.902</td>
</tr>
<tr>
<td>JHJY</td>
<td>1.537</td>
<td>Tropical</td>
<td>2497.6</td>
<td>2694.8</td>
<td>2616.159</td>
<td>30.539</td>
</tr>
</tbody>
</table>
According to Figure 2 and Table 2, all MyRTKnet stations produced high estimated mean ZPD values (>2600mm). It can be noticed that these stations are located in the low latitude region which is experiencing high variability and large amounts of water vapour. The highest mean ZPD value is at station GETI and followed by BANT, PEKN, USMP and JHJY. There are sudden drops in the estimated ZPD values (see Figure 2) between day of year 209-215 for all MyRTKnet stations. This condition can be compared to the amount of rainfall at 5 nearby weather stations, which is operated by Malaysia Meteorological Department (MMD) in Peninsula Malaysia. From the Figure 3, it shows that for the day of year 209 – 214, no precipitation was observed at the weather stations. Hence, the lower of ZPD values indicated the absence of precipitations.
Figure 3: Three months rainfall amounts of five weather stations operated by MMD from 1st Jun to 31st August 2008.
b) The Estimated ZPD for ARGN stations.

In Figure 4, the time series of estimated ZPD for nine ARGN stations (ALIC, CEDU, COCO, DARW, HIL1, KARR, MOBS, SYDN and TOW2) are shown. Table 3 shows the statistics of these time series.

Figure 4: The time series of estimated ZPD for ARGN stations.
Table 3: Statistical properties of the estimated ZPD for the ARGN stations.

<table>
<thead>
<tr>
<th>Station</th>
<th>Latitude</th>
<th>Climate</th>
<th>Min</th>
<th>Max</th>
<th>Mean</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>COCO</td>
<td>-12.188</td>
<td>Tropical</td>
<td>2423.2</td>
<td>2688</td>
<td>2544.468</td>
<td>48.005</td>
</tr>
<tr>
<td>DARW</td>
<td>-12.844</td>
<td>Tropical</td>
<td>2319.3</td>
<td>2581.1</td>
<td>2439.712</td>
<td>53.971</td>
</tr>
<tr>
<td>TOW2</td>
<td>-19.269</td>
<td>Tropical</td>
<td>2336.7</td>
<td>2614.9</td>
<td>2459.138</td>
<td>57.168</td>
</tr>
<tr>
<td>KARR</td>
<td>-20.981</td>
<td>Tropical</td>
<td>2305.4</td>
<td>2570.7</td>
<td>2378.089</td>
<td>51.774</td>
</tr>
<tr>
<td>ALIC</td>
<td>-23.67</td>
<td>Arid</td>
<td>2177.5</td>
<td>2362.6</td>
<td>2237.341</td>
<td>32.786</td>
</tr>
<tr>
<td>HIL1</td>
<td>-31.826</td>
<td>Subtropical</td>
<td>2314.6</td>
<td>2550.2</td>
<td>2414.645</td>
<td>29.16</td>
</tr>
<tr>
<td>CEDU</td>
<td>-31.867</td>
<td>Temperate</td>
<td>2299.4</td>
<td>2458.2</td>
<td>2367.691</td>
<td>25.831</td>
</tr>
<tr>
<td>SYDN</td>
<td>-33.781</td>
<td>Temperate</td>
<td>2310.4</td>
<td>2539.6</td>
<td>2402.75</td>
<td>41.87</td>
</tr>
<tr>
<td>MOBS</td>
<td>-37.829</td>
<td>Temperate</td>
<td>2321.4</td>
<td>2497.3</td>
<td>2401.646</td>
<td>24.734</td>
</tr>
</tbody>
</table>

The statistic of estimated ZPD in Table 3 shows that the mean value of ZPD estimates for the COCO station is the highest (2544.468mm) and ALIC station is the lowest (2237.341mm) levels. It could be related to the geographical location of the COCO stations which are located in the low latitude region which is experiencing high variability and large amounts of water vapour. In the case of ALIC station, the location is located in the arid region which could influence the result of the lowest mean ZPD value.
c) GPS ZPD data quality

The quality of the estimated ZPD will be examined through comparison with the ZPD at the IGS stations (BAKO, CEDU, COCO, KARR, PIMO, SYDN, TOW2 and NTUS) which is based on one month data. The difference between the expected and observed values was at -43.5 to 42.9 mm level (see Figure 5) and the RMS from 4.281 to 11.667 mm (see statistics in Table 4). A possible explanation for the main ZPD differences between the expected and observed is due to the different setup of the network configuration (in term of network size and design) and processing strategies. Moreover, a technique to assess the ZPD value needs to be established by exploiting information from the expected IGS ZPDs. From Figure 5, a “worse” ZPD from IGS stations can be determined. For example, station PIMO has 42.9mm ZPD difference at day of year 170.

![Figure 5: The difference of estimated ZPD for the IGS stations.](image-url)
Table 4: Statistical properties of the difference estimated ZPD for the IGS stations.

<table>
<thead>
<tr>
<th>Station</th>
<th>Min</th>
<th>Max</th>
<th>Mean</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>BAKO</td>
<td>-31.6</td>
<td>27.6</td>
<td>-1.381</td>
<td>7.229</td>
</tr>
<tr>
<td>CEDU</td>
<td>-15.9</td>
<td>14.5</td>
<td>-2.024</td>
<td>4.281</td>
</tr>
<tr>
<td>COCO</td>
<td>-25.2</td>
<td>38.1</td>
<td>-3.002</td>
<td>7.694</td>
</tr>
<tr>
<td>KARR</td>
<td>-21.2</td>
<td>19.2</td>
<td>-2.006</td>
<td>6.052</td>
</tr>
<tr>
<td>PIMO</td>
<td>-43.5</td>
<td>42.9</td>
<td>0.127</td>
<td>11.667</td>
</tr>
<tr>
<td>SYDN</td>
<td>-30.4</td>
<td>21.4</td>
<td>-3.187</td>
<td>8.013</td>
</tr>
<tr>
<td>TOW2</td>
<td>-23.3</td>
<td>19.7</td>
<td>-1.5</td>
<td>6.127</td>
</tr>
<tr>
<td>NTUS</td>
<td>-25.1</td>
<td>16.6</td>
<td>-0.27</td>
<td>4.873</td>
</tr>
</tbody>
</table>

4.0 CONCLUSION

It has been demonstrated on the analysis of the data set, the highest and short term variability of the estimated ZPD can be observed in the low latitude region, the area which experiences a large amount of water vapour. The quality of the estimated ZPD is examined through comparison with the ZPD at the IGS stations to validate the consistency of the result. The result has shown that the estimated ZPD difference between the expected and observed values varies from -43.5 to 42.9 mm and a RMS from 4.281 to 11.667 mm. The refinement of the processing strategy is required to achieve better absolute accuracy for the ZPD estimation. For future work, a near real time estimation of ZPD and IWV is planned in Peninsular Malaysia for operational weather forecasting.

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