

A Study on the Impact of GPS-Derived Tropospheric Delay over some Nigerian Stations

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Abstract

The effect of GPS-derived tropospheric delay on radio propagation oversome Nigerian stations is examined. The stations are located in the African equatorial region, and include: Abuja (8.9°N, 7.4°E), Akure (7.3°N, 5.2°E), Enugu (6.5°N, 7.5°E), Lagos (6.5°N, 3.4°E), and Port Harcourt (4.8°N, 7.0°E). This is the first study in the African equatorial region that uses in-situ meteorology measurements as well as GPS satellite measurements to present the impact of tropospheric delay on radio propagation, especially with respect to varying elevation angles. Data used for the study covered the twelve-month period from January to December 2013, and the modified Hopfield model was used to derive the tropospheric delays. The results show that GPS-derived tropospheric delays vary significantly with elevation angles of the satellites. The values of the tropospheric delays are typically about 2.5 m when the radio transmission path is at around 90° of elevation, and the values increase to over 20 m when the radio transmission is at around 10° of elevation. The rate of change of the tropospheric delay (with respect to elevation angle) increases with decreasing elevation angle. The tropospheric delay typically increases by about 3% when the elevation angle changes from 90° to 80°, and by about 60% when the elevation angle changes from 20° to 10°. Time-dependent maps of the tropospheric delay reveals a pattern which indicates that variation of the tropospheric delay is significantly controlled by elevation angles of the Global Positioning System (GPS) satellites.

Keywords: Tropospheric delay, GPS, meteorology, elevation angle, radio propagation.

INTRODUCTION

The troposphere is the part of the atmosphere closer to the Earth's surface (from sea level to about 10 km above sea level). Its index of refraction varies with altitude. The variation of refractive index causes an excess path delay of signals from satellites to receivers in a phenomenon usually called tropospheric delay [1]. The delay introduces errors to positions estimated by global navigation satellite system (GNSS) receivers. This error due to improper estimation of tropospheric delay can be

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over 10 m because the tropospheric delay can range from 2 m at the zenith to over 20 m at lower elevation angle [2]. The troposphere affects radio propagation in diverse ways ranging from propagation delay, signal bending to ducting. These arise due to the non-dispersive nature of the troposphere. As radio signals traverse the neutral atmosphere, they are affected by the variation in the refractive index of the atmosphere. In effect, the speed of propagation slows down as the time to traverse the distance becomes longer. These result to tropospheric delay. This delay, expressed in meters, is a measure of path difference traversed by the signals due to the effect of the troposphere. It is a major source of error in radio propagation and its effect decreases with increasing elevation angles.

Accurate modelling of tropospheric delay in radio propagation is useful for mitigating effects of the troposphere on the GPS (Global Positioning System) accuracy.

The GPS is a space based radio navigation technology with system receivers that provide exact time and location information for every user across the globe in all weather, day and night. Its ability to operate in all-weather becomes an advantage to deploy it in a number of scientific uses. One of such use is in radio propagation. Three GPS frequencies are available for public use, namely $L_1=1.57542$ GHz, $L_2=1.22760$ GHz and $L_3=1.338105$ GHz. Several works have presented models to compute GPS delay within the troposphere. Reference [3] studied how to illustrate and model the effect of the atmospheric constituents such as water vapour, clouds, rain and snow on the GPS frequencies. The result, among others, showed that the differential phase shift in case of rain was caused by rain drops. It further showed that the differential phase shift doesn't depend on temperature but increases with increase in frequency such that at L_1 it is 6° /km, at L_2 , it is 5° /km and at L_3 it is 5.4° /km. Reference [4] estimated tropospheric delay using 3 days GPS pseudo-range observations (157 d, 158 d and 159 d) and compared the total estimated delay from the permanent GPS data with that obtained from radiosonde measurement at Thessaloniki airport. Reference [1] reported that this tropospheric delay is a distant-dependent error which varies with changes in meteorological conditions. It further reveals that tropospheric error increases with the increase in the baseline length between two stations.

LITERATURE REVIEW

Several works have been done on modelling of the tropospheric delay (e.g. [5-7]) and several other works have been done to validate these models (e.g. [1, 3, 8]). The tropospheric delay is usually constituted by a dry (or hydrostatic) component, and a wet component. These respectively account for the effects of dry gases and water vapour pressure, and they are specifically referred to as zenith hydrostatic and zenith wet delays when the lines of sight are in the zenith direction. It is established that the wet delay constitutes about 10% of the total delay, while the dry/hydrostatic delay accounts for about 90% of the total delay [5, 6, 9-11]. Reference [13] showed that zenith tropospheric delay (ZTD) is about 2.5 m. Reference [8] obtained ZTD of 2.33 m with error value of 0.45 m while references [5 and 6] got 2.36 m and 2.39 m respectively. The zenith tropospheric delay model adopted for the North Atlantic Treaty Organization (NATO) standard troposphere model is based on reference atmosphere. It is a function of height above sea level and the mean sea-level refractivity of 324.8 N-units was obtained [18].

There is lacking report on the African equatorial region that uses in-situ meteorology measurements to investigate variation of GPS-derived tropospheric delay as a function of the satellite elevation angle. This is the first detailed report of GPS-derived tropospheric delay variation with emphasis on the satellite elevation angle, making use of in-situ meteorology measurements in the African equatorial region. The paper evaluated the impact of tropospheric delay variation with respect to GPS satellite elevation angles, varied from 10° to 90° at five stations in the region. The research is unique in the region because it made use of real observations from a combination of both GPS and meteorological data, and went ahead to demonstrate the variation of tropospheric delay with elevation angle of the GPS satellites. GPS measurements were obtained from the Nigerian Permanent GNSS Network while meteorological measurements were obtained from corresponding atmospheric stations of the Centre for Atmospheric Research. This offered a more detailed report of delay effect in the region as it factored the real effect of weather which is precarious in the region.

STUDY AREA AND DATA

Data from the following five locations are investigated in this study: Abuja (8.9°N , 7.4°E), Akure (7.3°N , 5.2°E), Enugu (6.5°N , 7.5°E), Lagos (6.5°N , 3.4°E), and Port Harcourt (4.8°N , 7.0°E). These locations are described as detailed in Table 1 and as shown in Figure 1. The locations are in the African equatorial region, and they have a tropical savannah climate. The climate is humid, and this

humidity is at its highest between March and November. Its main seasons are rainy season and dry season. The Dry season runs from November to March while rainy season runs from April to October. The Harmattan has cool dry wind that blows from the northeast in the Western Sahara and is strongest from around November to March. It usually carries large dust which affects space operations creating poor visibility. Refractivity gets higher generally during the rainy season hence increasing the rate of signal path loss and attenuation due to high humidity and water vapour [12].

Data used in this work comprises of in-situ meteorological measurements and GPS satellite observations. The meteorological measurements include data of temperature, pressure and relative humidity obtained from the Centre for Atmospheric Research (CAR), National Space Research and Development Agency (NASRDA), for the twelve-month period from January to December 2013. Corresponding GPS data for the same period and locations were obtained from the Nigerian Permanent GNSS receiver Network (NIGNET).

METHODS

Tropospheric delay increases with the increase in refractive index and can be measured as a function of atmospheric temperature, pressure and humidity [13]. When the electromagnetic wave in the atmosphere propagates just slightly slower than in the vacuum or the refractive index is a little above unity, the refractive index is more conveniently expressed by the term Refractivity, N :

Table 1. Detailed description of the measurement sites used in this work.

S.N.	Site Name	Height above sea level (m)	Longitude	Latitude	Weather
1	Lagos	46.4	3.4°E	6.5°N	Coastal and Humid Forest
2	Port Harcourt	49.4	7.0°E	4.8°N	Coastal and Humid Forest
3	Akure	416.0	5.2°E	7.3°N	Inland and Humid Forest
4	Enugu	259.9	7.5°E	6.5°N	Inland and Derived Savanna
5	Abuja	532.6	7.4°E	8.9°N	Inland and Derived Savanna

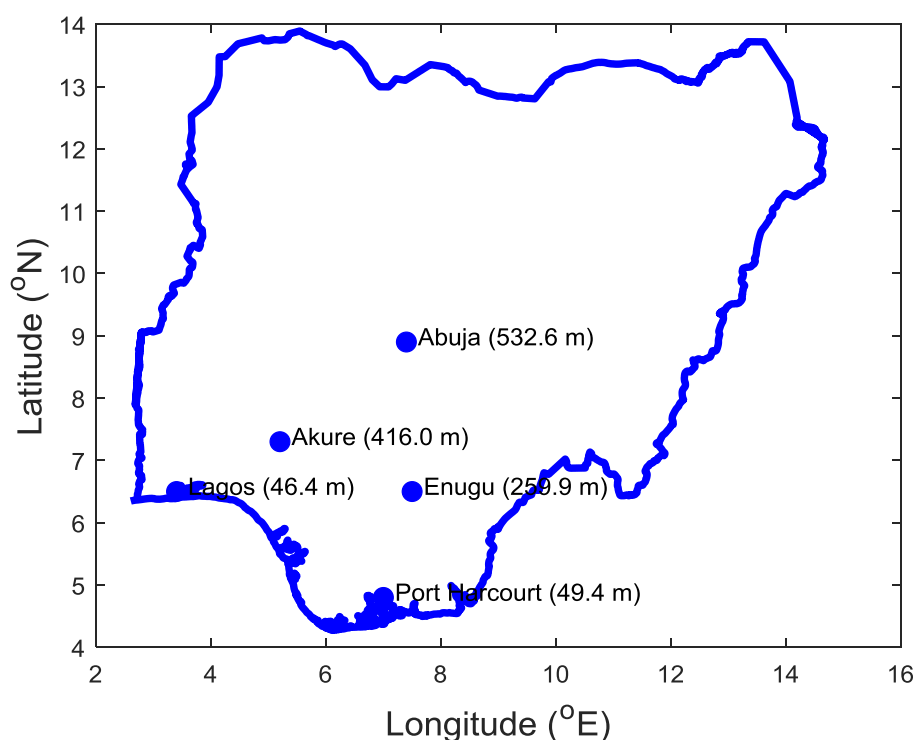


Figure 1. Map of Nigeria with in-built altitudes of the stations used in this work.

$$N = 10^6(n-1) \quad (1)$$

Where; n is the refractive index. The refractivity was derived using the expressions in [14]:

$$N = k_1 \frac{P_d}{T} + k_2 \frac{e}{T} + k_3 \frac{e}{T^2} \quad (2)$$

Where; P_d is the partial pressure due to dry gases, including CO_2 ; e and k_i are constants empirically determined in laboratory, with values of $k_1 = 77.6848$; $k_2 = 71.2952$ and $k_3 = 375463$ [15, 16]. By substituting the values of refractivity constants, Equation 2 reduces to:

$$N = (n-1) \times 10^6 = \frac{77.6P}{T} \times 3.0 \times 10^5 \frac{e}{T^2} \quad (3)$$

Where; P is the atmospheric pressure, e is partial pressure of water vapour, and T is absolute temperature. Total refractivity is the sum of the hydrostatic component and wet components of refractivity. The zenith hydrostatic delay (ZHD) contributes about 90% of the total zenith tropospheric delay (ZTD) while the zenith wet delay (ZWD) contributes about 10% of the total tropospheric delay [5, 6, 9-11]. The tropospheric delay being a linear combination of hydrostatic and wet components is represented as:

$$d_{trop} = 10^{-6} \int_{path} N_h ds + 10^{-6} \int_{path} N_w ds \quad (4)$$

Where; N_h is hydrostatic refractivity and N_w is refractivity due to wet gases.

The Tropospheric delay is the delay calculated in the zenith direction over the antenna on the ground, hence we have:

$$d_{trop}^z = d_h^z + d_w^z \quad (5)$$

Where; d_h^z and d_w^z are zenith hydrostatic and zenith wet delays respectively.

Reference [17] found out that there is correlation between the wet zenith delay and surface water vapour as expressed in equation (6). The equation was derived based on ray-tracing results obtained using data from 50 radiosonde stations distributed worldwide, mainly in the northern mid-latitudes as described by reference [17]. There are a few of the stations within the equatorial region. The correlation therefore varies from weak to strong, depending on the location.

$$d_w^z = 0.0122 + 0.00943e \quad (6)$$

On the other hand, reference [7] had shown that the dry zenith delay could also be obtained using a model for dry refractivity profile and developed the following:

$$d_d^z = 10^{-6} N_{ds} \frac{H_d^e - H_s}{5} \quad (7)$$

Where; d_d^z is dry zenith delay, N_{ds} is the dry component of refractivity, H_s is the height of the station from which the meteorological data was obtained and H_d^e is the equivalent height of the troposphere. Reference [19] showed that modified Hopfield solution model is a tropospheric delay solution based on the meteorological data of the station which can be expressed as:

$$ZTD_{ModHop} = ZTD_{dry} + ZTD_{wet} \quad (8)$$

$$ZTD_i = 10^{-6} N_i \sum_{k=1}^9 \frac{f_{k,i}}{k} r_i^k, i = dry, wet \quad (9)$$

$$\left. \begin{aligned}
 r_i &= \sqrt{(R_E + h_i)^2 - R_E^2 \sin^2 z - R_E \cos z} \\
 f_{1,i} &= 1, \quad f_{2,i} = 4a_i, \quad f_{3,i} = 6a_i^2 + 4b_i, \quad f_{4,i} = 4a_i(a_i^2 + 3b_i) \\
 f_{5,i} &= a_i^4 + 12a_i^2b_i + 6b_i^2, \quad f_{6,i} = 4a_ib_i(a_i^2 + 3b_i) \\
 f_{7,i} &= b_i^2(6a_i^2 + 4b_i), \quad f_{8,i} = 4a_ib_i^3, \quad f_{9,i} = b_i^4 \\
 a_i &= -\frac{\cos z}{h_i}, \quad b_i = -\frac{\sin^2 z}{2h_i R_E} \\
 h_d &= 4136 + 148.72(T_{sta} - 273.16), \quad h_w = 11000 \\
 N_d &= 77.64 \frac{P_{sta}}{T_{sta}}, \quad N_w = -12.96 \frac{e}{T_{sta}} + 371800 \frac{e}{T_{sta}^2}
 \end{aligned} \right\} \quad 10$$

Where; z is zenith angle of the satellite and R_E is the radius of the earth.

A modified Hopfield model [20] was used in this work to compute tropospheric delay from the meteorology and GPS measurements as detailed in the flowchart of Figure 2. Adopting the modified Hopfield model of computing tropospheric delay, we developed a program that computes the means of the GPS-derived tropospheric delays with respect to the satellite elevation angles, starting from 10° to 90° in steps of 10° [21]. Data from the GPS receivers was obtained in RINEX format, and the GPS-TEC Analysis software [22, 23] was used to derive satellite elevation angles from the RINEX files.

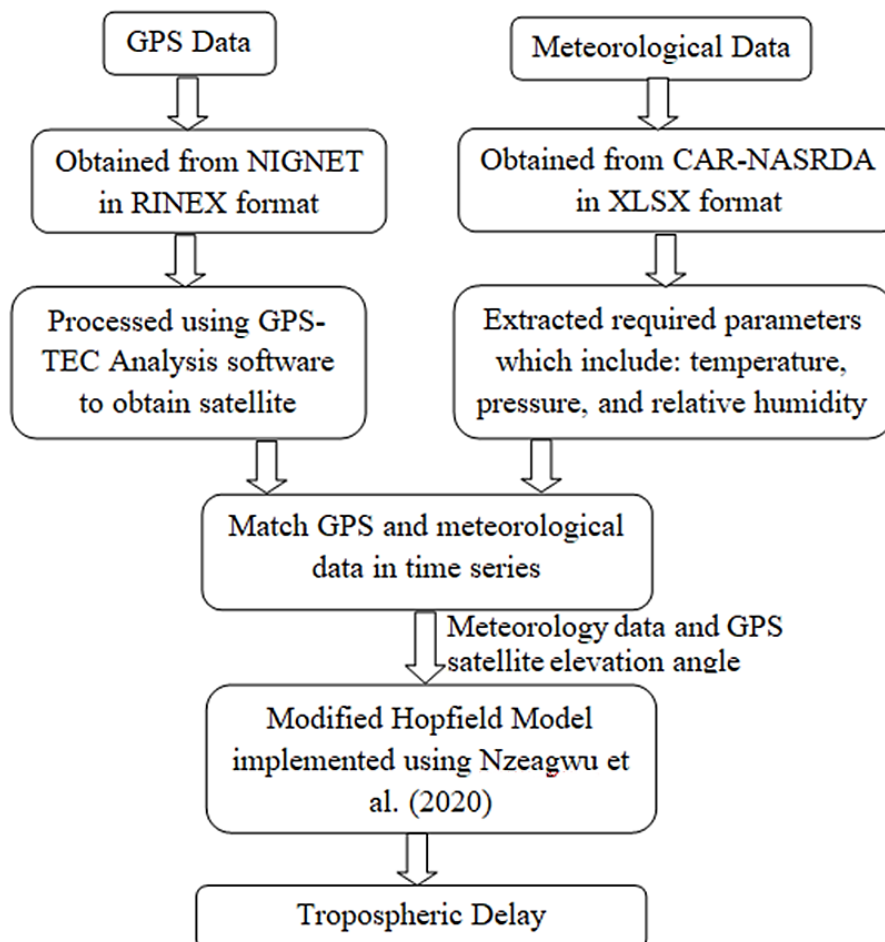


Figure 2. Flowchart of processes used to derive tropospheric delay from GPS and meteorological data,

RESULTS

Figure 3 shows variations of the mean tropospheric delays as functions of the GPS satellite elevation angles at the five locations.

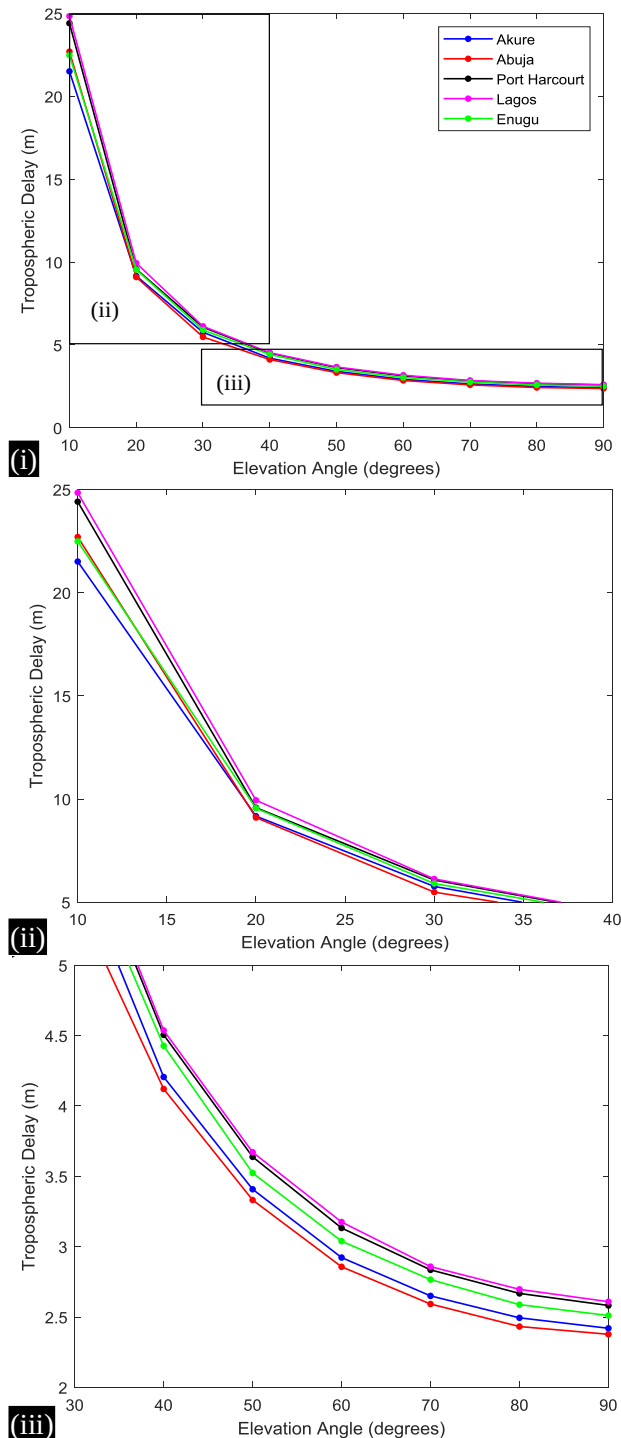


Figure 3. Variation of tropospheric delay with elevation angle at Akure, Abuja, Port Harcourt, Lagos and Enugu. Figure 3(i) shows the complete profiles for the five stations, while (ii) and (iii) show parts of the profiles as inserted in (i). The reasons for (ii) and (iii) are to provide clearer and distinct views of each profile.

Table 2 shows percentage decrease in the tropospheric delays when elevation angles are increased from 10° to 90° , in steps of 10° for the five locations. The last column of the table represents average of the percentage decrease for the five locations.

The plots in Figure 4 represent variations of the mean tropospheric delay as a function of hour of the day (in Universal Time, UT). Local time in Nigeria is 1 hour ahead of UT. The figure is illustrated using data for Enugu location. Enugu location is chosen because the station has the most complete pair of meteorology and GPS datasets. The observations are binned in intervals of 10° elevation angle, so the plot labelled 10° constitutes observations for satellites with elevation angles from 0° to 10° , the plot labelled 20° constitutes observations for satellites with elevation angles from above 10° to 20° , and so on.

Statistics of the monthly distribution of tropospheric delays are shown in the box and whisker plots of Figure 5. On each box, the central mark indicates the median, and the bottom and top edges of the

Table 2. Percentage decrease in tropospheric delay as the elevation angle is increased by 10 degrees at the five locations.

Change in elevation angle (degree)		Percentage decrease in tropospheric delay (%)					
From	To	Akure	Abuja	Port-Harcourt	Lagos	Enugu	Average
10	20	57.38	59.92	60.76	59.99	57.54	59.12
20	30	37.13	39.72	36.62	38.35	38.19	38.00
30	40	27.02	24.86	25.80	25.96	24.99	25.73
40	50	18.97	19.15	19.25	19.08	20.41	19.37
50	60	14.24	14.25	13.90	13.52	13.77	13.94
60	70	9.32	9.26	9.49	9.99	8.98	9.41
70	80	5.88	6.18	5.91	5.65	6.43	6.01
80	90	2.98	2.27	3.21	3.25	2.99	2.94

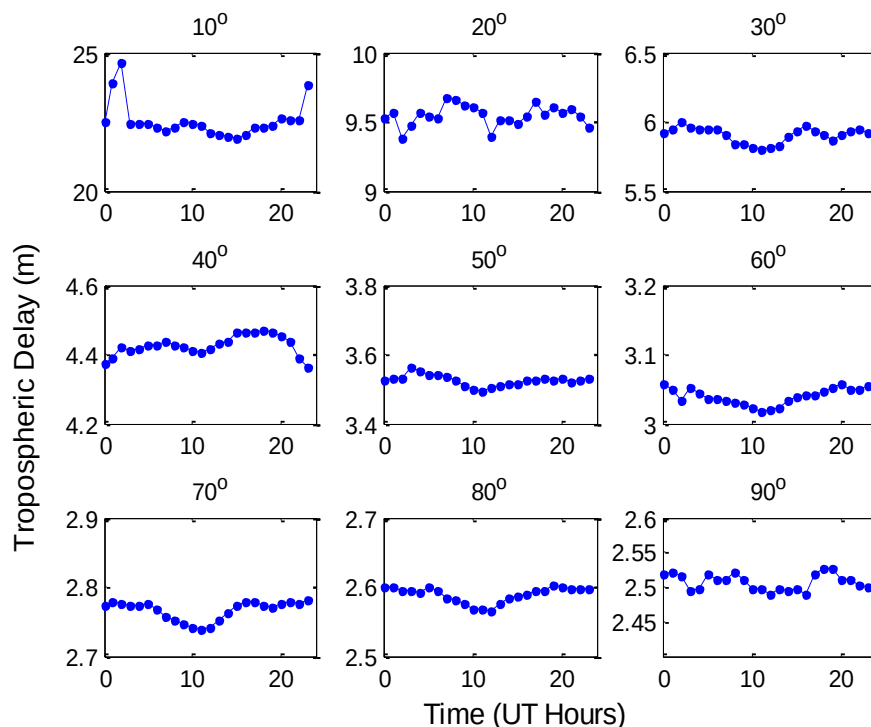


Figure 4. Time of day variation of tropospheric delay for various elevation angles, at Enugu.

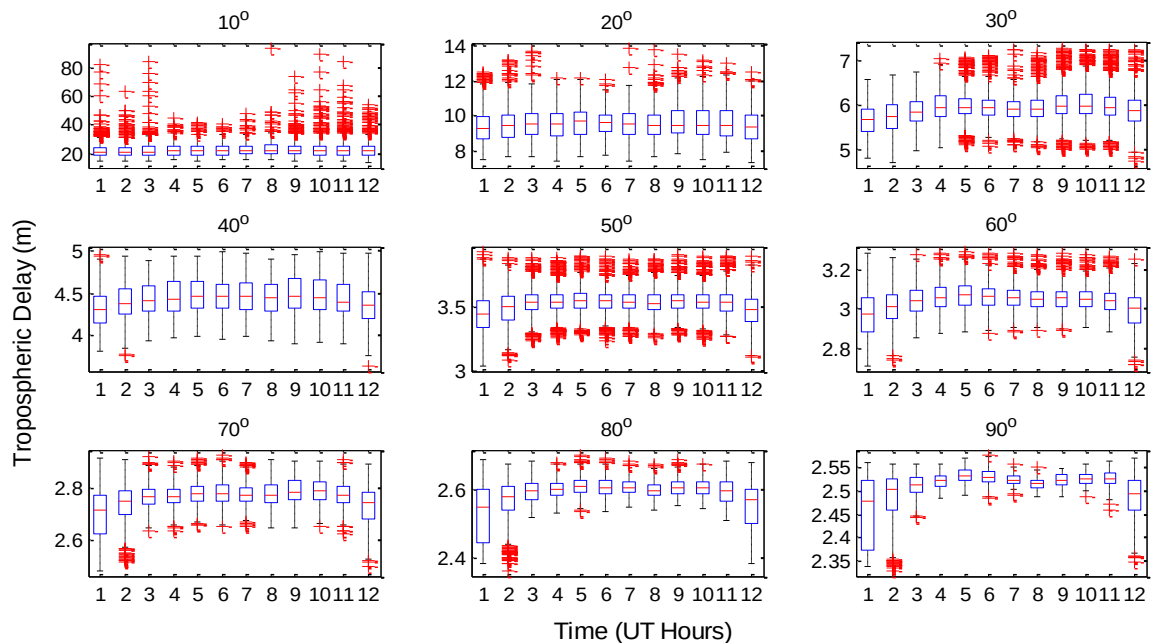


Figure 5. Box and whisker plots of monthly variation of tropospheric delay at Enugu, for various elevation angles.

box indicate the 25th and 75th percentiles respectively. The whiskers extend to the most extreme data points now considered outliers, and the outliers are plotted individually using the ‘+’ symbol [24]. The monthly distribution in Figure 5 presents information on seasonal variation of tropospheric delay at Enugu location. The observations are also binned in 10° interval of elevation angles, so the first plot (labelled 10°) contains observations for elevation angles of 10° or less, the second plot (labelled 20°) contains observations for elevation angles in the range 10° < el < 20°, and so on up to the ninth plot (labelled 90°) which contains observations for elevation angles in the range 80° < el < 90°.

Patterns of the GPS-derived tropospheric delays recorded at Enugu and Lagos are respectively shown in the colour maps of Figures 6(a) and (b). The maps represent mean values of the tropospheric delay computed for GPS satellites that have elevation angles greater than 45 degrees. The maps show hour-to-hour variations (vertical axis) and day-to-day variations (horizontal axis) of the mean tropospheric delay variations for all days in the years represented. As shown by the colour bars, the red colours indicate higher values of tropospheric delay (around 3.5 m and above), the blue colours indicate lower values of tropospheric delay (around 2.5 m and below), and the green colours indicate moderate values of tropospheric delay (around 3 m). The white spaces indicate no available complete pair of GPS and meteorology data at the time. The two stations illustrated have the most pair of GPS and meteorology data for the period of this study.

DISCUSSION OF RESULTS

The results in Figure 3 show that the tropospheric delay decreases with increasing elevation angles. In the five locations under study, the values of the delay are about 2.5 m for elevation angles of around 90°, and they exceed 20 m when the elevation angles drop to around 10°. The higher tropospheric delays observed at low elevation angles are connected to the fact that signals have higher attenuations at low elevation angles due to the longer transmission path lengths they have to traverse, and the underlying atmospheric conditions (such as humidity, pressure, and temperature) along the path traversed by the signal. There are not much differences in the tropospheric delay profiles for the five locations, since they belong to the same tropical savanna climate. It is because of these insignificant differences that the profiles overlap in Figure 3(i). This necessitated the zoom into the figure, so as to provide clearer and distinct views of the profiles as shown in Figures 3(ii) and (iii).

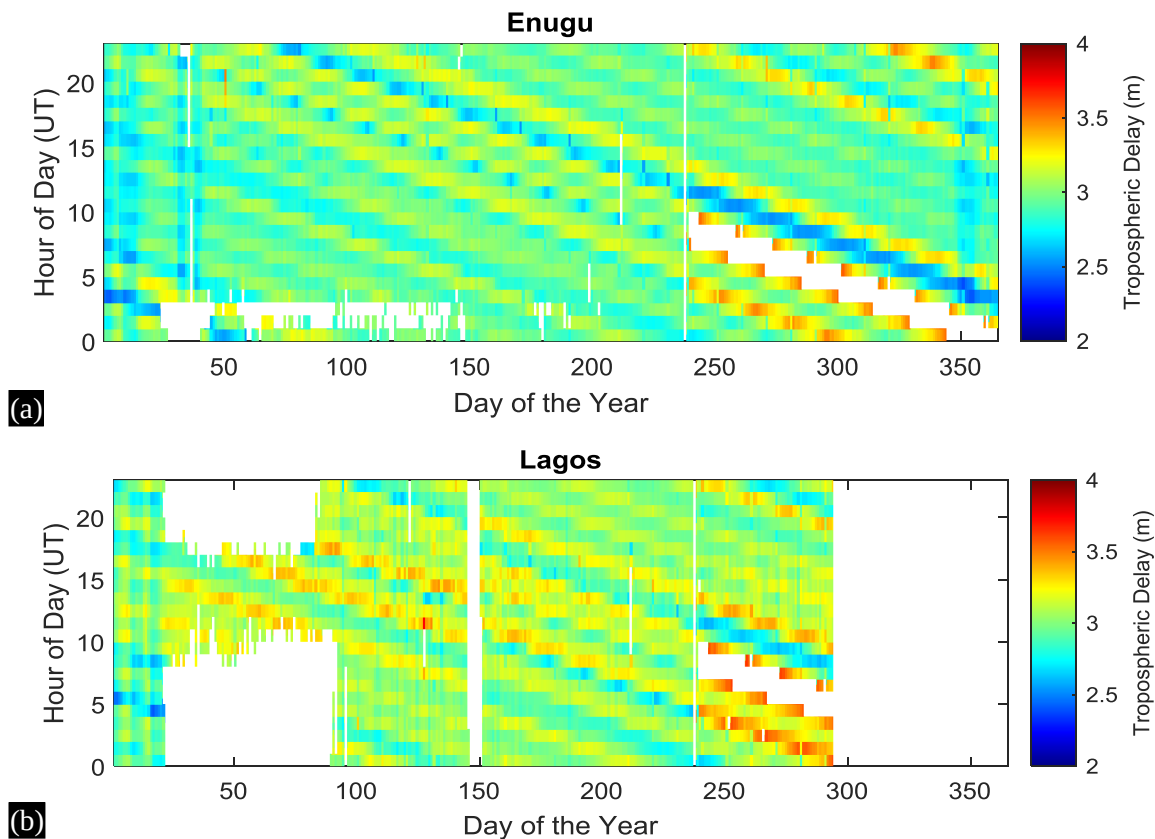


Figure 6. Colour maps of GPS-Derived Tropospheric Delays at (a) Enugu, and (b) Lagos. Values are averaged for GPS satellites with elevation angles greater than 45 degrees.

The figures show that the tropospheric delay is consistently higher in Lagos than in the other four locations. This can be explained by the fact that Lagos is in a coastal region, and so experiences higher tropospheric delays that result from corresponding higher humidities. Lagos is closely followed by Port Harcourt (which is also in a coastal region) in terms of the tropospheric delay. Table 1 also shows that Port Harcourt is at a slightly higher height above sea level than Lagos. This could also account for the slightly greater tropospheric delay observed in Lagos than in Port Harcourt.

For elevation angles greater than 20 degrees, the tropospheric delay is lower in Abuja than in the other four locations. Generally, the order of decreasing tropospheric delay for the five locations is: Lagos, Port Harcourt, Enugu, Akure, and Abuja. The reason Abuja records the least tropospheric delays can be attributed to its relatively lower humidities, following its inland location when compared to the location of the other cities.

For elevation angles higher than 50° , the tropospheric delay is typically lower than 3.5 m, and for elevation angles lower than 30° , the delay is typically greater than 6 m. The slopes of the curves are also higher for lower elevation angles, and they are lower for higher elevation angles. This is corroborated by results of the analysis presented in Table 2.

Table 2 shows that the changes in tropospheric delay are more rapid at lower elevation angles. The tropospheric delay changes by as much as about 60% for a 10° change in elevation angle between 10° and 20° . The change is only about 3% for same 10° change in elevation angle between 80° and 90° .

Most of the profiles in Figure 4 reveal diurnal patterns in which the tropospheric delays are higher during the early hours of the day, decrease to a minimum around local day time, and then increase

towards the late hours of the day. The first two profiles (for elevation angles of about 10° and 20°) exhibit rapid fluctuations of the tropospheric delay, which are associated with rapid changes in the tropospheric delay at lower elevation angles, as noted in Figure 3. The tropospheric delay profiles at around 10° and 20° elevation angles display somewhat erratic pattern that may be difficult to predict in propagation planning. This is attributed to the adverse weather effects on the satellite signals at these angles. The profiles in Figure 4 generally show that minima of the tropospheric delay profiles occur at around 10:00 to 12:00 UT. This can be inferred to be connected with decrease in humidity that is associated with daily sunrise activity.

Statistics of the monthly tropospheric delay distribution shown in the box and whisker plots of Figure 5 connote seasonal variations of the tropospheric delay. The plots typically show that the mean tropospheric delay values are higher during the months from March to September and lower during the months from November to February. These observations can be explained to be due to the reason that the months from March to September represent the rainy season for the region, when humidity is high, thereby contributing to the propagation delay. On the other hand, the months from November to February represent the dry season for the region, which is characterized by dry cold air during harmattan. The humidity is low during these months, and so the observed lower values of propagation delay.

For elevation angles of 10° and less (first plot in Figure 5), the monthly medians of tropospheric delays typically exceed 20 m, and occasionally reach 80 m, as indicated by the outliers. The outliers represent unusual data points which do not fit into the set within the lower and upper quartiles of the distributions. At around 20° (second plot in Figure 5), the monthly medians are about 9 m. The lower and upper quartiles of the distributions typically fall between 8 and 12 m. A decrease in the tropospheric delay is observed as we move across the plots in order of increasing elevation angles. This further corroborates the results in Figures 3 and 4, where the tropospheric delay decreases with increasing elevation angles.

The maps in Figure 6 reveal feature of diagonally-oriented structures in the maps. These structures are observed to be mainly due to the motion of the GPS satellites over the horizons at those locations. Higher tropospheric delay values are recorded when the satellites are at lower elevation angles, and lower tropospheric delays are recorded when the satellites are at higher elevation angles. The diagonal structures reveal a pattern in which the satellites reach similar elevation angles at some earlier times in the subsequent days than in the prior days. The tropospheric delay values are therefore similar at some earlier times in the subsequent days than in the prior days. The results indicate that the satellite elevation angle is the most dominant factor influencing the variation of GPS-derived tropospheric delay. However, variations of the tropospheric delay are also influenced by the changes in meteorological parameters of temperature, pressure and relative humidity. Variations in elevation angles however create the most conspicuous variations of the tropospheric delay. The reason is that, changes in elevation angles cause the tropospheric delay to change more significantly compared to changes that may be caused by the meteorological parameters.

CONCLUSION

The effect of GPS-derived tropospheric delay on radio propagation over some stations in the African equatorial region was examined. The tropospheric delays were observed to be higher in coastal cities, like Lagos and Port-Harcourt, than at inland cities like Abuja. This observation was attributed to the higher humidity of the coastal cities than at the inland cities.

Tropospheric delays were observed to exhibit an inverse relation with elevation angles. In the locations studied, the tropospheric delay values are about 2.5 m for elevation angles of around 90° , and they exceed 20 m when the elevation angles drop to around 10° .

Variations of the tropospheric delay are more rapid at lower elevation angles, and more gradual at higher elevation angles. The change in tropospheric delay is about 60% for a change in elevation angle from 10° to 20°, and about 3% for a change in elevation angle from 80° and 90°.

Diurnal profiles of the tropospheric delay exhibit minima at around 10:00 to 12:00 UT (which is 11:00 to 13:00 local time). This is obviously attributed to the fact that the relative humidity (which is a major factor contributing to the tropospheric delay) drops during these times of the day [25, 26]. The seasonal profiles exhibit minima during the months of November to February (which is the dry season), and maxima during the months of March to September (which is the rainy season). This is also obviously due to the fact that the relative humidity is at its minimum during the dry season and its maximum during the rainy season [27].

Time-dependent maps of the tropospheric delay indicate that elevation angle is the most influential factor in the variation of GPS-derived tropospheric delay. Changes in the satellite elevation angles cause the tropospheric delay to change more significantly, compared to changes that are caused by the meteorological parameters.

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REFERENCES

1. J. Dodo, M. Kamarudin, and M. Yahya, M. The Effect of Tropospheric Delay on GPS Height difference along Equator. *Survey and Land Information Science*: 2008; 68 (3):145-154.
2. A. Dodson, W. Chew, H. Bulcer et al. Assessment of EGNOS tropospheric correction model. *Proceedings of the 12th International meeting of Satellite Division of the Institute of Navigation*, Nishville, Tennessee: 1999; 54(1): 1401-1408.
3. A. Dheyaa, and H. Fayez, H. Estimation of Propagation Delays Induced in GPS Signals by some Atmospheric Constituents. *IOSR Journal of Applied Physics*: 2014; 5: 07-13
4. S. Katsougianapoulos.(2006 JANUARY 1) Tropospheric Refraction Estimation using various Models, Radiosonde measurements and permanent GPS data. *Researchgate*[Online] Available from [researchgate.net/publication/251893857_Tropospheric_Refraction_Estimation_Using_Various_Models_Radiosonde_Measurements_and_Permanent_GPS_Data](https://www.researchgate.net/publication/251893857_Tropospheric_Refraction_Estimation_Using_Various_Models_Radiosonde_Measurements_and_Permanent_GPS_Data)
5. J. Saastamoinen. "Saastamoinen J. Atmospheric correction for troposphere and stratosphere in radio ranging of satellites. 3rd ed. *Int Symp on the Use of Artificial Satellites for Geodesy*. 01 January 1972
6. Saastamoinen J. Contributions to the theory of atmospheric refraction. *Bulletin Géodésique* (1946-1975).1972;105(1):279-298.
7. H. Hopfield. Two quartic Tropospheric Refractivity profile for correcting Satellite data. *Journal Geophysical Research*: 1969; 74: 4487-4499.
8. J. Dodo, L. Ojidi & S. Tsebeje. Determination of the best fit Tropospheric delay model on the Nigerian Permanent GNSS network. *Journal of Geosciences and Geomatics*:2015; 3: 488-495.
9. J. Spilker. Tropospheric Effects on GPS,in Spilker and Parkinson(eds). *GPS Theory and Applications*: 1996; 163: 517-546.
10. Skone, S. Atmospheric Effects on Satellite Navigation Systems, ENGO 633 Course Notes: Ionosphere Phenomena and Indices.2007; Department of Geomatics Engineering, University of Calgary, Canada. 2007
11. S. Nister and S. Buda. Determination of Zenith tropospheric delay and precipitable water vapour using GPS Technology. *Mathematical Modelling in Civil Engineering*: 2016; 12 (1): 21-26.

12. E. Daniel, O. Mfon, and J. Amajana. Investigation of the Radio Refractivity Pattern Validation during rainy season in Calabar, Cross River State, Nigeria. *International Journal of Science, Engineering and Technology Research (IJSETR)*: 2015; 4: 4225-4227.
13. S. Shrestha. Investigation into the Estimation of Tropospheric delay and wet refractivity using GPS measurements. [GEOMATICS ENGINEERING]. [Calgary, Alberta, Canada]: UNIVERSITY OF CALGARY; July 2003.
14. E. Smith and S. Weintraub. The Constants in the Equation for Atmospheric refractive index in radio frequencies. *Proceedings of IRE*: 1953; 4:1035-1037.
15. Y. Olasoji. Effect of Atmospheric Refraction on wave propagation with variations based on Geographical Locations in Tropical Environments. *International Journal on Innovations in Engineering and Technology (IJET)*: 2016; 7(1): 37-40.
16. M. Bevis, S. Businger, S. Chiswell, T. et al. Mapping Zenith Wet Delay unto Precipitable Water. *Journal of Applied Meteorology*: 1994; 33: 379-386.
17. V. Mendes and R. Langley. Tropospheric Zenith Delay Prediction Accuracy for Airborne GPS High-Precision Positioning. *Journal of the Institute of Navigation*: 1999; 46 (1); 25-34.
18. G. Bean and G. Thayer. Models of the Atmospheric radio refractive index. *Proceedings of Institute of radio Engineers*: 1959; 47: 740-775
19. Jiao, G., Song, S., Su, K. et al. The Research on Optimal Tropospheric Combined Model Based on Multi-GNSS PPP: 2019 May 4; China: Springer Nature Singapore Pte Ltd. 2019.
20. T. Takasu. 2008. GPS Precise Analysis Software GPS Tools: Libraries. [online] Available from: <http://gpspp.sakura.ne.jp/gpstools/help/gpstools6/htm>.
21. J.N. Nzeagwu, J.U. Urama, A. E. Chukwude et al. 2020 June. Program to compute Means of GPS derived tropospheric delay with respect to elevation angles of GPS Satellites. [online] Available from: <https://zenodo.org/record/3886724>
22. P.R. Rao, K. Niranjana, D. Prasad et al. On the validity of the ionospheric pierce point IPP altitude of 350 km in the Indian equatorial and low- latitude sector. *Annales Geophysicae*: 2006; 24(8), 2159–2168.
23. G.K. Seemala and C.E. Valladares. Statistics of total electron content depletions observed over the South American continent for the year 2008. *Radio Science*: 2011; 46(5):1-14
24. Mathworks. 2020. Mathworks Documentation and Boxplot [online] Available from: <https://www.mathworks.com/help/stats/boxplot.htm>.
25. B. G. Ayantunji, P. N. Okeke, and J.O. Urama. Diurnal and Seasonal Variation of Surface Refractivity over Nigeria. *Progress In Electromagnetics Research B*: 2011; 30: 201–222.
26. A. Li, L. Huang, and T. Zhang. Field test and analysis of microclimate in naturally ventilated single-sloped greenhouses. *Energy and Buildings*: 2017; 138 (1): 479-4892.
27. O. R. Salau. The changes in temperature and relative humidity in Lagos state, Nigeria. *World Scientific News*: 2016; 49 (2); 295-306.