Regional Assessment of the GPS Tropospheric Delay Models on the African GNSS Network

Dodo, J. D. and Idowu, T. O

1Department of Surveying and Geoinformatics, School of Environmental Sciences, 2Federal University of Technology, Yola, Adamawa State, Nigeria.

Corresponding Author: Dodo, J.D

Abstract
Recently, considerable interest has been generated in the use of the Global Positioning System (GPS) for meteorological application leading to what is now called GPS Meteorology. A major source of error in the measurements, for GPS meteorology, is the propagation delay of the GPS signal caused by the two main layers of the atmosphere. These are the ionosphere and troposphere. The ionospheric effects can be mitigated by the use of double difference ionosphere-free linear combination. The tropospheric effects, on the other hand, are reduced to the barest minimum using the global tropospheric models, derived experimentally and based on the available radiosonde data. In order to determine a suitable tropospheric model for African GNSS network, an investigation on the reliability of the different standard tropospheric models is needed. Therefore, it is the objective of this paper to assess the reliability of the three standard tropospheric models for the reduction of tropospheric effect in GPS observations. The models used are the refined Saastamoinen model, the modified Hopfield model and Neil model. The results show that there are insignificant differences in the performance of the three models at significance level of 0.05. However, the refined Saastamoinen model seems to produce a better mitigation of the tropospheric effect with an average percentage of 33.6% while Neil and modified Hopfield models have 13.8% and 12.5% percentages respectively. The result further indicates that the refined Saastamoinen model has the lowest mean average zenith tropospheric delay (ZTD) of 2.1m with RMS of 0.0051m. This suggests that the refined Saastamoinen model has better performance than Hopfield and Neil models.

Keywords: African GNSS, tropospheric delay, refined saastamoinen model, neil model and modified hopfield model.

INTRODUCTION
Tropospheric delay is an important source of error in space geodetic observations which include very long baseline interferometry (VLBI), Global Positioning System (GPS), satellite altimetry (SAT) and interferometric synthetic aperture radar (InSAR) (Li et al, 2008). Satellite signals travelling through the earth’s atmosphere are refracted due to variation in the refractive index of the troposphere. This tends to bend the signals from their original path at varying heights. That is, the index is a function of the tropospheric path through which the signal passes from the receiver antenna to the end of the troposphere (Leick, 2004; Kaplan and Hegarty, 2006). The bending effect of the signals due to heights variation is known as the tropospheric delay. This depends on temperature, pressure, humidity and the location of the GPS signal antenna (Guochang, 2003). It limits the reliability of GPS Network Positioning. Such signal delay caused by the troposphere ranges between 2 m at zenith and 20 m at low elevation angles such as angles below 10° (Farah et al, 2005).

Several standard models, which were empirically derived from available radiosonde data obtained mostly in the European and North American continents, are being employed to correct the effect of tropospheric delay. The global atmospheric parameters used as constants in these models provide broad approximations of the tropospheric conditions but ignore the actual atmospheric conditions on a given location. That is, they do not take into account the latitudinal, seasonal, diurnal and daily variations in the atmosphere (Roberts and Rizos, 2001). In Africa, study on the assessment of the impact of the tropospheric delay on GNSS signal is still very limited, whereas, what should be of particular interest to the GNSS users is which standard tropospheric model is suitable for precise positioning. In order to attempt the determination of the best-fit tropospheric model for GNSS data processing in Africa, an assessment of different tropospheric delay models on the International GNSS Service (IGS) stations, located in South Africa, was carried out. This paper presents the outcome of such research conducted using three global tropospheric delay models, namely Refined Saastamoinen model, Modified Hopfield model and Neil model.

The Tropospheric Delay
The troposphere, generally referred to as the neutral atmosphere, is the lower part of the atmosphere close to the earth surface. It is about 9km from the earth’s surface over the pole and 16km over the equator.
(Sickel, 2008). It extends from the sea bed to about 50km (Hoffman-Wellenhof et al., 2001). The troposphere is a non dispersive region with an index of refraction, slightly greater than one, that varies with altitude. Due to the highly variable tropospheric water vapour content in this region, it will be difficult to achieve the desired positioning accuracy from GPS observations (Ahn, et al., 2006). However, Tajul et al. (2006) showed that the use of network-based GPS Real Time Kinematics (RTK) approach can significantly reduce the tropospheric errors for long baselines thereby enhancing positioning accuracy. The tropospheric delay has been shown to be directly proportional to the refractive index and this is functionally expressed as (Hoffman-Wellenhof et al., 2001):

$$D_{trop} = \int (n - 1) ds$$

(1)

Expressing in terms of refractivity,

$$D_{trop} = 10^6 \int N_{trop} ds$$

(2)

That is,

$$N_{trop} = 10^{-6} (n - 1)$$

(3)

Where $N_{trop}$ = tropospheric refractivity and $n$ = refractive index.

Figure 1: Schematic diagram of the Dry and Wet components of the troposphere

The tropospheric delay consists of the dry and wet components as shown in Figure 1. The dry (i.e. the dry gasses) component is a function of surface pressure and accounts for about 90% while the wet (i.e. water vapour) component is a function of the distribution of water vapour in the atmosphere and represents about 10% of total delay (Misra and Enge, 2001). Therefore, the delay of the GPS signal can be functionally expressed as the sum of the dry and wet contributions to the total delay.

That is,

$$N_{trop} = N_{d}^{trop} + N_{w}^{trop}$$

(4)

Where $N_{d}^{trop}$ = dry tropospheric refractivity

$N_{w}^{trop}$ = wet tropospheric refractivity

Hence,

$$D_{z}^{trop} = 10^6 \int N_{d}^{trop} ds + 10^6 \int N_{w}^{trop} ds$$

(5)

The delay is generally calculated along the zenith direction over the GPS station, hence the term zenith tropospheric delay. This gives a combination of the zenith hydrostatic delay and zenith non-hydrostatic delay. Several models have been developed to mitigate this effect in order to enhance navigational and positional accuracy. These models, considered in this research, are briefly reviewed below.

The Refined Saastamoinen Model

The Saastamoinen model in Saastamoinen (1972), is expressed as a function of height of the observation station and the zenith angle. This was later modified and functionally expressed as (Guochang, 2003):

$$D_{z}^{trop} = \frac{0.002277}{\cos z} \left[ P + \frac{1255}{T} + 0.05 \right] P_e - B \tan^2 z + \delta R$$

(6)

Where $z$ = zenith angle of satellite

$P$ = pressure (mbar)

$T$ = temperature (K)

$P_e$ = partial pressure of water vapour

$B$ and $\delta R$ are the corrections that depends on height ($h$) of the station and $z$. 

114
The Modified Hopfield model

Hopfield (1969) used data from different parts of the world to develop an empirical tropospheric delay model. This was based on the dry refractivity components as a function of station height. The model was later refined to be a function of length of the satellite position vectors above the earth’s surface. One of the modified Hopfield models is expressed as (Guochang, 2003):

\[ T_{ro_i} = 10^{-6} N^{cargo} \left[ \sum_{k} \frac{f_{k+1}}{f_k} \right] \]

Where \( d \) = dry component, \( k \) = tropospheric layer, \( T_{ro_i} \) = Topospheric delay \( w \) = wet component, \( i \) = hydrostatic and non-hydrostatic components

The Neil Model

The Neil Model is a combination of the Saastamoinen zenith path delay together with Neil mapping functions (Neil, 1996). The parameters \( a, b, c \) used in the dry and wet components of the models as expressed in equations (8) and (9) are calculated based on the interpolation of the average and seasonal variation (amplitude) values as functions of latitude and time.

For the dry component:

\[ m_d = \frac{1}{\sin \varepsilon} \left[ \frac{1}{a_d} \right] \]

For the wet component:

\[ m_w = \frac{1}{\sin \varepsilon} \left[ \frac{1}{a_w} + \frac{1}{b_w} \right] \]

\[ \varepsilon = \sin^{-1} \left( \frac{a_w + b_w}{a_w} \right) \]

Where: \( m_d \) and \( m_w \) = mapping functions for dry and wet components respectively
\( \varepsilon \) = satellite elevation angle, \( H \) = orthometric height
\( a_d, b_d, c_d \) = coefficients in the dry component
\( a_w, b_w, c_w \) = coefficients in the wet component
\( a_{tw}, b_{tw}, c_{tw} \) = coefficients in the height component

Study Area

Table 1 and Figure 2 show the current IGS tracking stations (as red dots) in Africa. South Africa is leading the rest of the African countries towards the implementation of GNSS with six (6) IGS tracking stations followed by Gabon with two (2) stations. The International GNSS tracking stations in South Africa, shown in Figure 3, form the Southern African continuous operating reference stations. These were used as the regional network reference stations in this study. Also, Table 2 shows description of the GNSS stations as obtained from the International GNSS Services (IGS, 2009).
METHODOLOGY

Data Acquisition

Twenty-four hours (24hrs) raw GPS data at 30-second data rate in RINEX format for the stations shown in Figure 2 and precise satellite ephemeris data for GPS week 1409 were downloaded from the International GNSS Service (IGS) day of year (DoY) 07/2007. Ocean Tide Loading data for each station were obtained (Ocean Tide Loading, 2009). Also, the Earth Orientation Parameters and the Ionosphere models were abstracted from Bernese (2009). Summary of the data sets used are given in Table 3.

Table 3: Summary of the Processing Parameters

<table>
<thead>
<tr>
<th>Station ID</th>
<th>Station Location</th>
<th>Latitude (°) deg. min. sec.</th>
<th>Longitude (°) deg. min. sec.</th>
<th>Ellipsoidal Height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HARB</td>
<td>Hertbeesthoek</td>
<td>25 53 13.09800</td>
<td>27 42 47.839043</td>
<td>1556.200</td>
</tr>
<tr>
<td>RBAY</td>
<td>Richards Bay</td>
<td>28 47 44.10600</td>
<td>32 04 42.19680</td>
<td>34.231</td>
</tr>
<tr>
<td>SIMO</td>
<td>Simon’s Town</td>
<td>34 11 16.42200</td>
<td>18 26 22.36560</td>
<td>34.851</td>
</tr>
<tr>
<td>SUTH</td>
<td>Sutherland</td>
<td>32 22 48.75900</td>
<td>22 48 37.64534</td>
<td>1799.766</td>
</tr>
<tr>
<td>SUTM</td>
<td>Sutherland</td>
<td>32 22 53.16699</td>
<td>20 48 39.27596</td>
<td>1797.601</td>
</tr>
</tbody>
</table>

Data Processing

The data sets were processed using the Bernese GPS software version 5.0. Four processing strategies were employed. These include:

- **Strategy I**: Processing without the application of the tropospheric model. The Root Mean Square Error (RMSE) of ionosphere-free double difference (IF DD) residuals and final coordinates were obtained.
- **Strategy II**: Processing with the application of the Refined Saastamoinen model. The RMSE of IF DD residuals, final coordinates and zenith tropospheric delay were obtained.
- **Strategy III**: Processing with the application of the Modified Hopfield model. The RMSE of IF DD residuals, final coordinates and the zenith tropospheric delay were obtained.
- **Strategy IV**: Processing with the application of the Neil model. The RMSE of IF DD residuals and final coordinates were obtained.

PRESENTATION OF RESULTS

The RMSE of the coordinates of survey stations are shown in Table 4. Also, four baselines were formed using the survey stations from where the RMSE of IF DD residuals were computed for the satellites as shown in Table 5. Furthermore, the computed percentage improvements in the RMSE of IF DD residuals, based on the application of the tropospheric models, are shown in Table 6. Also, Zenith Tropospheric Delay (ZTD) was calculated in the zenith direction over the GPS station. This gives insight into the tropospheric conditions above the GPS site based on the application of the three tropospheric delay models. The results obtained are shown in Table 7.
Table 4: Summary RMSE of stations coordinates

<table>
<thead>
<tr>
<th>Station</th>
<th>No Model</th>
<th>Saastamoinen Model</th>
<th>Modified Hopfield Model</th>
<th>Neil Model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N (m)</td>
<td>E (m)</td>
<td>Up (m)</td>
<td>N (m)</td>
</tr>
<tr>
<td>HAR B</td>
<td>0.04</td>
<td>0.03</td>
<td>0.08</td>
<td>0.01</td>
</tr>
<tr>
<td>R B A Y</td>
<td>0.03</td>
<td>0.03</td>
<td>0.07</td>
<td>0.01</td>
</tr>
<tr>
<td>S I M O</td>
<td>0.03</td>
<td>0.03</td>
<td>0.07</td>
<td>0.02</td>
</tr>
<tr>
<td>S U T H</td>
<td>0.03</td>
<td>0.03</td>
<td>0.07</td>
<td>0.02</td>
</tr>
<tr>
<td>S U T M</td>
<td>0.03</td>
<td>0.03</td>
<td>0.07</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Table 5: Summary of baseline RMSE of IF DD residuals

<table>
<thead>
<tr>
<th>Baseline Length (km)</th>
<th>Total RMS error (mm) of IF DD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No Model</td>
</tr>
<tr>
<td>H A R B - S U T M</td>
<td>984.9</td>
</tr>
<tr>
<td>R B A Y - S U T M</td>
<td>1149.3</td>
</tr>
<tr>
<td>S I M O - S U T M</td>
<td>298.2</td>
</tr>
<tr>
<td>S U T H - S U T M</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Table 6: Percentage improvement in the RMS IFF DD residuals after applying tropospheric delay models

<table>
<thead>
<tr>
<th>Baseline</th>
<th>Refined Saastamoinen Model (%)</th>
<th>Modified Hopfield Model (%)</th>
<th>Neil Model (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H A R B - S U T M</td>
<td>44.4</td>
<td>8.3</td>
<td>8.3</td>
</tr>
<tr>
<td>R B A Y - S U T M</td>
<td>40.0</td>
<td>27.3</td>
<td>40.0</td>
</tr>
<tr>
<td>S I M O - S U T M</td>
<td>50.0</td>
<td>14.3</td>
<td>6.7</td>
</tr>
<tr>
<td>S U T H - S U T M</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 7: Statistics for the ZTD estimate at each GPS station with the application of tropospheric delay model

<table>
<thead>
<tr>
<th>Station</th>
<th>Mean (m)</th>
<th>RMS (m)</th>
<th>Max (m)</th>
<th>Min (m)</th>
<th>Mean (m)</th>
<th>RMS (m)</th>
<th>Max (m)</th>
<th>Min (m)</th>
<th>Mean (m)</th>
<th>RMS (m)</th>
<th>Max (m)</th>
<th>Min (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H A R B</td>
<td>2.0334</td>
<td>0.0051</td>
<td>2.0734</td>
<td>1.9445</td>
<td>2.0236</td>
<td>0.0053</td>
<td>2.0678</td>
<td>1.9316</td>
<td>2.0525</td>
<td>0.0052</td>
<td>2.0881</td>
<td>1.9732</td>
</tr>
<tr>
<td>R B A Y</td>
<td>2.3298</td>
<td>0.0063</td>
<td>2.5978</td>
<td>2.4848</td>
<td>2.5156</td>
<td>0.0066</td>
<td>2.5790</td>
<td>2.4655</td>
<td>2.4505</td>
<td>0.0065</td>
<td>2.6237</td>
<td>2.5001</td>
</tr>
<tr>
<td>S I M O</td>
<td>2.4242</td>
<td>0.0051</td>
<td>2.4521</td>
<td>2.3961</td>
<td>2.4155</td>
<td>0.0054</td>
<td>2.4389</td>
<td>2.3889</td>
<td>2.4380</td>
<td>0.0053</td>
<td>2.4737</td>
<td>2.4008</td>
</tr>
<tr>
<td>S U T H</td>
<td>1.9074</td>
<td>0.0045</td>
<td>1.9293</td>
<td>1.8857</td>
<td>1.8981</td>
<td>0.0047</td>
<td>1.9210</td>
<td>1.8793</td>
<td>1.9256</td>
<td>0.0046</td>
<td>1.9497</td>
<td>1.8945</td>
</tr>
<tr>
<td>S U T M</td>
<td>1.9069</td>
<td>0.0044</td>
<td>1.9275</td>
<td>1.8839</td>
<td>1.8977</td>
<td>0.0047</td>
<td>1.9192</td>
<td>1.8778</td>
<td>1.9254</td>
<td>0.0046</td>
<td>1.9505</td>
<td>1.8930</td>
</tr>
<tr>
<td>Average</td>
<td>2.1204</td>
<td>0.0051</td>
<td>2.1960</td>
<td>2.1190</td>
<td>2.1501</td>
<td>0.0053</td>
<td>2.1852</td>
<td>2.1086</td>
<td>2.1584</td>
<td>0.0052</td>
<td>2.2171</td>
<td>2.1323</td>
</tr>
</tbody>
</table>

ANALYSIS OF RESULTS

The analysis of the results was done based on the IF DD residuals, the final station coordinates and the zenith tropospheric delay obtained from each of the global tropospheric delay models.
Assessment of the Tropospheric Delay Models based on the Baseline IF DD Residual

One of the tools used in the assessment of tropospheric models is the comparison of the baseline IF DD residuals (Don et al, 2004). That is, the performance of each models is characterized by the Root Mean Square Error (RMSE) of IF DD residual. This implies that the smaller the RMSE value, the better the performance of the tropospheric model. Four baselines were formed from where the RMSE were computed for the satellites as shown in Table 5.

A two-tailed Chi-square hypothesis test at 5% level of significance was used to determine if the values of RMSE for each tropospheric model is statistically significant. Also, a two-tailed F-test hypothesis at 5% level of significance was employed to determine if the values of the RMSE given by the models are significantly different from one another. The IF DD residuals of strategy I have the largest magnitude of RMSE compared to values obtained from strategies II, III and IV. This outcome was envisaged because no model was applied. This shows that the use of the three models is able to reduce the size of the residuals. However, the results of the statistical tests show that the RMSE values for the three models are not significantly different from one another. The SUTH-SUTM, with the shortest baseline, has RMSE IF DD residual value of 0.8mm in all cases. This seems to confirm that the tropospheric delay is distance dependent. That is, the longer the baseline, the more the effect of the troposphere on GPS measurement. Therefore, based on the quantities of the RMSE values for all the strategies used, it can be infer that the refined Saastamoinen model gave a better result.

Further assessment from Table 5 shows that the percentage improvement of the models varies from 0% to 50%. That is, the baseline RBAY-SUTM with the longest distance (1,149.3km) has higher percentage improvement across the models, whereas, the baseline with the shortest distance (0.1km) has the lowest percentage improvement. This seems to indicate that, percentage improvement increases with increase in baseline. The refined Saastamoinen model has the highest percentage improvement with an average of 33.6% while the modified Hopfield and Neil models have almost the same percentage improvements. It is observed that the baseline SUTH-SUTM with the shortest baseline of 0.1 km has 0% percentage improvement in all cases. This, further, reaffirms that the tropospheric delay is distance dependent.

Assessment of the Tropospheric Models based on the Coordinate Differences

To assess the tropospheric delay models on the estimated station coordinates, the coordinate differences of the stations were analysed. Table 4 and Figures 4, 5, 6 and 7 give the pictures of the coordinate differences for each station based on the models used. These show no significant differences in the coordinate differences produced by the application of the tropospheric delay models. However, the Saastamoinen model shows considerable improvement with network standard deviation of 1.9m, 1.3m and 1.5m in the north, east and up components respectively while the Neil Model followed closely with network standard deviation of 2.4m, 1.3m and 1.6m. Also, the Saastamoinen model has lower RMSE values in the Up component, which ranges between 0.02m and 0.04m. This seems to confirm that the Saastamoinen model performs better when compared to the rest of the tropospheric delay models.
Assessment of the Tropospheric Models based on the Zenith Tropospheric Delay (ZTD) ZTD gives insight into the tropospheric conditions above the GPS site. Table 7 and Figures 8 to 10 show the time series analysis and the statistics of the zenith tropospheric delay for each of the GPS station based on the application of each tropospheric delay model. The time series analysis indicates that the three models have similar pattern of the ZTD on the network for the 24hrs time window. High ZTD was experienced between 12.00hrs and 16.00hrs. This suggests that the effect of the troposphere is more in the afternoon. The mean ZTD produced by the three tropospheric models ranges between 1.9m and 2.5m. The Neil model produced the highest ZTD values of 2.62m, while the Hopfield has the lowest ZTD value of 1.89m. The Saastamoinen model has the lowest mean average network ZTD of 2.1m and smallest RMS value of 0.0051m. This further shows the supremacy of Saastamoinen model over others.
CONCLUSION

This paper has experimentally demonstrated the influence of different tropospheric models on the African GNSS network with particular focus on the Southern African IGS network. The three models investigated i.e. the Saastamoinen, Hopfield and Neil models show no statistical significant difference in their performances. Also, it has been shown that increase in the length of baseline produces higher tropospheric effect. Better improvement on the coordinate differences was achieved by the application of the Saastamoinen model than the Hopfield and Neil models. Therefore, it is concluded that the Saastamoinen model shows better performance in mitigating the tropospheric effect hence it is recommended for the processing of the GPS observations.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the Department of Geomatic Engineering, Universiti Teknologi Malaysia for the Bernese GPS Software used in this study.

REFERENCES


