Determination of the best-fit Tropospheric Delay Model on the Nigerian Permanent GNSS Network (NigNet)

Joseph D. DODO, Tahir, A. YAKUBU, Lazarus M. OJIGI, and Samuel TSEBEJE. Nigeria

Key words: Tropospheric delay, Hopfield model, Saastamoinen model, Neil model, NigNet

SUMMARY

The most dominant spatially correlated bias in satellite-based positioning is the atmospheric effects on the GNSS signals caused by the troposphere. The troposphere is the lower part of the atmosphere close to the earth surface; it is considered as a neutral atmosphere, with an index of refraction that varies with altitude. The variability of refractive index causes an excess group delay of the GPS signal thereby resulting to variation in GPS positioning; and is a matter of great concern to the geodetic community in terms of high accuracy applications. Compensation for the tropospheric bias is often carried out using a standard tropospheric model. In order to determine the best-fit tropospheric delay model for the Nigerian Permanent GNSS Network (NigNet), GNSS data collected from the NigNet were modelled using different global tropospheric delay models. This paper compares the results derived from the use of three different standard tropospheric models, namely the Saastamoinen model, Hopfield model and Neil model. The results are very useful to enhance the effectiveness and reliability of the tropospheric delay resolution process for regional GPS network users. Similarly, the result provides the best global tropospheric delay model for the NigNet.

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1. INTRODUCTION

One of the fundamental issues in Network GPS is the ability to mitigate all potential errors and biases in the system. The term *bias* here refers to a physical phenomena whereas the term *error* refers to the quantity remaining after the bias has been mitigated (Bingley, 2004). Error sources are the satellite-related errors, (satellite coordinate errors, satellite clock offsets and satellite ephemeris errors), the atmospheric-related errors (tropospheric and ionospheric errors) and the station-related errors (receiver clock offsets, antenna phase centre variations, multipath, solid earth tides and ocean tide loading). The carrier phase measurements are compromised by these errors; as such most of the errors except for troposphere, receiver clock and ionospheric delay can be mitigated to some extent through modelling (Rizos, 2002). The ionospheric delay which is a function of the total electron content along the signal path, and the frequency of the propagated signal can be eliminated because of its frequency dependency by using double-frequency ionospheric free linear combination (Leick, 2004; Hofmann-Wellenhof et al., 2001).

The troposphere, lower part of the atmosphere close to the earth surface, is 9 km over the poles and 16 km over the equator (Sickel, 2008) and extends from the sea to about 50 km (Hofmann-Wellenhof et al., 2001). It is considered as a neutral atmosphere. This region has an index of refraction that varies with altitude. The index of refraction is slightly greater than unity, causing an excess group delay in the signal waveform beyond that of free space. Hence it is regarded as a non-dispersive region affecting the L1 and L2 signals by the same amount. Due to the highly variable tropospheric water vapour content, it is difficult to achieve desired accuracy in this region (Ahn et al., 2006).

The tropospheric delay is a function of elevation and altitude of the receiver which depends on factors such as atmospheric temperature, pressure and relative humidity. It is not frequency-dependent as is the case with the ionosphere and cannot be eliminated through linear combination of L1 and L2 observations (Satirapod and Chalermwattanachai, 2005).

Several global tropospheric models such as the Saastamoinen model, Hopfield model, Neil model etc. have been empirically developed and employed in GPS timing receivers to correct for the tropospheric delay. These models are derived using data from available radiosonde obtained from Europe and North America continents. The global atmosphere conditions, used as constants in these models, provide a broad approximation of the tropospheric conditions, but ignore the actual atmospheric conditions on a given location, i.e., do not take into account the latitudinal and seasonal variations in the atmosphere (Roberts and Rizos, 2001). Besides, daily variation in temperature, pressure and relative humidity can lead to error in tropospheric delays obtained using the global tropospheric models especially in the height components. (Dodo and Kamarudin, 2008). The location of Nigeria in the equatorial and tropical region makes it susceptible to high tropospheric effect thereby having an adverse effect on the GPS signals which, in turn, affects positioning.

A study conducted by Tajul et al. (2005) in the South-East Asia, investigating tropospheric delay at the regional level revealed that there is a wide variation in tropospheric delay which has impact on the precision of the GPS positioning activities in the region. The variation becomes high during the months of November to early March and early May to August which are regarded as periods of high rainfall. The result also shows that, the *a priori* models could not effectively remove the residual troposphere delay except with the application of a scale factor in the least square estimation process.

In order to determine the best-fit tropospheric model for processing of data collected from the Nigerian Permanent GNSS Network, the need to investigate the impact of the different global tropospheric models on the network becomes imperative. This paper presents the outcome of such research conducted using three global tropospheric delay models, namely Refined Saastamoinen model (Saastamoinen, 1973), Modified Hopfield model (Hopfield, 1969) and Neil model (Neil, 1996). At least one of these models is available in most GPS software packages.

The paper is arranged in five sections. The second section describes the Test Network (MyRTKnet) and data collected. The third section explains the data processing strategy employed. The fourth section presents the analysis of the results obtained, followed by conclusions as the final section.

2. THE NIGERIAN PERMANENT GNSS REFERENCE NETWORK (NIGNET)

The Nigerian Permanent GNSS Reference Network (NIGNET) is established by the Office of the Surveyor General of the Federation (OSGoF). The goal of the NIGNET is to implement new reference frame for Nigeria in line with the recommendation of the United Nation Economic Commission of Africa (UNECA) through Committee on Development, Information Science and Technology (CODIST) (Jatau et al, 2010).

The core of NIGNET is formed by network of Global Navigation Satellite System, Continuous Operating Reference Stations (CORS). It is expected that, NIGNET will directly contribute to the Africa Reference Frame (AFREF). Presently, there are eleven (11) NIGNET CORS stations as shown in Figure 1. With the growing capabilities of GPS as a high precision positioning system for surveying and mapping, monitoring geophysical hazards, sea level change and as well as coordinating geodetic activities; there is a necessity for the NIGNET stations to be defined on the precise reference system such as International Terrestrial Reference System (ITRS) that managed the International Terrestrial Reference frame (ITRF).

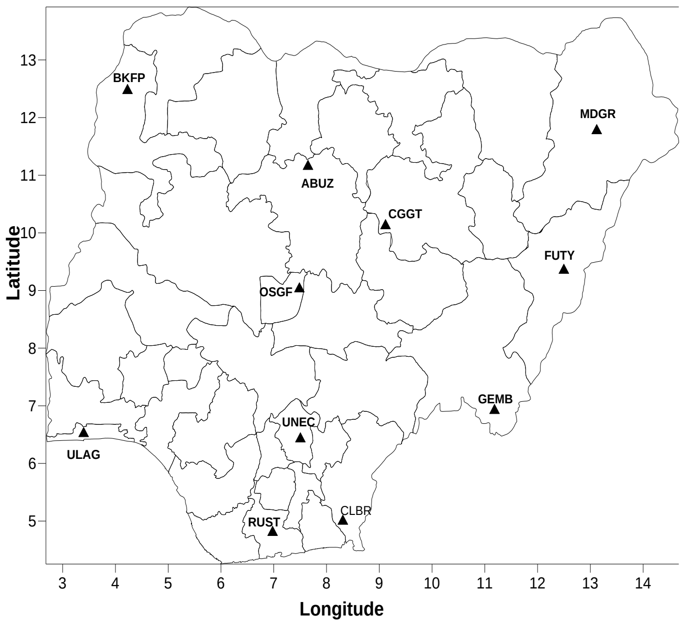

Figure 1: The Nigerian Permanent GNSS Reference Network (NIGNET)

3. MATERIALS AND METHOD

The use of network of reference stations, instead of the single reference station, has become widely acceptable within the GNSS community as solution for high precision satellite positioning applications (Vollath et al, 2000). This allows modelling of the atmospheric errors such as the tropospheric propagation delays that complicate the process of ambiguity fixing, which is often considered necessary for high-precision positioning and thus, significantly reducing the errors for long baselines thereby enhancing positioning accuracy

3.1 Study Area

Six (6) stations of the Nigerian Permanent Network of Continuously Operating Reference Stations (CORS) were used. The choice of these stations is due to data availability from these stations for the period of study compared to other stations of the network. Table 1 shows description of the six (6) NIGNET stations used in this research.

Table 1 Description of the NIGNET Site

Station ID	Station locations	Receiver	Antenna	Antenna ht(m)	App. Lat.(N)	App. Long.(E)	Ellipsoidal height (m)
ULAG	University of Lagos, Lagos	Trimble	Choke Ring	0.1710	06^0 31'2.375''	03^0 23'51.444''	44.5752

RUST	River State Univ. of Sc. and Tech. Port Harcourt	Trimble	Choke Ring	0.1710	04^0 48'6.609''	06^0 58' 42.677''	45.5892
UNEC	University of Nigeria Enugu campus	Trimble	Choke Ring	0.1710	06^0 25' 29.301''	07^0 30' 17.968''	254.4055
BKFP	Birnin Kebbi Fed. Polytechnic	Trimble	Choke Ring	0.1710	12^0 28'6.876''	04^0 13' 45.271''	250.0118
CGGT	Centre for Geodesy & Geodynamics, Toro	Trimble	Choke Ring	0.1710	10^0 07' 23.141''	09^0 07' 5.922''	916.4462
FUTY	Fed. Univ. of Technology, Yola	Trimble	Choke Ring	0.1710	09^0 20'59.073''	12^0 29' 52.072''	247.4052

3.2 Data Aqcuisition

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) for the DoY 01/2011 to 07/2011. Ocean Tide Loading data for each station were obtained from http://www.oso.cha/mers.se/~loading (Last accessed: 20th September 2009) via email. Similarly, the Earth Orientation Parameters and the Ionosphere models were downloaded from the Bernese website at http://www.bernese.unnibe.ch/ (Last accessed: 21st September 2009). The datasets were processed using the Bernese GPS Software version 5.0. Summary of the parameters used are given in Table 2.

Table 2: Summary of General Processing Parameters

RINEX data at 15 second sampling rate
IGS final orbit
24 hours sliding window processing
Ocean tide loading FES2004
ITRF 2008 reference frame
Cut-off satellite elevation angle at 10^0
Quasi-Ionosphere free (L_3) ambiguity free
Troposphere delay mapping function of $^1/_{cosz}$
Station coordinate constrained

3.3 Procesing Strategy

Four processing strategies using the BERNESE GPS software were employed. They include:

- Strategy I: In this strategy, the processing is done without the application of the tropospheric model. The ionosphere-free double difference (IF DD) residuals and final coordinates are extracted for analysis.

- Strategy II: Processing with the application of the Refined Saastamoinen model and standard atmosphere, the IF DD residuals, final coordinates and the zenith tropospheric delay are extracted for analysis.
- Strategy III: Processing with the application of the Modified Hopfield model and standard atmosphere; the IF DD residuals, final coordinates and the zenith tropospheric delay are extracted for analysis.
- Strategy IV: Processing with the application of the Neil model and standard atmosphere; the IF DD residuals and final coordinates are extracted for analysis purpose.

4. ANALYSIS OF RESULT

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 model.

4.1 Assessment of the Tropospheric Delay Models on the basis of the Baseline IF DD Residual

One of the tools used in the assessment of tropospheric model in a GPS network is the comparison of the baseline IF DD residuals over which the tropospheric models are being assessed (Don et al, 2004). The performance of the models is characterized by the Root Mean Square Error (RMSE). Fifteen baselines were formed from where the RMSE were computed for all satellites. The results presented in Table 3.

Table 3 summarises the numerical results for all the baselines in terms of the RMS DD IF residuals. The IF DD residuals of strategy I (No model) have the largest magnitude of RMS compared to strategies II, III and IV respectively. This outcome was envisaged because no model was applied. The result indicates that, the three models were able to reduce the size of the residuals. No significant residual differences in the three models noticed. The FUTY-CGGT with the shortest baseline has RMS IF DD residual value of 8.1mm when no model is applied, while the longest baseline ULAG-FUTY has RMS value of 17.0m. This presupposes that, the tropospheric delay is distance-dependent error. The longer the baseline; the more the effect of the troposphere. The refined Saastamoinen model gives a better result.

Table 3: Summary statistics of baseline RMS DD IF residual

Baseline	Baseline Length (km)	Total RMS error (mm) of IF DD			
		No Model	Saastamoinen Model	Modified Hopfield	Neil Model
BKFP-CGGT	595.1	11.3	8.1	8.2	8.5
BKFP-FUTY	974.8	10.4	8.9	9.1	9.3
BKFP-RUST	906.2	13.6	9.8	10.0	10.5
RUST-CGGT	636.2	15.8	9.7	9.8	10.2
RUST-FUTY	794.3	16.0	10.0	10.6	10.6

BKFP-ULAG	667.1	11.9	8.5	8.6	8.7
ULAG-CGGT	749.1	16.3	8.6	8.5	8.6
ULAG-FUTY	1060.5	17.0	9.0	9.4	9.2
ULAG-RUST	440.4	14.9	9.2	9.6	14.0
BKFP-UNEC	762.6	13.2	8.6	8.8	9.1
UNEC-CGGT	446.7	12.3	8.7	8.3	10.6
UNEC-FUTY	940.1	13.5	9.0	9.1	9.1
UNEC-RUST	188.8	11.9	11.3	11.2	13.0
UNEC-ULAG	455.2	12.3	8.8	8.4	9.7
FUTY-CGGT	381.0	8.1	8.7	9.0	8.5

Further assessment in Table 4 provides the percentile improvement in the RMS DD IF residuals for strategies II, III and IV respectively. From the table, percentage improvement varies from 8% to 91%. The refined Saastamoinen model has the most percentage improvement in the network with an average of 44.6%. The modified Hopfield and Neil models show almost the same percentage improvements.

Table 4: Percentage improvement in the RMS DD IF residuals after applying tropospheric delay models

Baseline	Refined Saastamoinen Model (%)	Modified Hopfield Model (%)	Neil Model (%)
BKFP-CGGT	39.51	37.805	32.9
BKFP-FUTY	16.85	14.286	11.8
BKFP-RUST	38.78	36.000	29.5
RUST-CGGT	62.89	61.224	54.9
RUST-FUTY	60.00	50.943	50.9
BKFP-ULAG	40.00	38.372	36.8
ULAG-CGGT	89.53	91.765	89.5
ULAG-FUTY	44.44	38.298	41.3
ULAG-RUST	61.96	55.208	6.4
BKFP-UNEC	53.49	50.000	45.1
UNEC-CGGT	41.38	48.193	16.0
UNEC-FUTY	50.00	48.352	48.4
UNEC-RUST	5.31	6.250	8.5
UNEC-ULAG	39.77	46.429	26.8
FUTY-CGGT	25.29	21.111	28.2

Average	44.61	42.95	38.01

4.2 Assessment of the Tropospheric Models in the Position Domain

To study the tropospheric delay models on the estimated station coordinates, the coordinate differences of the station in the North, East and Up components were computed and analysed. Figures 3, 4, and 5 show the standard deviation of the coordinates in North, East and Up components.

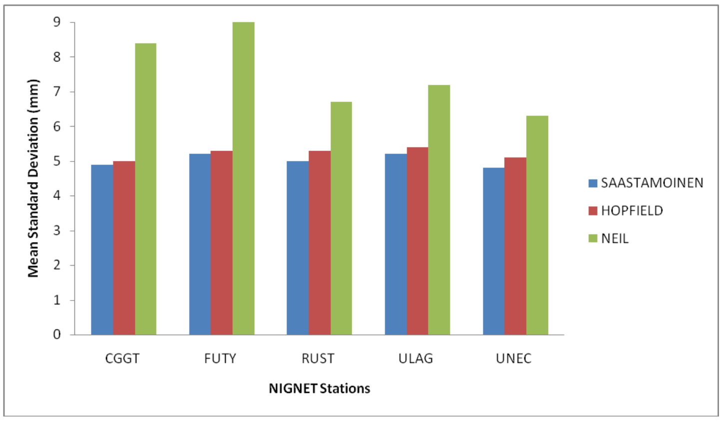

Figure 3: Standard deviation in the North component

The result reveals that, the Saastamoinen and Hopfield models show no significant deviations in the North and East components respectively. However, the differences in the application of the tropospheric delay models reveals that, the Saastamoinen model shows considerable improvement with network standard deviation of 5.02m, 3.72m in the north and east component respectively, while the Hopfield Model followed closely with network standard deviation of 5.22m and 3.8m in the north and east components respectively.

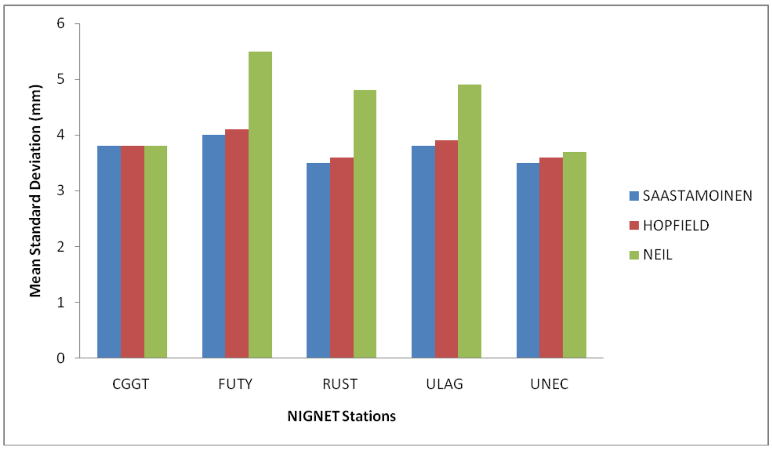

Figure 4: Standard deviation in the East component

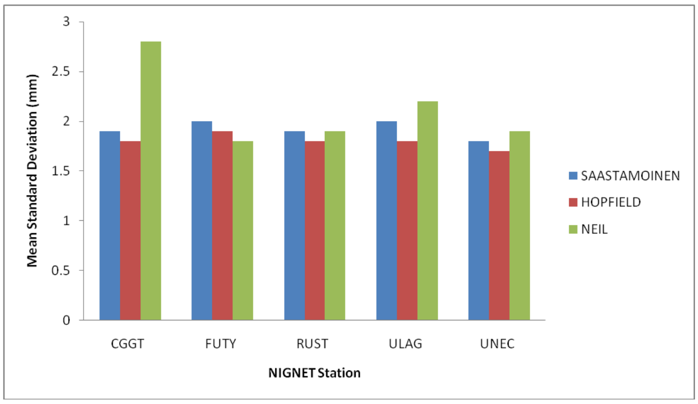

Figure 5: Standard deviation in the Up component

5. MEAN ZENITH TROPOSPHERIC DELAY (ZTD) AT EACH STATION

Tropospheric delay is calculated in the zenith direction over the GPS station, hence the term Zenith Tropospheric Delay (ZTD). The ZTD gives insight into the tropospheric conditions above the GPS site. Table 5 show the statistics of the zenith tropospheric delay for each of the GPS station based on the application of each tropospheric delay model.

The mean ZTD produced by the three tropospheric delay models range between 2.16m and 2.59m in the network. The Neil model has the highest ZTD values of 2.592m, while Saastamoinen has the lowest ZTD value of 2.162m. The Saastamoinen model has the lowest mean average network ZTD of 2.36m with the smallest RMS value of 0.0045m.

Table 7: Statistics of the ZTD estimate at each GPS station

Station	**Refined Saastamoinen Model**				**Modified Hopfield Model**				**Neil Model**			
	Mean (m)	RMS (m)	Max (m)	Min (m)	Mean (m)	RMS (m)	Max (m)	Min (m)	Mean (m)	RMS (m)	Max (m)	Min (m)
BKFP	2.323	0.0041	2.337	2.303	2.341	0.0063	2.352	2.332	2.326	0.0072	2.333	2.319
CGGT	2.172	0.0033	2.181	2.162	2.187	0.0076	2.195	2.169	2.182	0.0078	2.192	2.170
FUTY	2.363	0.0041	2.376	2.352	2.364	0.0064	2.371	2.358	2.369	0.0056	2.375	2.362
RUST	2.485	0.0055	2.503	2.471	2.535	0.0054	2.562	2.521	2.566	0.0076	2.592	2.529
ULAG	2.435	0.0057	2.573	2.405	2.479	0.0058	2.511	2.422	2.539	0.0067	2.570	2.474

UNEC	2.382	0.0047	2.413	2.332	2.407	0.0053	2.429	2.385	2.405	0.0078	2.440	2.380
Average	**2.36**	**0.0045**	**2.391**	**2.336**	**2.386**	**0.0061**	**2.403**	**2.365**	**2.398**	**0.0071**	**2.417**	**2.372**

6. CONCLUSION

This research has experimentally demonstrated the influence of different tropospheric models on the Nigerian Permanent GNSS Network. The residual tropospheric delay still affects the position precision. Increase in baseline length results in higher tropospheric effect, this is noticed on baseline ULAG-FUTY with the highest baseline length of 1060.5km.. Tropospheric delay increases during the morning hours and decreases at sunset. The three models investigated i.e. the Saastamoinen, Hopfield and Neil models show no significance difference in their performance; better improvements in the position domain were achieved by the application of the Saastamoinen model compared to Hopfield and Neil models. The Saastamoinen model produced a better mitigation of the tropospheric delay, with an average percentage improvement of 44.6% while; Hopfield and Neil models have 42.50% and 38.01% percentage improvement respectively. The result also indicates that, the Saastamoinen has the lowest mean average zenith tropospheric delay (ZTD) of 2.33m with RMS of 0.0045m. On the overall, the Saastamoinen model has better performance in the network in this research.

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