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Analysis of the Spatio-Temporal Variability and Impact of Tropospheric Delay on the Positional Accuracy in GNSS PPP Observations.

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Keywords: Precise Point Positioning, Tropospheric Delay, GNSS, CORS, RTKLib

SUMMARY

As global measurement trend in GNSS positioning begins to shift focus from RTK to PPP (COR Stations being a major application of PPP) investigations into the effect of tropospheric delay on its positional accuracy is becoming increasingly large.

While several works abound on tropospheric modelling in RTK, and their results have identified the saastemoinen model as the best model for reducing tropospheric effect on positional accuracy in GNSS observations, not much has been done to determine the spatio-temporal variability of tropospheric delay in GNSS positioning either at regional or global scales especially considering the climate dependent nature of the error and its relevance in metrological applications (integrated water vapour estimation, Zenith wet delay estimation, Hydrostatic delay estimation e.t.c). This paper attempts to access the impact and spatio-temporal variability of tropospheric delay on PPP positioning technique in GNSS observations across Nigeria.

24 hours data from six CORS across the six geopolitical zones in the country have been processed at three months interval (January – July, 2014) using the RTKLIB software in the PPP static post processing mode and at an elevation mask angle of 15º. Results obtained indicate a leap frog pattern of variation in the tropospheric delay across the country with least delay observed in January (during the dry season).

ANALYSIS OF THE SPATIO-TEMPORAL VARIABILITY AND IMPACT OF TROPOSPHERIC DELAY ON THE POSITIONAL ACCURACY IN GNSS PPP OBSERVATIONS

J. O. Odumosu, O. G. Ajayi, Y. D. Opaluwa, A.A. Kuta and A. Taiwo

ABSTRACT

Improvements in dual frequency observations with multiple differencing techniques have led to the development of the Precise Point Positioning (PPP) observation technique. Envisaged to have reduced positioning error; the tropospheric delay and multipath error remain the most outstanding factors that mitigating its positional accuracy in PPP observations. This paper attempts to access the impact and spatio-temporal variability of tropospheric delay on PPP positioning technique in GNSS observations across Nigeria. 24 hours data from six CORS across the six geopolitical zones in the country have been processed at three months interval (January – July, 2014) using the RTKLIB software in the PPP static post processing mode. Results obtained indicate a leap frog pattern of variation in the tropospheric delay across the country with least delay observed in January (during the dry season).

1.0 INTRODUCTION

Tropospheric delay is a major error source in PPP carrier phase measurements (Kouba and Heroux, 2001). Tropospheric delay depends on temperature, humidity and pressure (İsmail and Mustafa, 2012). It also varies with the height of receiver setup point and the type of terrain below signal path. Signals from satellites at low elevation angles have longer propagation period through the troposphere than those of higher elevation angles, the effect of which results in minimised tropospheric delay at the user's zenith (about 2 - 2.5m) and maximum delay at the horizon (about 20 – 28m) (Brunner and Welsh, 1993; Leick, 1995). It is thus obvious that the tropospheric delay should be a spatio-temporal variable with its effects differing based on temperature, humidity and pressure.

As the use and awareness of PPP in GNSS observations increases amongst users within the geospatial community, analysis of its positioning accuracy and precision will continue to remain a core research focus for many years. Having identified the troposphere as a major error source in GNSS observations, several mathematical models have been investigated to ascertain their performance level in terms of result precision. Şanlio Ğlu and Zeybek (2012) investigated GPS heighting accuracy with use of tropospheric models in commercial GPS softwares for different heights, Maduabughichi et al., (2014) also worked on tropospheric modelling in GNSS observations. Both research recommended the saastomoinen model as an optimal model for tropospheric delay estimation. SanlioGlu and Zeybek (2012) also identified that the Trimble Geomatics Offices software is not running in 0˚ by Saastamoinen tropospheric model and that tropospheric delay is constant for a few tens of kilometres.

This paper attempts to assess the impact and spatio-temporal variability of tropospheric delay on PPP positioning technique in GNSS observations across Nigeria. This will further validate the second inference given by SanlioGlu and Zeybek (2012). Since low elevation mask angles are to be avoided, the analysis have been done using an elevation mask angle of 15˚ through-out the analysis.

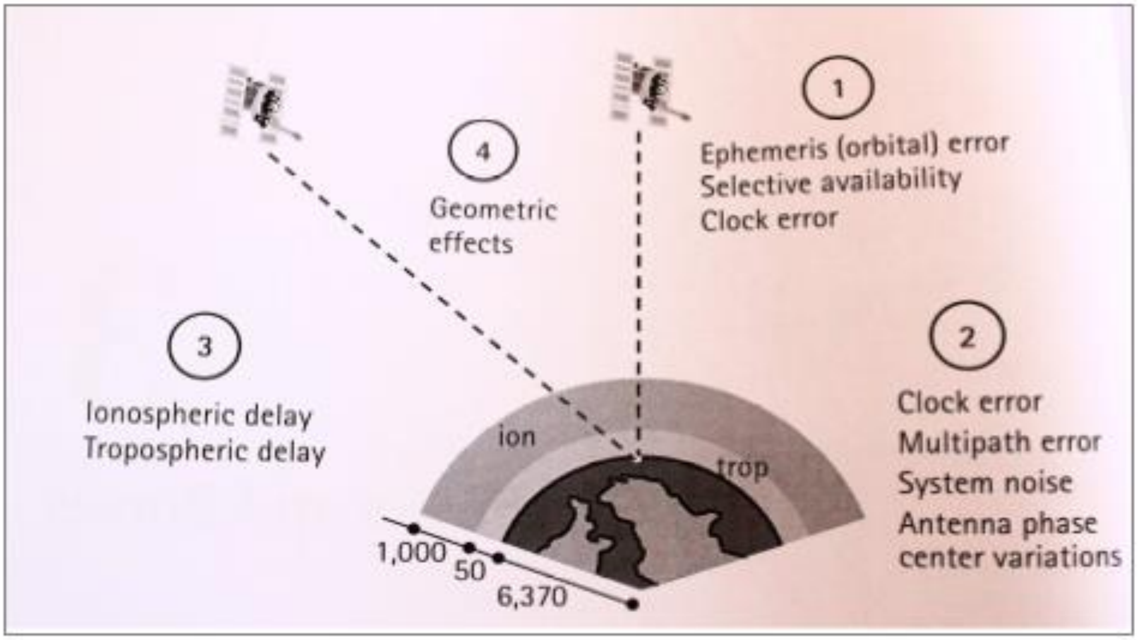


Fig 1: GPS errors and biases. (El-Rabbany A, 2002)

1.1.THEORETICAL FRAMEWORK FOR PPP

The ionospheric free combination of dual frequencies GPS pseudo range (P) and carrier phase observation (Φ) are related to user position, clock, troposphere and ambiguity parameters by the following simplified observation equations given by (Kouba and Heroux, 2000).

$ʅ_{\rho}$ = ρ_3+C (dT-dt) +Tr + εp (1)

$ʅ_{\Phi}$ = ρ_3+C (dT-dt) + $T_r + N_{\lambda} + \varepsilon_{\Phi}$ ` (2)

Where

$ʅ_{\rho}$ (ρ_3) = ionosphere-free combination of P1 and P2 pseudo range.

$ʅ_{\Phi}$ ($ʅ_3$) = Ionosphere-free combination of L1 and L2 carrier phases.

dT = Station receiver clock offset from GPS time.

dt = Satellite clock offset from GPS time.

c = vacuum speed of light.

Tr = Tropospheric delay.

N = Non-integer ambiguity of the carrier phase ionospheric-free combination.

$\lambda_1, \lambda_{2,} \lambda$ = carrier phase L1, L2 and L3 combined

$\varepsilon_p, \varepsilon_\Phi$ = measurement noise including multipath.

$\rho_3 =$ geometric range computed by iteration from satellite position (Xs,Ys,Zs) and station position (x,y,z) at transmission and reception epoch t and T respectively.

Therefore, $\rho = \sqrt{[X_s - x]^2 + [Y_s - y]^2 + [Z_s - z]^2}$ (3)

Relative positioning using single differencing technique however results in equ. 4 (for Pseudo-range observations) – 5 (for Carrier Phase observations)

$$\text{ʅ}_{\rho \mathrm{ij}}^{K} = \Delta\rho_{\mathrm{ij}}^{K} + c\Delta dT_{\mathrm{ij}} + \Delta T_{rij}^{k} + \Delta\varepsilon_{pij}^{k} \qquad (4)$$

$$\text{ʅ}_{\Phi ij}^{k} = \Delta p_{ij}^{k} + c\Delta dT_{ij} + \Delta T_{rij}^{k} + \Delta N_{ij}^{k}\lambda + \Delta\varepsilon_{\Phi ij}^{k} \qquad (5)$$

$\Delta(\ldots)_{ij}^{k} =$ single differenced

A second subtraction will form a set of double differenced observation equation. This double differencing technique eliminates error in station clock i.e. ΔdT_{ij} is cancelled out. The resulting equations become equ. 6 - 7:

$$\text{ʅ}_{pij}^{kl} = \Delta p_{ij}^{kl} + \Delta T_{rij}^{kl} + \Delta\varepsilon p_{ij}^{kl} \qquad (6)$$

$$\text{ʅ}\Phi_{ij} = \Delta p_{ij}^{kl} + \Delta T_{rij}^{kl} + \Delta N_{ij}^{kl}\lambda + \Delta\varepsilon_{\Phi ij}^{kl} \qquad (7)$$

Where $\Delta(\ldots)_{ij}^{kl}$ = double differenced.

As described by equ. 7, dual differencing observation technique theoretically eliminate satellite and receiver clock biase from the observations thereby reducing the factors that compromise positional accuracy in PPP GNSS observation to only the tropospheric delay and measurement noise (ΔT_{rij}^{kl} and $\Delta\varepsilon_{\rho ij}^{kl}$) which also are smaller compared to the original error (Tr and ε_p) given in Equation 1.

The above set of mathematical derivation efficiently describes the underlying principle behind PPP. Therefore, given the pseudo range and phase clock (consistent with resolved L1 and L2 phase ambiguities) for GPS satellites; precise point positioning can be achieved without a base station (Collins, 2008).

Precise Point Positioning (PPP) implementation is an important example of carrier phase-based GNSS Data Processing (Dagoberto Jos´e, 2010). It has been shown that code-based point positioning solution could be improved to match the Differential Global positioning systems (DGPS) solution through the use of ionosphere-free, undifferenced pseudorange with precise ephemeris and clock data (Seredovich et al, 2012).

2.0.MODELS FOR TROPOSPHERIC DELAY ESTIMATION

Although, previous research in tropospheric delay modelling have shown that the saastemoinen model is actually the best for estimating the effects of total zenith delay especially for low latitude region (e,g Satirapod, and Chalermwattanachai, 2004, Opaluwa et al., 2013, Maduabughichi et al., 2014), this research has further attempted to compare the suitability of using SBAS (Satellite Based Augumented System) estimates of tropospheric delay with the Saastemoinen model. A brief discussion on the two (2) delay estimation models used in this work are herein presented subsections 2.1 and 2.2:

2.1. SAASTEMOINEN MODEL:

(Saastamoinen, 1972) computed the total zenith delay as presented by (Katsougiannopoulos et al, 2006):

$$\Delta L = \frac{2.277*10^{-3}}{COS(90°-V)}\left[P_0 + \left(\frac{1255}{T_0} + 0.05\right).e_0 - 1.16.tan^2(90° - V)\right] \qquad (8)$$

Where: $\Delta L = Zenith\ Total\ Delay$

$P_0 = Surface\ Pressure$ in mbar

$T_0 = Surface\ Temperature\ in\ degrees\ Kelvin$

$e_0 = Partial\ Water\ surface\ pressure\ in\ mbar$

ZTD = ZHD + ZWD

Where ZTD = Zenith Total Delay

ZHD = Zenith Hydrostatic Delay

ZWD = Zenith Wet Delay

2.2. SBAS (SATELLITE BASED AUGUMENTED SYSTEMS) MODEL:

These are a set of satellite based solutions that are made available by the IGS. The IGS products are downloaded from the IGS website for the specific GPS day of the year of observation. Tropospheric corrections come with ".trp" extension and after download are inputted into the RTKLIB software to run the analysis.

3.0 STUDY AREA:

Nigeria is a vast country that has almost equivalent East-West and North-South Spread. With a land mass area of approximately 924,000 Sq Km it is has a population of about 174 million people. Consequent upon its vast land mass and enormous population, accurate geospatial measurements upon which an efficient land administration will be based is highly relevant. With the advent of PPP, fifteen (15) CORS have been installed across the country.

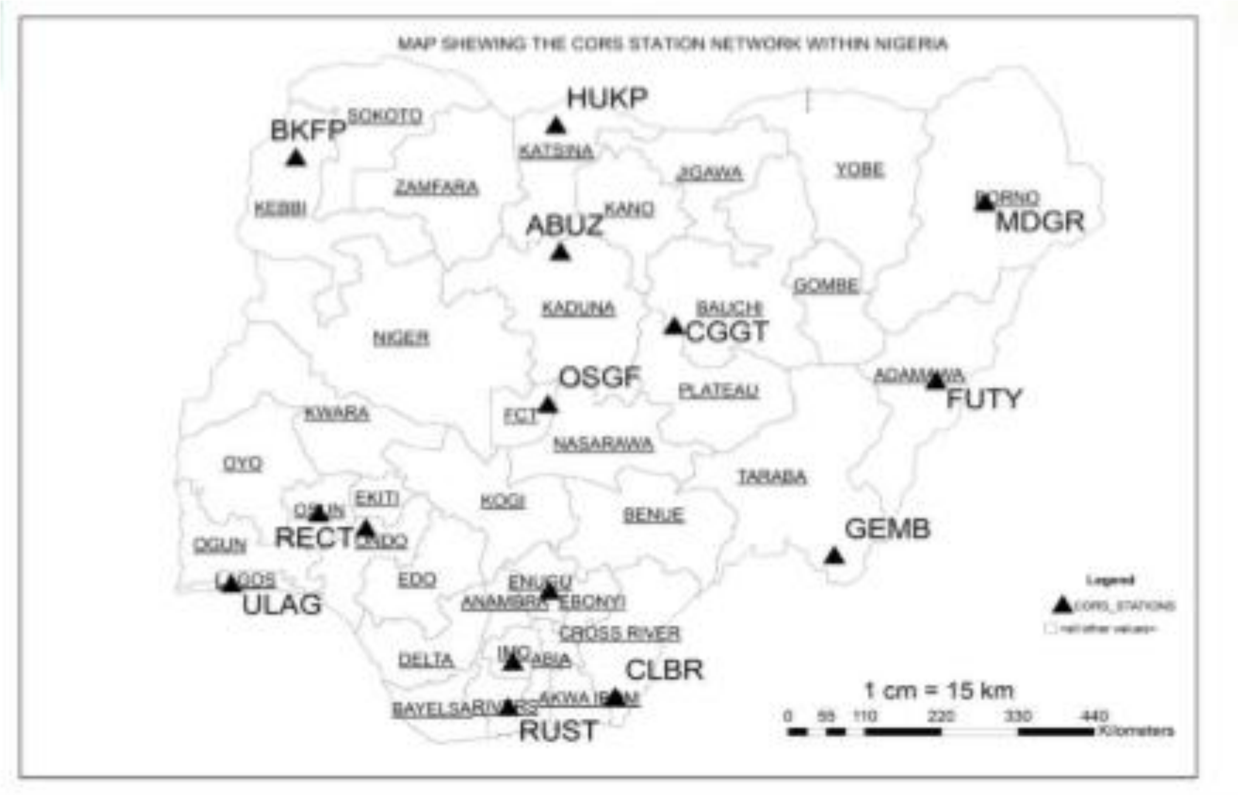


Fig 2: CORS Network in Nigeria (Nwilo et al, 2013)

This paper will thus provide GNSS users across the vast length and breadth of Nigeria with an a-priori information on the positional accuracy obtainable from GNSS observations across the country in various regions based on the tropospheric variability.

4.0 DATA USED

24 hours data was collected from six (6) CORS across Nigeria at three months interval beginning at 1st of January, 2014 to 1st of June 2014 from Nignet website (www.nignet.net). Also, the IGS corrections for troposphere were obtained from the IGS website (www.igscb.jpl.nasa.gov/components/data.html)

The COR stations used for this research were:

1. ABUZ: Located in Ahmadu Bello University, Zaria in Kaduna State.
2. BKFP: Located in Bernin Kebbi, Kebbi State.
3. CLBR: Located in Calabar, Cross Rivers State.

4. HUKP: Located in Katsina.
5. ULAG: Located in University of Lagos, Lagos state.
6. UNEC: Located in University of Enugu, Enugu State.

The orbit navigation files and the rinex (observation) files for each station and day of the year

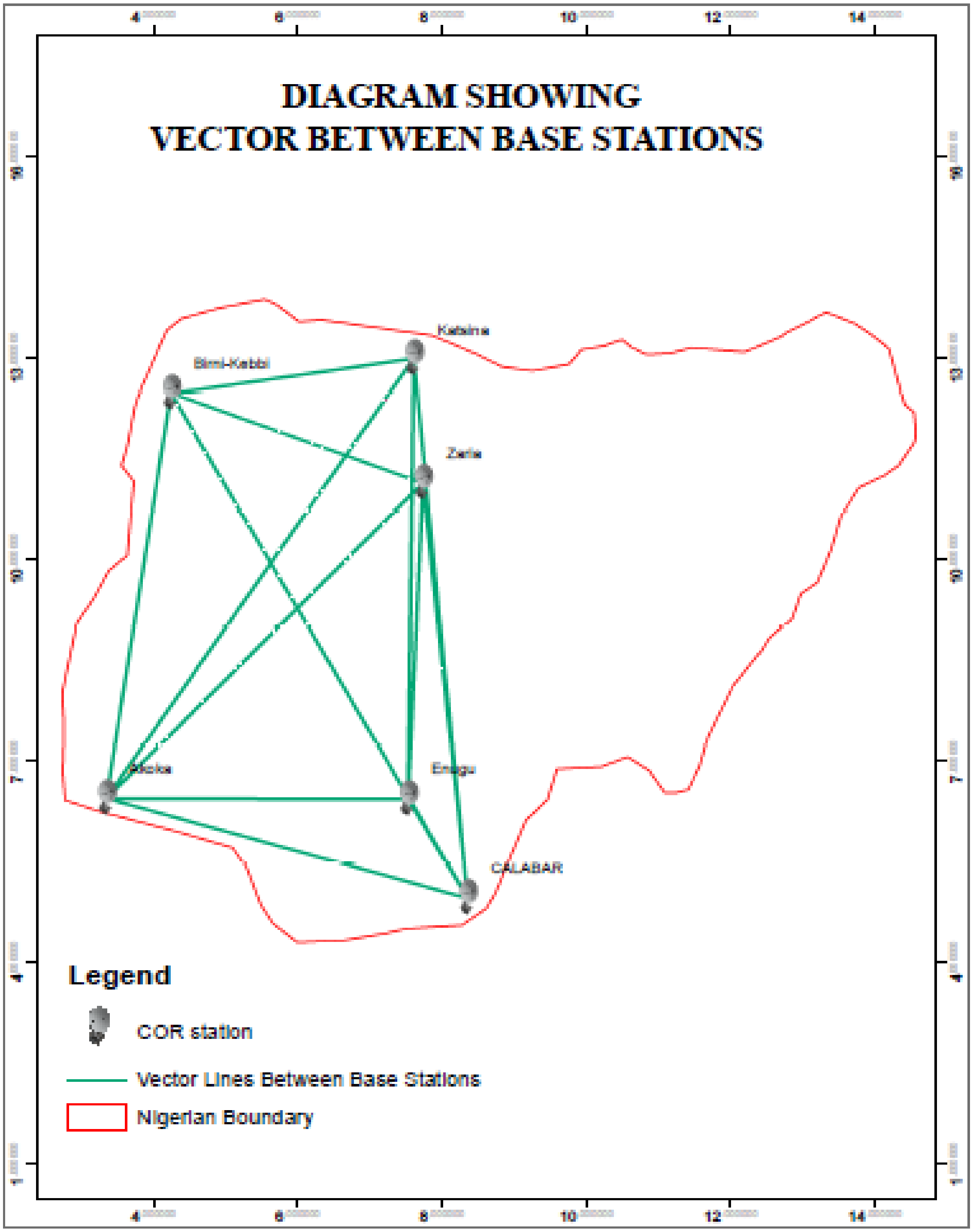


Figure 2(b): Baseline vectors between the base stations

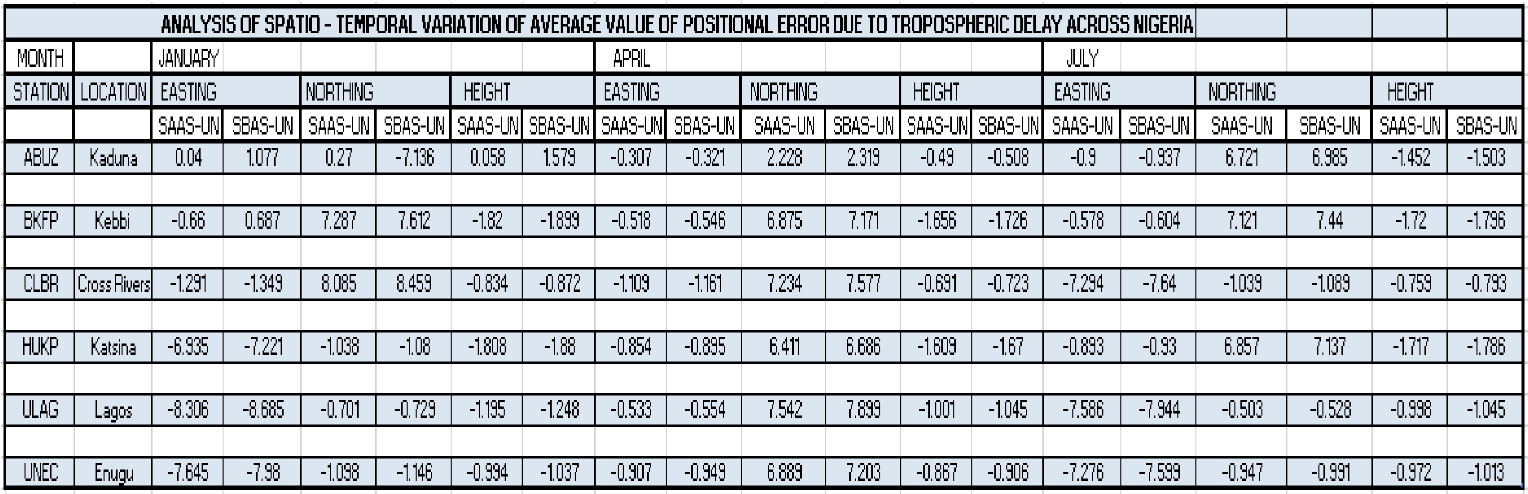
6.0. RESULTS

Table 1 shows an estimate of the monthly average positional effect of the troposphere on the Eastings, Northings and Up at each of the stations under study.

Tables 2 – 4 show the monthly averages of the effects of tropospheric delay on positional accuracy in the Eastings, Northings and Up direction.

The results have been presented to show the difference between the Saastemoinen corrected values and the Uncorrected (solely Broadcast Dependent) values in one row (SAAS – UN) while the difference between the SBAS corrected values and the Uncorrected values are shown in another row (SBAS – UN)

Table 1: Estimate of the monthly average positional effect of the tropospheric delay.



ANALYSIS OF SPATIO - TEMPORAL VARIATION OF AVERAGE VALUE OF POSITIONAL ERROR DUE TO TROPOSPHERIC DELAY ACROSS NIGERIA

MONTH		JANUARY						APRIL						JULY					
STATION	LOCATION	EASTING		NORTHING		HEIGHT		EASTING		NORTHING		HEIGHT		EASTING		NORTHING		HEIGHT	
		SAAS-UN	SBAS-UN	SAAS-UN	SBAS-UN	SAAS-UN	SBAS-UN	SAAS-UN	SBAS-UN	SAAS-UN	SBAS-UN	SAAS-UN	SBAS-UN	SAAS-UN	SBAS-UN	SAAS-UN	SBAS-UN	SAAS-UN	SBAS-UN
ABUZ	Kaduna	0.04	1.077	0.27	-7.136	0.058	1.579	-0.307	-0.321	2.228	2.319	-0.49	-0.508	-0.9	-0.937	6.721	6.985	-1.452	-1.503
BKFP	Kebbi	-0.66	0.687	7.287	7.612	-1.82	-1.899	-0.518	-0.546	6.875	7.171	-1.656	-1.726	-0.578	-0.604	7.121	7.44	-1.72	-1.796
CLBR	Cross Rivers	-1.291	-1.349	8.085	8.459	-0.834	-0.872	-1.109	-1.161	7.234	7.577	-0.691	-0.723	-7.294	-7.64	-1.039	-1.089	-0.759	-0.793
HUKP	Katsina	-6.935	-7.221	-1.038	-1.08	-1.808	-1.88	-0.854	-0.895	6.411	6.686	-1.609	-1.67	-0.893	-0.93	6.857	7.137	-1.717	-1.786
ULAG	Lagos	-8.306	-8.685	-0.701	-0.729	-1.195	-1.248	-0.533	-0.554	7.542	7.899	-1.001	-1.045	-7.586	-7.944	-0.503	-0.528	-0.998	-1.045
UNEC	Enugu	-7.645	-7.98	-1.098	-1.146	-0.994	-1.037	-0.907	-0.949	6.889	7.203	-0.867	-0.906	-7.276	-7.599	-0.947	-0.991	-0.972	-1.013

Table 2: Monthly average of variation in tropospheric delay across Nigeria in January, 2014

MONTH	JANUARY					
STATION	EASTING		NORTHING		UP	
	SAAS-UN	SBAS-UN	SAAS-UN	SBAS-UN	SAAS-UN	SBAS-UN
ABUZ	0.04	1.077	0.27	-7.136	0.058	1.579
BKFP	-0.66	0.687	7.287	7.612	-1.82	-1.899
CLBR	-1.291	-1.349	8.085	8.459	-0.834	-0.872
HUKP	-6.935	-7.221	-1.038	-1.08	-1.808	-1.88
UNEC	-7.645	-7.98	-1.098	-1.146	-0.994	-1.037
ULAG	-8.306	-8.685	-0.701	-0.729	-1.195	-1.248

Table 3: Monthly average of variation in tropospheric delay across Nigeria in April, 2014

MONTH	APRIL					
STATION	EASTING		NORTHING		UP	
	SAAS-UN	SBAS-UN	SAAS-UN	SBAS-UN	SAAS-UN	SBAS-UN
CLBR	-1.109	-1.161	7.234	7.577	-0.691	-0.723
UNEC	-0.907	-0.949	6.889	7.203	-0.867	-0.906
HUKP	-0.854	-0.895	6.411	6.686	-1.609	-1.67
ULAG	-0.533	-0.554	7.542	7.899	-1.001	-1.045
BKFP	-0.518	-0.546	6.875	7.171	-1.656	-1.726
ABUZ	-0.307	-0.321	2.228	2.319	-0.49	-0.508

Table 4: Monthly average of variation in tropospheric delay across Nigeria in July, 2014

MONTH	JULY					
STATION	EASTING		NORTHING		UP	
	SAAS-UN	SBAS-UN	SAAS-UN	SBAS-UN	SAAS-UN	SBAS-UN
ULAG	-7.586	-7.944	-0.503	-0.528	-0.998	-1.045
CLBR	-7.294	-7.64	-1.039	-1.089	-0.759	-0.793
UNEC	-7.276	-7.599	-0.947	-0.991	-0.972	-1.013
ABUZ	-0.9	-0.937	6.721	6.985	-1.452	-1.503
HUKP	-0.893	-0.93	6.857	7.137	-1.717	-1.786
BKFP	-0.578	-0.604	7.121	7.44	-1.72	-1.796

Tables 2 – 4 have been sorted such that the station with the least tropospheric delay appears first till the station with the largest error.

Figures 3 – 5 shows a graphical representation of the East, North, Up tropospheric delay at each of the six (6) stations in January, April and July respectively.

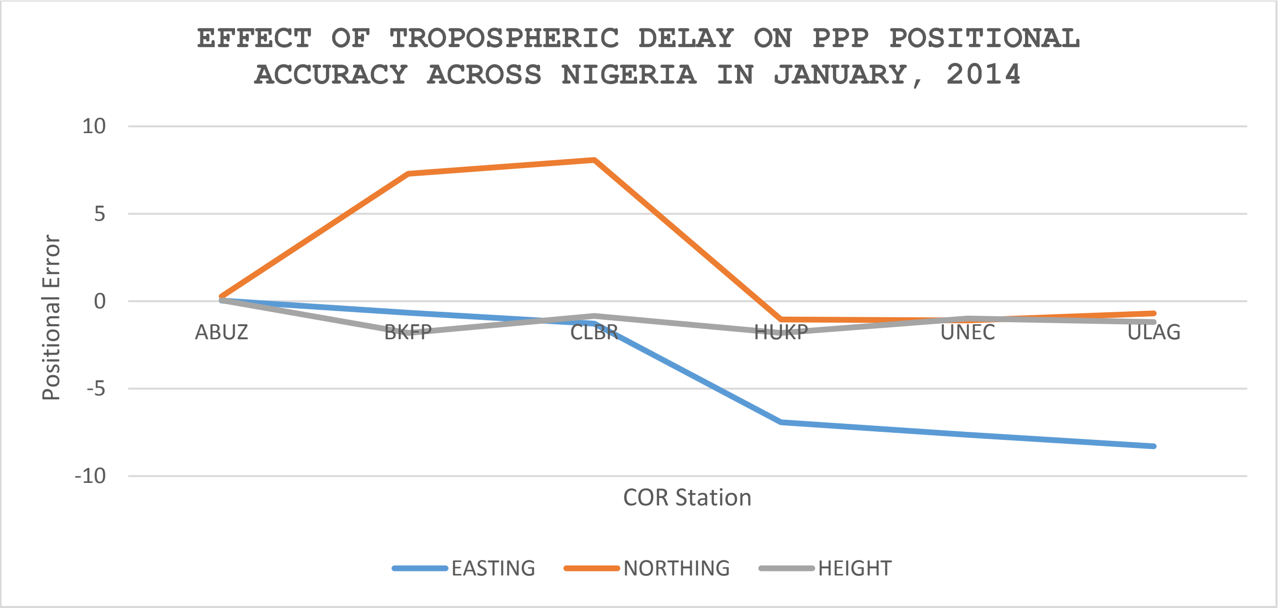


Figure 3. Tropospheric delay effects on PPP solution in January 2014.

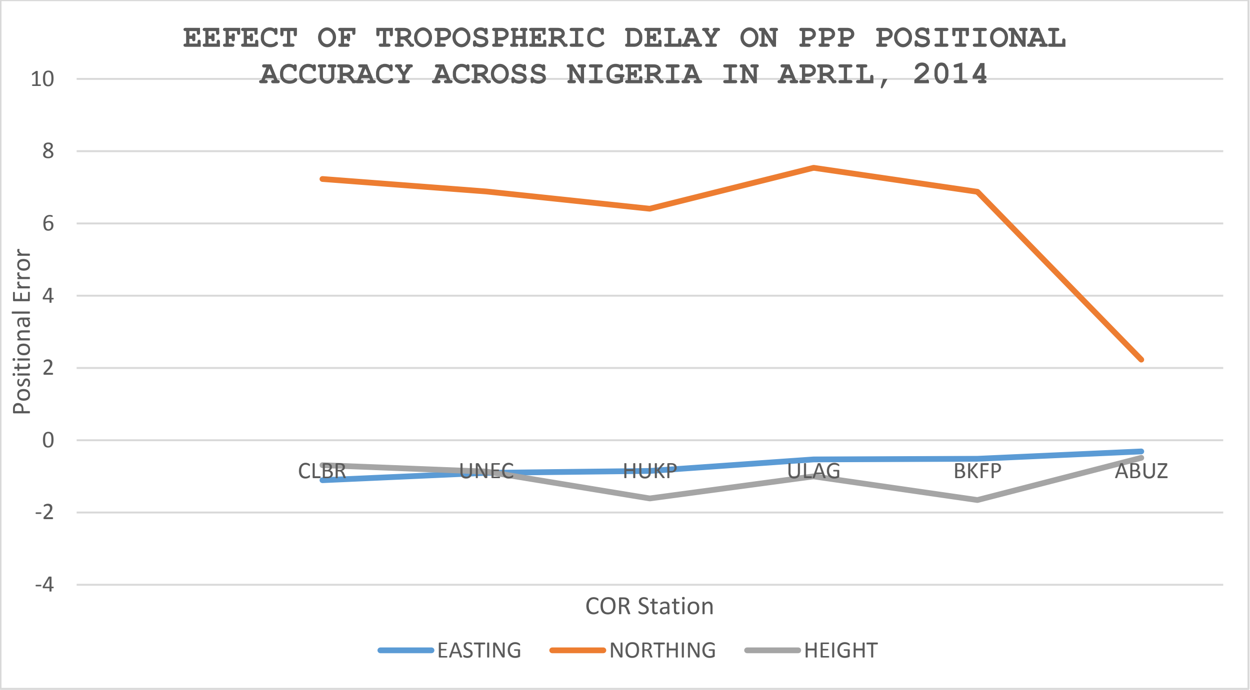


Figure 4: Tropospheric delay effects on PPP solution in April 2014.

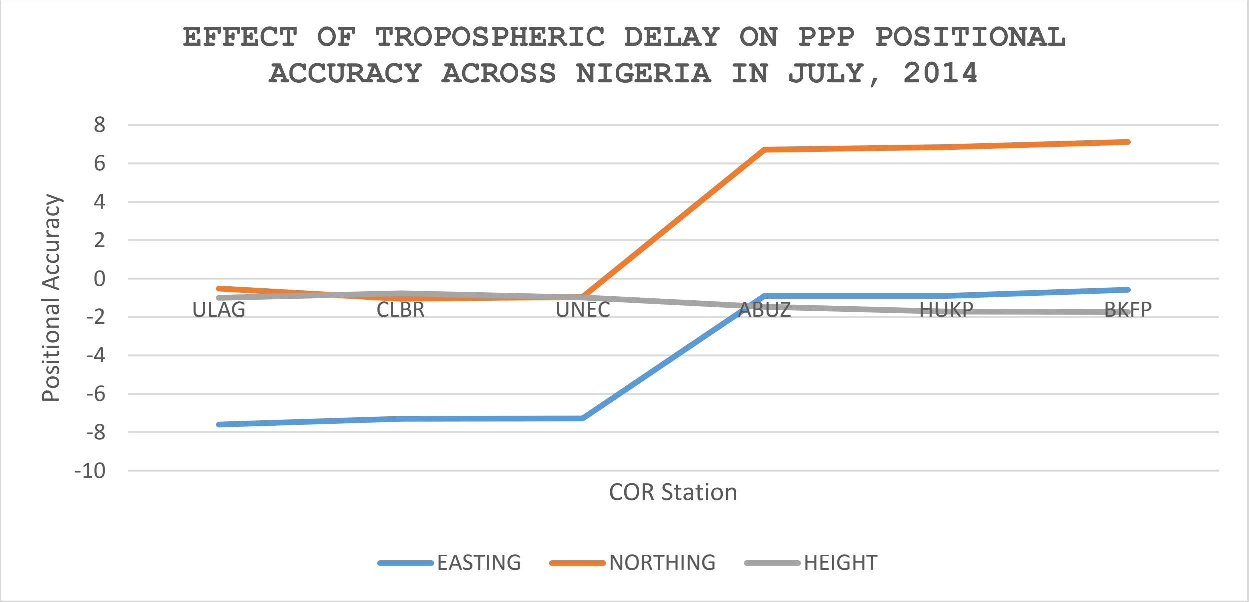


Figure 5: Tropospheric delay effects on PPP solution in July 2014.

7.0. DISCUSSION OF RESULTS:

From the results shown in tables 2 – 4 and further illustrated by Figures 3 – 5, ABUZ located in the North-western part of Nigeria has the least tropospheric delay through-out the period under study.

It was also discovered that the tropospheric effect in PPP was more on the North than in the East and up direction. This contradicts the general convention in GNSS positioning where tropospheric delay is assumed to have greater effect on the Height more than it does on the planimetric co-ordinates. However, such irregularities may be due to some station-dependent errors that are common to the CORS used in this study. For instance performance of different tidal models varies over different regions, therefore the choice of appropriate model to handle effects of ocean tide loading in GNSS data analysis over Nigeria need to be investigated.

Besides, in January and April, Calabar and Benin Kebbi experienced the greatest positional error in the Northings.

Figures 6 – 8 depicts the variation across the country in contour format. This shows that the tropospheric effect is negligible around the North-west areas of the country while the values are extremely high in the South-east and extremely low in the North-east, South-west and South-south regions in January. In April however, as shown in Figure 7 the region with least error spans from the North-west, to parts of the North-east and the South-southern region; while in July, least error is found within the mid-latitudes of Nigeria.

The above scenario is so because the high variability of tropospheric water vapour is majorly responsible for the devastation of GNSS signals in the tropospheric layer. This effect is more in the low-latitude (equatorial) region due to persistent sunlight which induces large amount of water vapour in the equatorial troposphere (Opaluwa et al., 2014d). The southern part of Nigeria being closer to the equator than the North is more susceptible to the influence of the tropospheric delay due to the fact the northern part of the country is generally drier than the south.

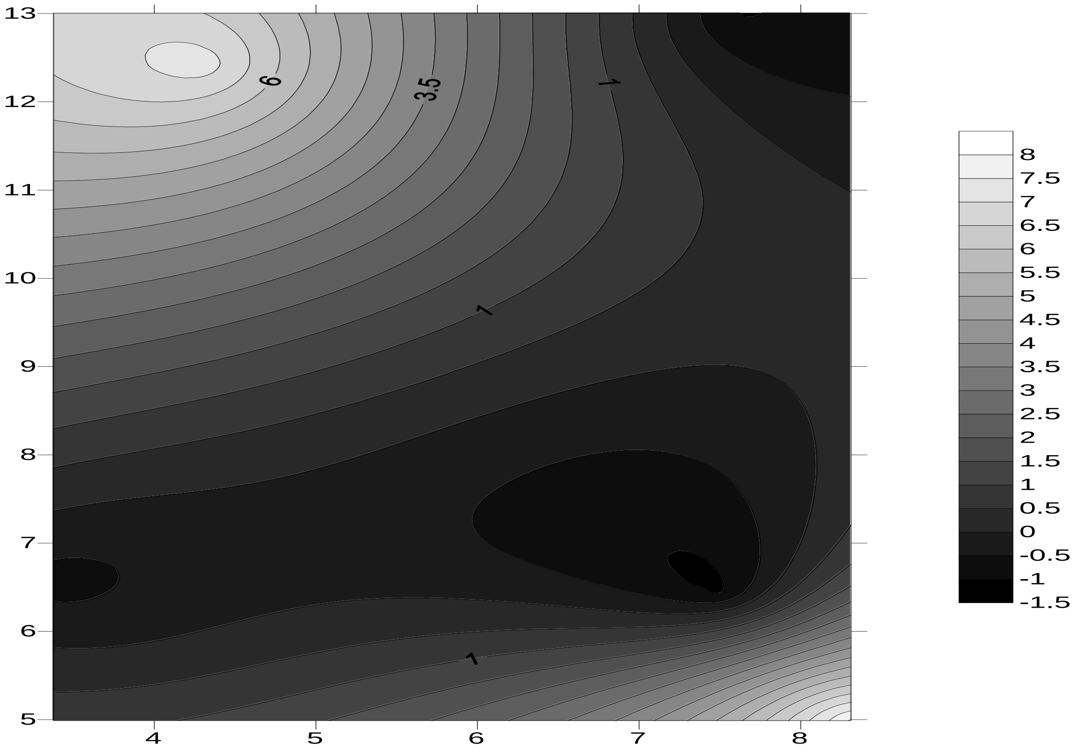


Figure 6: Contour Plot showing the spatio-temporal variation of the effect of Tropospheric delay in the positional error (Northings) across Nigeria in January, 2014.

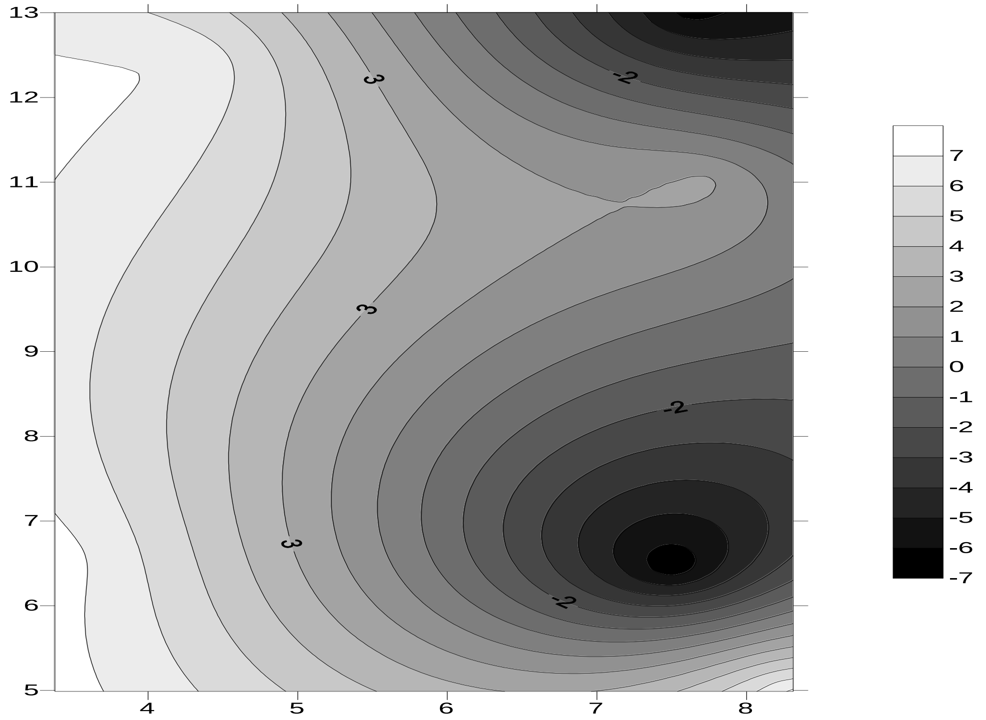


Figure 7: Contour Plot showing the spatio-temporal variation of the effect of Tropospheric delay in the positional error (Northings) across Nigeria in April, 2014.

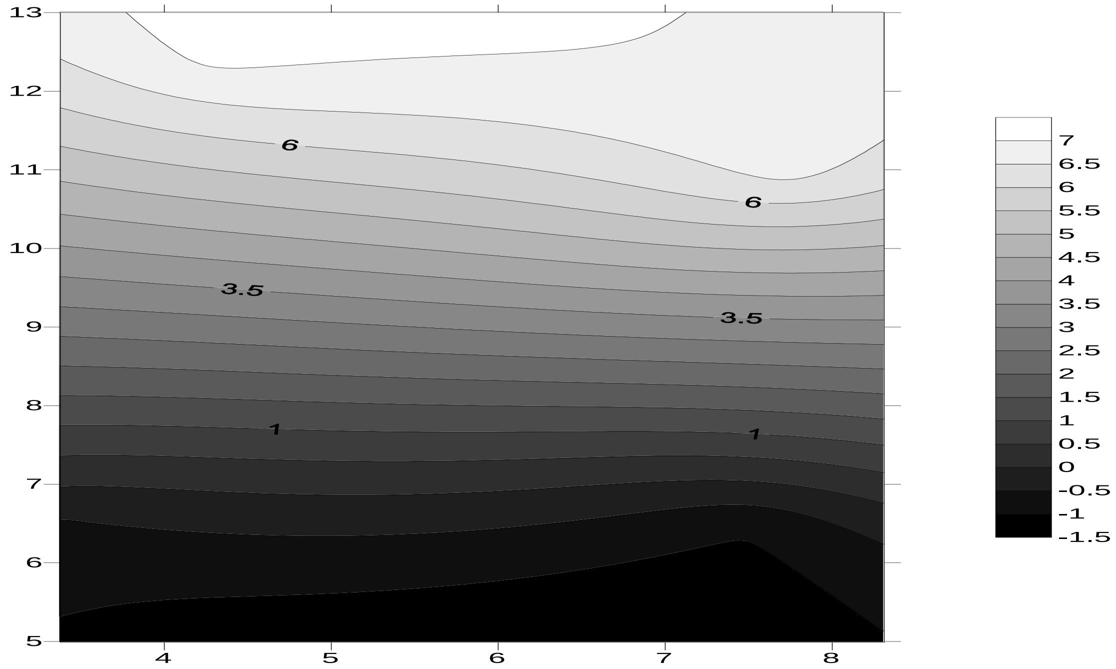


Figure 8: Contour Plot showing the spatio-temporal variation of the effect of Tropospheric delay in the positional error (Northings) across Nigeria in July, 2014.

CONCLUSION:

The effect of tropospheric delay on GNSS positioning in Nigeria has been investigated in this paper. Three months data (January, April and July 2014) from the Nigerian GNSS network (Nignet) was analysed based on PPP solution using RTKLib GNSS analysis software. From the study and results discussed above, it was found that:

1. The tropospheric delay has greater impact on the North than on the East and Up co-ordinates within the study area. This result however appears to contradict the popular notions that the positional impact of the tropospheric delay is more on the UP than on the East and North Direction. In order to understand the source of such uncertainty, further research is therefore recommended, especially using high precision post processing software such as the Bernese GNSS software, while the need to investigate the presence of other error sources such as station-dependent or environmental dependent errors has been highlighted.
2. Through-out the period under study, ABUZ located in the North-western part of Nigeria experienced the least positional error due to tropospheric delay. This suggests that the North-western regions of the country have least tendencies of troposphere based errors in positioning than other parts of the country. This was not unexpected because the north generally presents drier atmosphere than the south. However, further research may be conducted by analysing data over a longer period.
3. The spatio-temporal pattern of variability of the delay however appears to be “leap frog” in nature as least error is found predominantly in the North-western in January and spreads towards the North-east and South-south in April before returning to the nation’s ‘mid-latitudes” in July.

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